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ECHO TOPS FORECAST GENERATION AND EVALUATION OF AIR TRAFFIC FLOW MANAGEMENT NEEDS IN THE NATIONAL AIRSPACE SYSTEM†

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1. INTRODUCTION

Air traffic congestion in the United States (US) National Airspace System (NAS) has increased significantly in the past ten years. This congestion has resulted in a rise of air traffic delays, which can cause massive monetary and human costs. When convective weather impacts jet routes and airport terminals, particularly within the most congested airspace sectors, it causes a reduction in traffic capacity that can lead to significant delays. In an effort to increase airspace capacity and reduce air traffic delays, the Massachusetts Institute of Technology Lincoln Laboratory (MIT LL), in collaboration with the National Center for Atmospheric Research (NCAR) and the National Oceanic and Atmospheric Administration (NOAA) are tasked by the Federal Aviation Administration (FAA) to provide aviation weather decision support tools for the air traffic management (ATM) community.

To determine which weather products and data dissemination approaches will provide the greatest benefit in terms of increasing airspace capacity, MIT LL is performing ongoing marketing research analyses. The method consists of three primary steps (Ballentine 1994; Evans and Robinson 2005; Evans et al. 2003):

1) Study the system
2) Identify benefits
3) Prioritize opportunities

In practice, the execution of these three steps is an iterative process.

It is critical to understand how the air traffic system operates to assess the benefits of a weather product. For this reason many studies have been conducted by MIT LL where ATM users have been interviewed, use of decision support tools has been observed, and flight track data have been analyzed to extract the behavior of the pilot (Evans et al. 2003; Evans and Robinson 2005; Robinson et al. 2004; Rhoda et al. 2002; Allan et al. 2001; Bieringer et al. 1999; Rhoda and Pawlak 1999; Forman et al. 1999). These studies have provided valuable insight into how the NAS operates during weather impacts.

Weather impacts on the air traffic system can be classified into three basic types:

1) Terminal impacts (≤ 5 nm)
2) En route impacts
3) Transition impacts (between Air Route Traffic Control Centers (ARTCC) sectors and terminal operations)

Terminal impacts are those that occur in and around the airport, and are generally less than 5 nm from the runways. These impacts are small in dimension and occur at low altitude, and have been shown to be relatively insignificant to the overall delay problem (Evans et al. 2005). En route impacts occur within ARTCC's jet routes and sectors. These impacts can result in a route being totally or partially blocked and lead to a reduction in capacity. The en route impacts generally occur at high altitude. Transition impacts are those that occur within the zone between the ARTCC sectors and the terminal approaches.

By understanding the system one can then identify elements or areas of opportunities that can be exploited to help solve the airspace capacity problem. Weber et al. (2005) identifies four key elements for maintaining capacity during convective weather events:

1) Forecasts of convective weather
2) Capacity models where weather is an input
3) Strategy tools for ATM with weather as an input
4) Airspace capacity enhancements

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Forman et al. (1999) studied the terminal impact problem and found that the ATM users required precipitation forecasts that were reliable, updated rapidly (5-6 minutes), had high resolution (1 km), short lead times (1-2 hours), and were issued with fine time steps (10-15 minutes). MIT LL used this information to refine its terminal convective weather forecast (TCWF) and received very positive feedback from ATM personnel (Hallowell et al. 1999). Subsequently, the precipitation forecast was extended out to 2-hour-time horizons and was provided to the traffic managers working in busy Midwest and Northeast ARTCCs as part of the Corridor Integrated Weather System (CIWS) (See Klingle-Wilson and Evans (2005) for a description of the CIWS product). However, it was quickly determined that the precipitation product alone was not sufficient for identifying usable en route airspace, since occasionally significant precipitation (≥ level 3)[1] had relatively low storm tops (≤ 30 kft). Due to feedback from ATM users, MIT LL produced a high resolution (1 km) enhanced Echo Tops Mosaic weather product (Evans et al. 2003) that is used as a proxy for the cloud top height.

Since the operational inception of the CIWS enhanced Echo Tops Mosaic product in August 2002, FAA and airline traffic managers have become acutely aware of the benefits of high-resolution storm top information for efficient en route air traffic control (ATC) operations. CIWS field use assessment campaigns in 2003 revealed significant benefits attributed to use of the Echo Tops Mosaic product (Robinson et al. 2004). During interviews, traffic managers explained that in the past, if an aircraft deviated around a storm in high-traffic airspace, jet routes were closed by default, since pilot behavior was the only easily assessable information available about three-dimensional storm structure. After the CIWS Echo Tops Mosaic was introduced, traffic managers were able to differentiate between isolated storm top concerns, which are easily handled by keeping routes open and absorbing occasional, local deviations, and significant high-topped storm events, which legitimately require route closures and reroutes.

Post-event interviews in 2003 revealed that though FAA and airline users were very pleased with the availability and quality of the CIWS Echo Tops Mosaic product, they also needed to know both the past trend and predicted behavior of storm top heights. The CIWS Echo Tops Forecast (ETF) was introduced in May 2005 to meet some of the traffic management requests. This paper discusses the ETF product currently operational in CIWS. We will discuss the generation of the forecast algorithm and provide an initial assessment of the use of the ETF in the field.

[1]The VIL equivalent of the standard FAA precipitation levels.

2. FORECAST SYSTEM

In this section we present the forecast products that are computed and displayed in CIWS. There are two forecast products of interest: the Precipitation Forecast (PF) and the ETF. The PF is a forecast of the position, intensity, motion, and growth and decay trends of Vertical Integrated Liquid Water (VIL)[2]. The ETF is a forecast of the position, height, motion, and growth trends of the storms. The height estimate is the maximum altitude at which the radar reflectivity drops below 18 dBZ, and is a proxy for the cloud "precipitation" top (Smalley et al. 2003). We will primarily focus on the generation of the ETF, however the computation of the PF and ETF are coupled and when necessary parts of the PF algorithm will be discussed.

2.1 Forecast Displays

The forecast display is designed to show future locations of echo top heights and precipitation intensities in an easily understandable user interface. The PF and ETF products are currently displayed in separate windows on the CIWS Situation Display (SD) (see Figure 1). Since the PF was operational prior to the ETF, some of the display concepts from the PF were adopted in the ETF.

The ETF is displayed as an animated loop with 60 minutes of past echo top heights and 120 minutes of predicted echo top heights in 15 minute increments. The past Echo Tops are shown in 5 kft increments from 0 to 50+ kft above mean sea level, while the echo tops forecasts are provided for four discrete color intervals deemed operationally significant for traffic management (Table 1).

The PF can be viewed either as a forecast animation loop or as forecast contours on the current precipitation image. The animated loop shows past weather VIL that transitions to the forecast VIL after the current time out to the maximum forecast time horizon. For the forecast contour method, the contours are overlaid on the current weather VIL image. Contours of forecasted level 3 VIL and above for the 30, 60 and 120 minute forecasts can be displayed.

[2]In this paper Precipitation Forecast and VIL Forecast refer to the same forecast product.

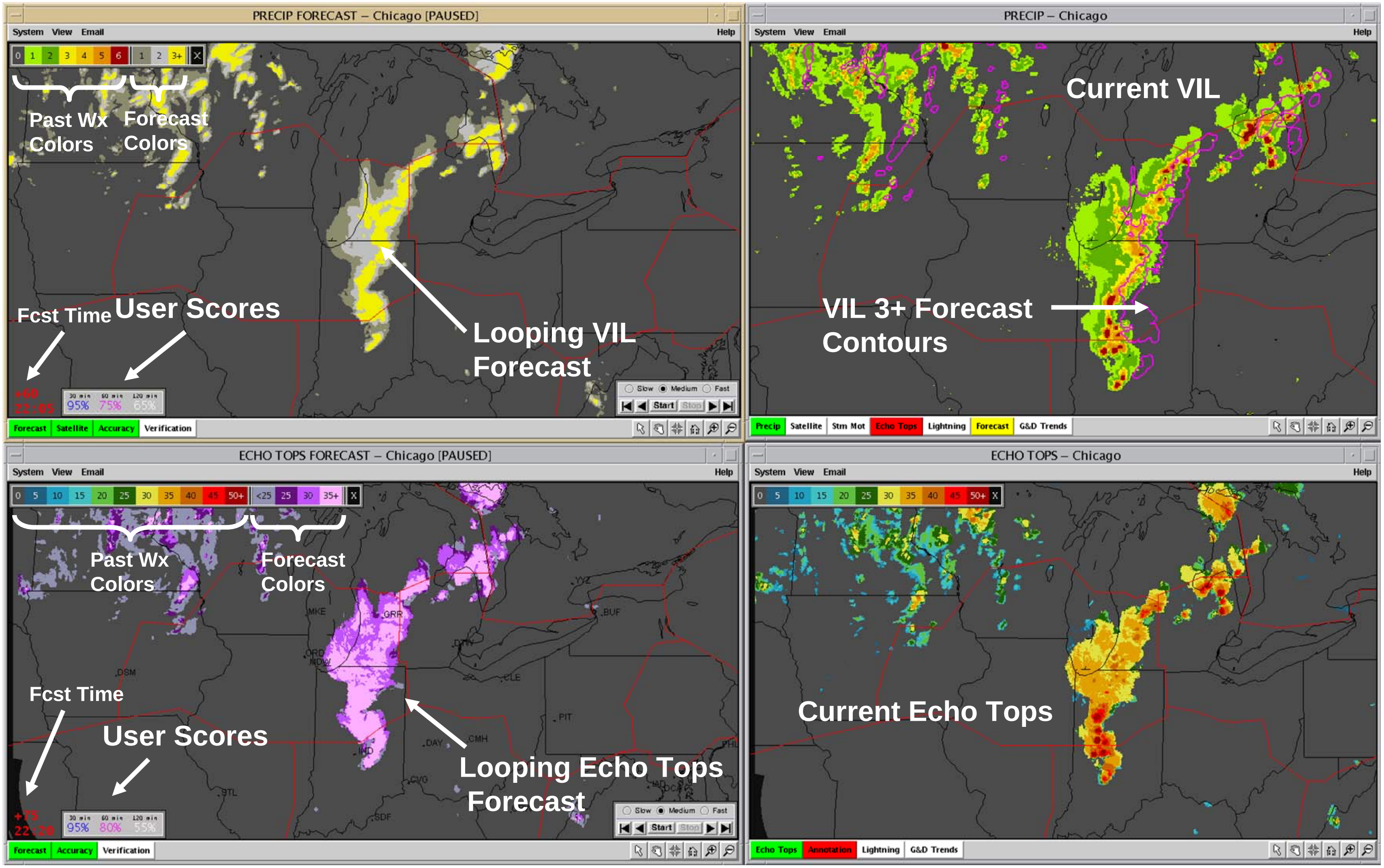


Figure 1: Display of Precipitation, Echo Tops, and 0-2 hour Forecasts of Precipitation and Echo Tops on CIWS Situation Display: The upper left window is the looping VIL Forecast. The lower left is the looping Echo Tops Forecast. The upper right is the current VIL with the 60 minute forecast level 3 contours overlay. The lower right is the current Echo Tops Mosaic.

Table 1
Echo Top Level Correspondence

Echo Tops Height (kft)	Echo Tops Forecast Level	Color
0	-	
5	1	Grey
10		
15		
20		
25	2	Dark Purple
30	3	Purple
35	4	Light Purple
40		
45		
50		

A forecast scoring metric for the ETF and the PF is also displayed on the SD. This is a “User Confidence Score” and provides real-time past performance of the algorithms. For the ETF the location of the 30 kft level is compared to the measured Echo Tops Mosaic at the validation times for 30, 60 and 120 minutes time horizons. In addition, forecast verification contours are displayed on the past Echo Tops Mosaic loop. The methods for calculating the ETF and PF scoring metrics are similar, and details of the PF scoring are discussed in Dupree et al. (2005) and Wolfson et al. (2004-b).

2.2 Echo Tops Forecast Algorithm

In this section we discuss the main areas of processing for the ETF system. The ETF algorithm is an extrapolation nowcast algorithm. It consists of a tracking step, a measurement of the growth and decay trends, and an extrapolation in horizontal and vertical space of the initial Echo Tops interest. The processing steps are as follows (Figure 2):

1) Scale Filter: Explicit scale extraction on VIL images
2) Track: Tracking of VIL images on multiple scales
3) Trends: Trending of both VIL and Echo Tops
4) Weather Classification
5) Echo Tops Cap: Past Echo Tops Maximum Height Estimate
6) Advect Interest: Motion Extrapolation
7) Echo Tops Forecast Engine: Storm Evolution Models

In the following sections we will discuss the construction of the ETF.

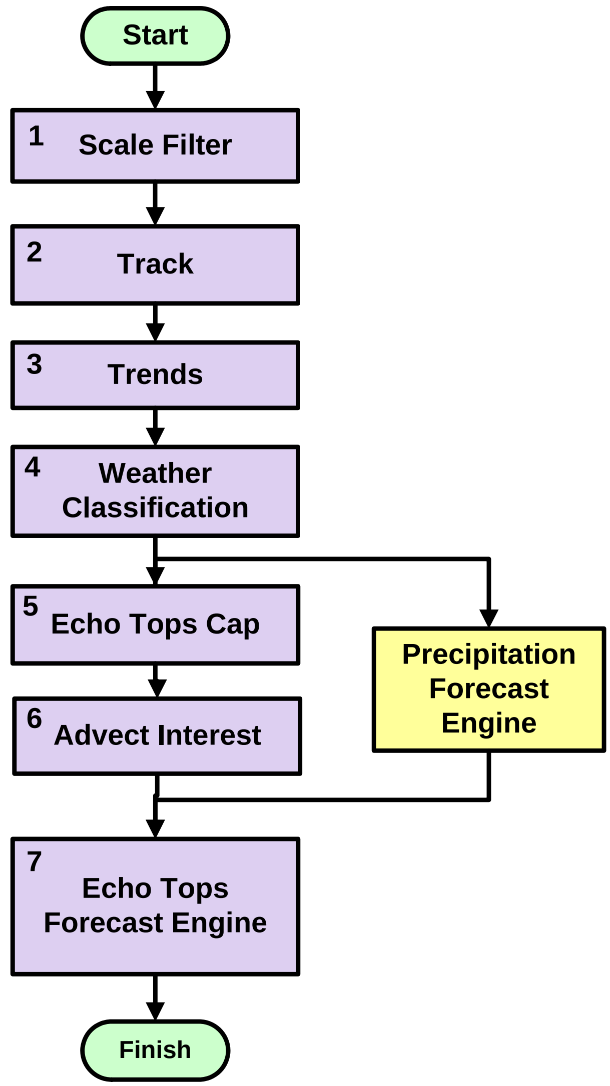


Figure 2: The functional flow of the ETF algorithm. The purple boxes represent the main components of the ETF algorithm. The yellow box depicts the generation of the precipitation VIL forecast. Note: The first four steps (Scale Filter, Track, Trends, and Weather Classification) are also steps in the generation of the precipitation VIL forecast but for simplicity the details are not depicted in this diagram.

A key component of the forecast system is the classification of weather based on storm cell phenomenology. Wilson (1966) showed that large scale features persisted longer than small scale features. Classification of the cellular nature of storms has been made by Weisman and Klemp (1986), where three distinct groupings were identified: airmass cells, multicellular (lines and squall lines), and supercells. In such a classification, airmass cells are typically short lived and it is difficult to predict where new cells will regenerate after collapse. Supercells and line storms tend to grow new cells along preferred boundaries and produce new groupings of cells. Using scale extraction techniques on radar imagery, one can improve tracking predictions of large scale motion (Bellon and Zawadzki 1994; Wolfson et al. 1999). Algorithms used to predict motion on multiple scales, with each demonstrating improved forecast performance, have been made by Seed and Keenan (2001), Dupree et al. (2002), and Lakshmanan et al. (2003).

2.2.1 VIL and Echo Tops Inputs

The ETF process relies on the NEXRAD Open Radar Product Generator (ORPG) high resolution enhanced VIL and Echo Tops products (Smalley et al. 2003) and VIL and Echo Tops data from the Canadian SIGMET radars. The high resolution 1 km VIL is chosen because it is a full column integration of precipitation, which serves as a more proportionate measure of updraft strength and overall storm severity than the traditional base reflectivity or composite reflectivity products. The high resolution enhanced Echo Tops product is free of the saw-tooth circular artifacts as observed in the legacy product and serves as a very reliable measure of the 18 dBZ storm tops.

The algorithm processes two basic types of images: per radar images and mosaiced images. Per radar images are two-dimensional Cartesian images that come from a single sensor. The mosaic images are composites from NEXRADs and Canadian SIGMET radars in the domain of interest. Details on the mosaicing of VIL and Echo Tops can be found in Wolfson et al. (2004-a).

2.2.2 Weather Classification

Weather Classification is a key component of the ETF system. Convective and stratiform partitioning classification schemes based on radar precipitation images have been studied by many researchers (Anagnostou 2004; Biggerstaff and Listemaa 2000; Awaka et al. 1997; Steiner et al. 1995). However, these schemes limit the classifications to three basic categories: convective, stratiform, and other.

Dupree et al. (2002) introduced the convective weather classification scheme that extracts lines, cells and stratiform precipitation regions from VIL images. This approach aims to classify the radar returns not only as convective or non-convective but assigns them a distinct phenomenological class. This algorithm was later enhanced to use additional input fields, and to provide growing and decaying sub-type categories (Wolfson et al. 2004-b). Weather types are constructed from the VIL, Echo Tops, and precipitation trend images using Functional Template Correlation (Delanoy et al. 1992) and image processing region analysis. Figure 3 shows an example of the weather classification image for a single radar mosaic.

A more in-depth explanation of the weather classification algorithm is given in Dupree et al. (2005) and Wolfson et al. (2004-a).

2.2.3 Scale Separation and Tracking

The MIT LL tracking scheme makes a simplifying assumption that the motion scales of interest are composed of two important scales: large scales (envelope) indicative of lines and large cells and small scales typical of airmass cells. The extraction and tracking of these scales is called the multiscale tracking method. This method has been discussed in detail elsewhere (Dupree et al. 2005; Wolfson et al. 2004-a; Dupree et al. 2002) therefore we will only briefly highlight the key points. First, envelope features are extracted by applying a series of rotated-elliptical-mean filters to the input VIL images. Then a cross-correlation tracking method (Chornoboy et al. 1994) is applied to successive images to produce envelope track vectors. A similar technique is applied to cell images to produce cell tracks.

Since the scales of motion can be connected to specific weather types, we use the weather type image as a sorter of raw track vectors and then interpolate the final vector sets to produce a mixed scale vector set for extrapolation. We also chose to use the VIL tracking motion to advect the Echo Tops interest since the echo tops and VIL data are derived from the same sensors and have similar characteristics.

2.2.4 Echo Top Trends

In this section we focus on the trending of the echo top heights. The rate of growth and decay of the echo top heights are measured by differencing the Echo Tops images between previous images in a Lagrangian sense. The previous Echo Tops images are advected forward using the tracking vectors appropriate for small scale features. Next the images are differenced in a pixel-wise sense. Finally a 7x7 mean filter is applied to the difference image to smooth spurious difference pixels. Shown in Figure 4 is an example of the mean echo top height rates. These values are used subsequently to vertically extrapolate the current echo top heights.

2.2.5 Echo Tops Cap

When forecasting echo top heights it is important to have a good estimate of what height one might expect the storms to achieve. To estimate these maximum height values we look at the statistics of previous storms within the region of interest. Estimates of the maximum tops are made by calculating the distribution of echo tops under a 51 km circular kernel that is applied to the current and two previous Echo Tops Mosaic images (up to 10 minutes in the past) (Figure 5). For each pixel in the domain, the 98^{th} percentile is found and placed on a separate “echo tops cap” image. This image serves as an estimate of the maximum growth height in the echo tops storm model described in the following section.

2.2.6 Echo Tops Storm Growth Model

Once the desired interest images are created they are combined to create a series of forecast time horizons. For the echo tops model we ingest VIL forecasts and use them in conjunction with the other interest images to create a trending and advection echo tops forecast. For the echo tops forecast engine, interest images are combined in a post-advection model. Post-advection combination can be achieved efficiently by pre-calculating a set of advection maps. These advection maps contain the indices of the grid locations where the interest is to be advected for each time horizon. This method ensures that all input images are moved in a consistent way to the same advection pixel. Additionally the echo tops cap, weather type, echo tops trends, and VIL are ingested. For each time horizon these images are advected.

The echo tops trends are applied to growing convective elements, weather types with line, and large, small and embedded cells (see Figure 6). These trends are in units of meters/min and we assume a linear growth model for the initial growth phase. Once the echo top has grown to the echo top cap, the top is held at this level for the remaining forecast time horizons. For the remaining weather classification types we do not apply the growth model but only apply advection, thereby not trending the tops for these types. In a final step, a 5x5 km median filter is applied to the final forecast images.

3. ECHO TOPS FORECAST FIELD USE ASSESSMENT

The established weather product development approach of MIT LL involves routine interaction with FAA and airline traffic managers with access to deployed prototypes. Through direct field observations and post-event exit interviews, we can identify whether expected user benefits are achieved and ensure that user-needs are driving and prioritizing potential enhancements. A significant component of this user-feedback endeavor was the CIWS field use assessment campaign conducted in June – August 2005 (Robinson and Evans 2006). As part of this effort, real-time observations of CIWS product usage during three multi-day thunderstorm events were carried out at six ARTCCs. Particular attention was paid to usage of the ETF product, since it was a new feature of CIWS, and in general, automated predictions of storm heights for use in optimizing operational traffic flow management were unavailable prior to this technology release.

CIWS product usage observations were encouraging. Overall, use of ETF to help improve airspace management efficiency and reduce air traffic delays during convective weather impacts was observed at each FAA facility visited in 2005. Specifically, Figure 7 shows that use of ETF information assisted traffic managers to realize 15 of the 16 identified CIWS benefits categories during the three product-usage assessment campaigns in 2005[3]. The ETF product provided substantial assistance when users sought to (a) diagnose impacts on jet routes, and (b) optimize route capacity and reroute efficiency when impacts were expected (Benefit Categories 1, 3, and 7 in Figure 7). Moreover, to achieve these and other operational benefits, ETF information proved extremely valuable by enhancing common situational awareness of predicted three-dimensional storm structure, thus facilitating quick, decisive inter/intra-facility coordination when developing tactical weather impact mitigation plans (Benefit Categories 12, 14, and 16 in Figure 7).

[3] The use of CIWS for enhanced runway planning is a traffic management benefit realized at terminal facilities. Since the 2005 CIWS field-use campaign included only ARTCCs, this benefit was not observed with this subset of users.

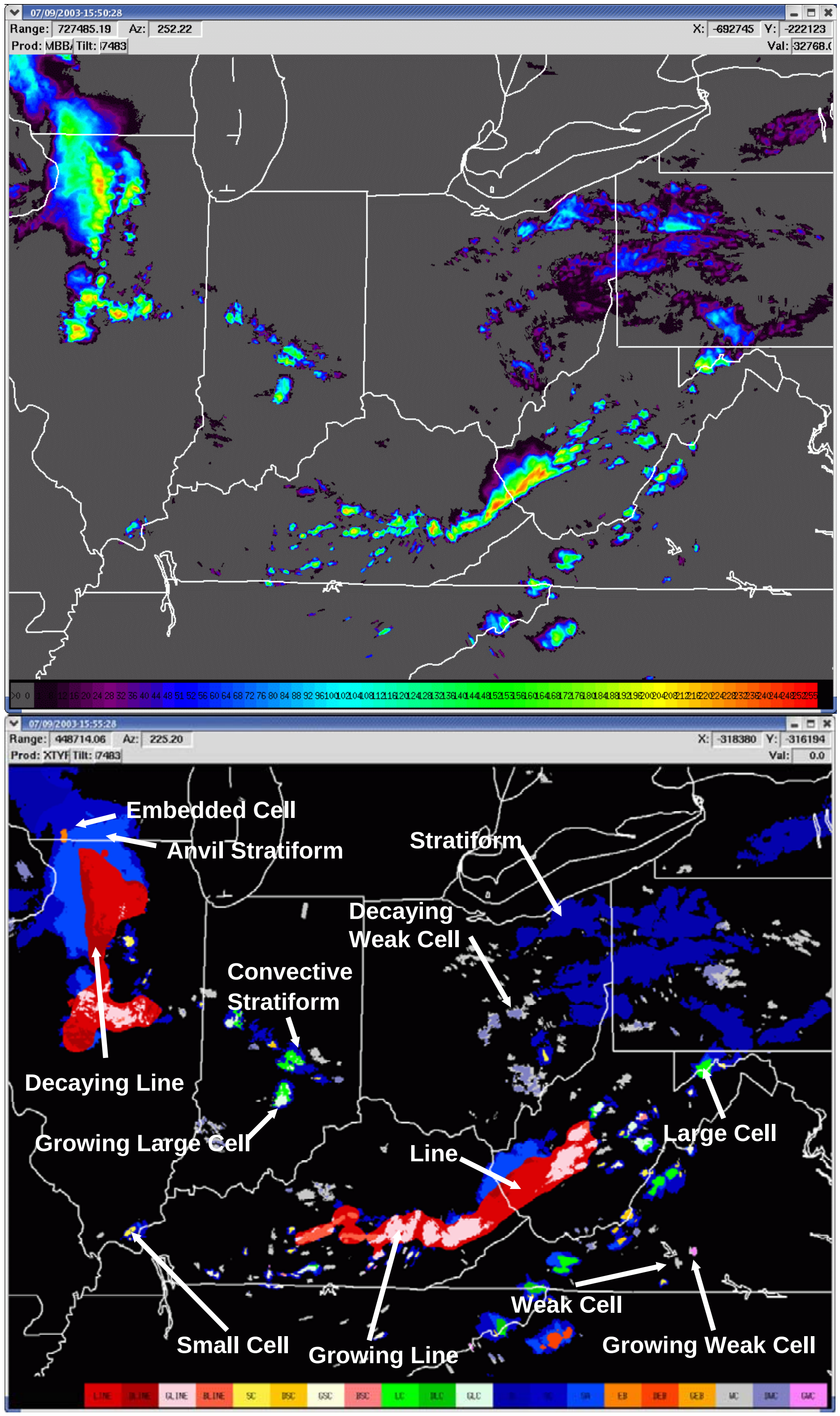


Figure 3: The VIL and weather classification image showing examples of weather features.

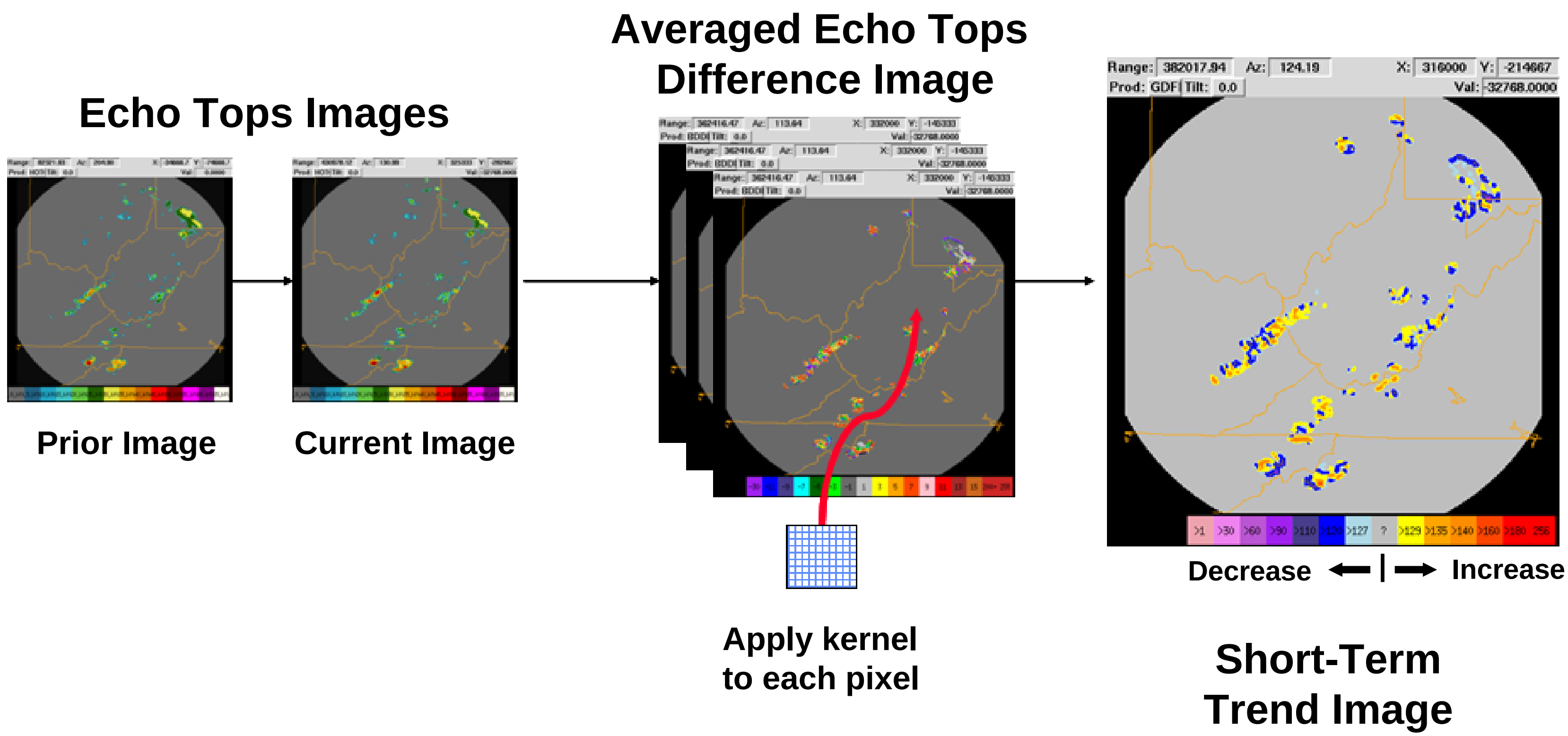


Figure 4: Echo Tops Trends: This figure shows the algorithm steps used to create the echo tops short-term growth and decay interest. The first step shows the differencing of prior images, the middle graphic is the step where previous images are temporally and spatially averaged, the right image is the final short-term echo tops growth and decay image.

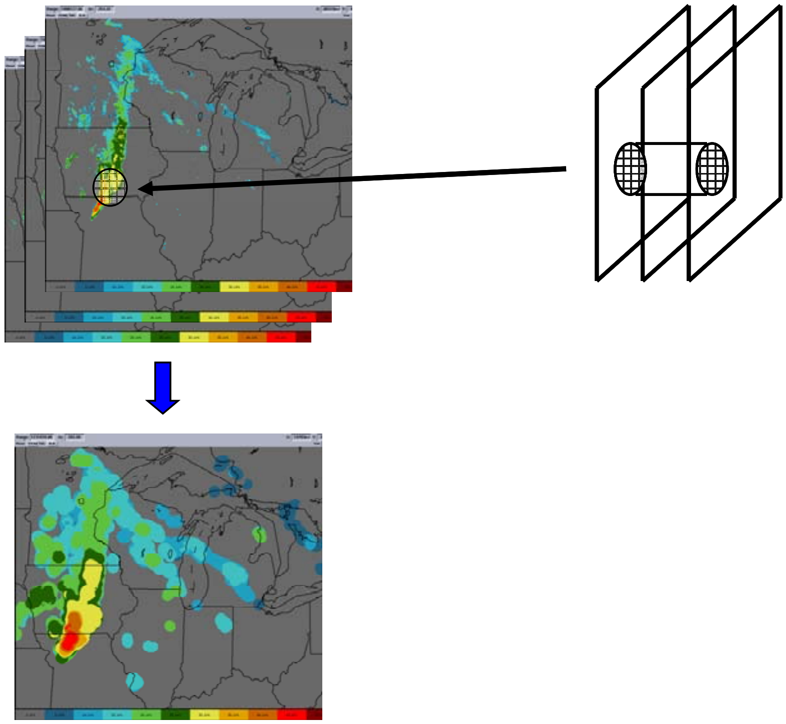


Figure 5: Echo Tops Cap Image: The echo tops cap is estimated by finding the 98th percentile of an echo tops distribution from the current and previous two echo tops images, 5 minutes apart and under a 51 km circular kernel.

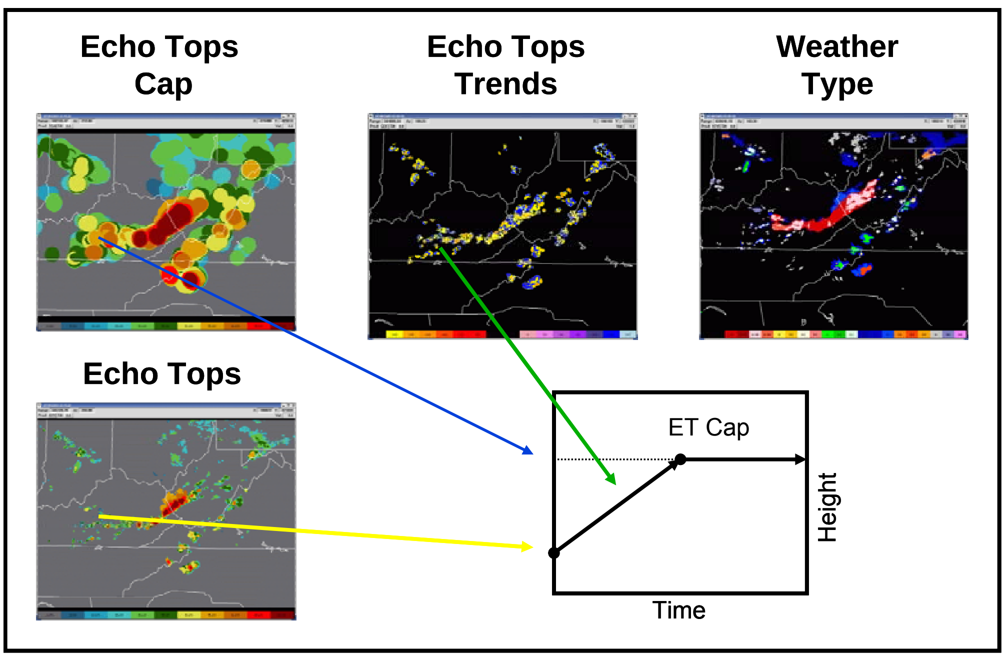
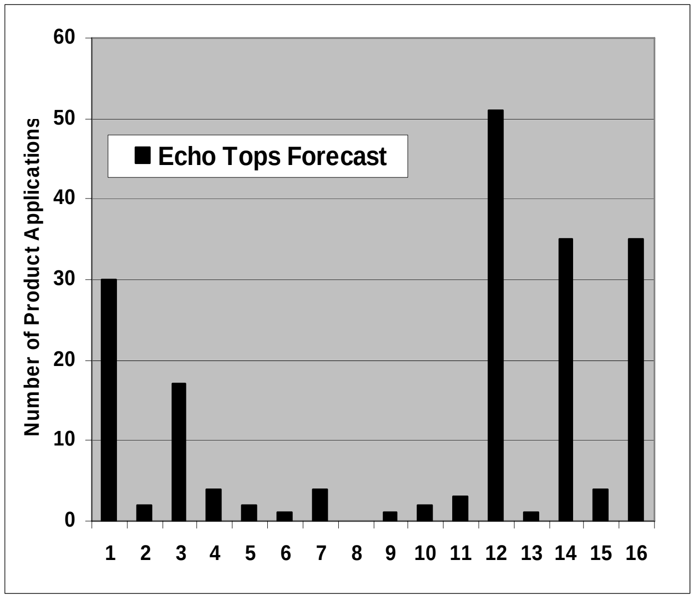


Figure 6: Echo Tops Forecast Engine. The echo tops forecast engine applies a simple growth model to the current echo tops height field. Short-term echo tops growth rates are applied as a function of forecast time horizon in regions of convective weather, until the echo top height reaches the maximum cap as measured by previous echo tops distributions in the area. Non-convective weather is simply advected and growth and decay trends are not used.



1	Routes open longer	8	Enhanced runway planning
2	Close routes proactively	9	Improved GDP management
3	Proactive, efficient reroutes	10	More SWAP departures
4	Improved Ground Stop Program management	11	Directing pathfinders
5	Reduced MIT restrictions; Proactive route management	12	Inter/Intra – facility coordination
6	Directing traffic through weather gaps	13	Improved safety
7	Improved ATA/DTA management	14	Increased TMU productivity
		15	FAA staffing assistance
		16	Improved situational awareness

Figure 7: Observed frequency of Echo Tops Forecast product usage to realize specific CIWS traffic management benefits at six FAA ARTCCs during three multi-day convective weather events in 2005. Acronyms: Miles In Trail (MIT), Arrival Transition Area (ATA), Departure Transition Area (DTA), Ground Delay Program (GDP), Severe Weather Avoidance Program (SWAP), and Traffic Management Unit (TMU).

The two most significant CIWS en route traffic management benefits, in terms of delay reductions and increased FAA productivity through improved decision-making, are (1) keeping established routes open longer or reopening closed routes sooner and (2) more proactive, efficient traffic reroutes (Robinson et al. 2004; Robinson and Evans 2006). The frequency of CIWS PF and Echo Tops Mosaic product usage in 2003 versus 2005 to achieve the two primary air traffic route management benefits is shown in Figure 8. The results demonstrate the importance of Echo Tops information for optimizing en route weather impact mitigation planning. Despite being a new product and a new weather tool concept, use of ETF in 2005 to improve airway and reroute management exceeded the rate of use of the 0-2 hour Precipitation Forecast during its first full summer of use in 2003. This high usage of the ETF product underscores the perceived importance of storm height predictions to air traffic managers.

An example of an ETF route management benefit typically observed during field use assessments is presented in Figure 9. Since the introduction of CIWS high-quality, mosaiced Echo Tops information, en route traffic managers have revolutionized their approach to weather impact mitigation planning. Now, storm height characteristics are consulted just as frequently as storm intensity data when determining airspace availability and degree of route/sector blockage. The ability to identify predicted trends in storm echo tops allows traffic managers to proactively plan for route closures and reopenings with an eye towards storm over flight potentials. Similar to the 6 June 2005 impact event (Figure 9), traffic managers were observed on numerous occasions using the CIWS ETF product to reopen closed routes early, by way of storm over flights and often independent of current and predicted storm precipitation intensity.

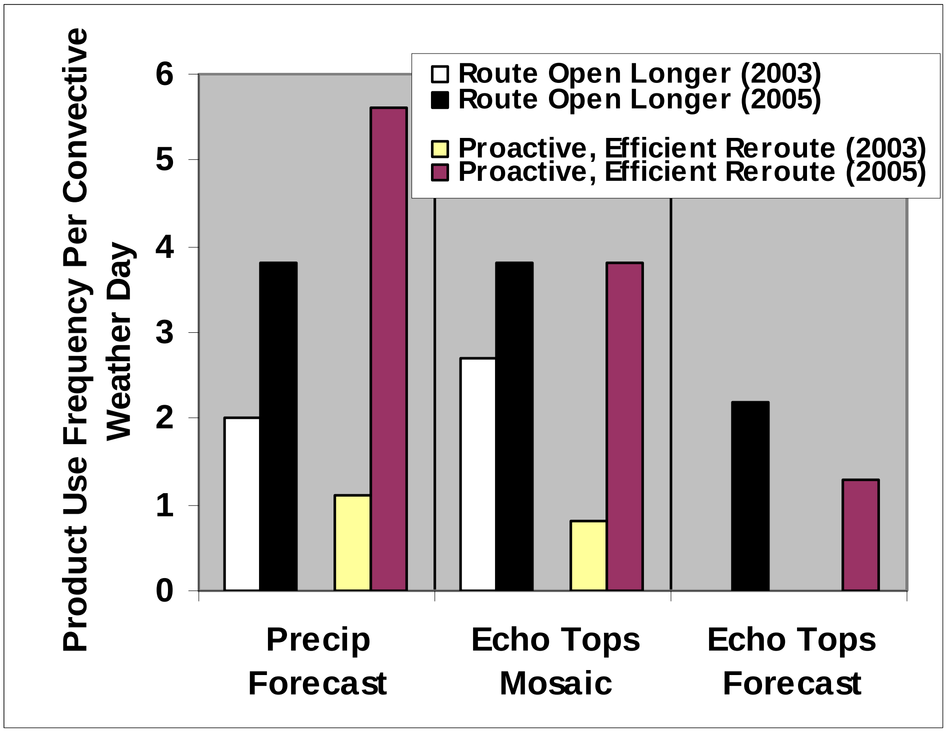


Figure 8: Frequency of CIWS Forecasts and Echo Tops Mosaic usage in 2003 versus 2005 to achieve two primary CIWS en route air traffic delay reduction and airspace complexity benefits: Keeping Routes Open Longer and More Proactive, Efficient Reroutes.

4. FLIGHT TRACK OBSERVATIONS

To provide weather products that have the greatest utility for ATM, it is important to gain an appreciation of pilot behavior in the presence of convective weather. Perhaps the best way to understand pilot behavior is through an analysis of flight track data. The following basic information regarding the impact of weather on pilot behavior has been obtained by observing ATC operations, flight data, and CIWS weather products:

1) Pilots routinely fly over low echo top weather in en route airspace even if the VIL levels are ≥ level 3.
2) Storm turrets are generally avoided.
3) High echo tops (≥30 kft) and high VIL (≥ level 3) are not always good predictors of route blockage (Figure 10).
4) Pilots will routinely fly over anvil blow off. However, there may be regions within the blow off that are undesirable, for example downwind from a turret where the air is often turbulent as it flows around the “obstacle”.
5) Echo tops may also be important as a proxy for convective turbulence in terminal airspace, where aircraft are climbing to cruise altitude but are not able to fly over storm tops (Figure 11).

Many of these observations were supported in a study by DeLaura and Evans (2006) that looked at more than 800 flight trajectories through two ARTCC super-sectors during five days in the summer of 2003. The objective of this study was to determine key parameters that could predict if a pilot would deviate around a storm. The best predictor of convective weather deviations was the difference between flight altitude and echo tops. More than 70% of pilots did not deviate when their planned jet route was above 5 kft of the storm to be encountered.

Observations 2 and 3 imply that detailed information about the vertical storm structure is needed in order to make an accurate assessment of the convective hazard. It is also important to relate storm top heights to flight altitudes in order to determine which flight levels may remain open to traffic that can fly over storm tops. This suggests that higher resolution is needed in the ETF, even at altitudes above 35 kft.

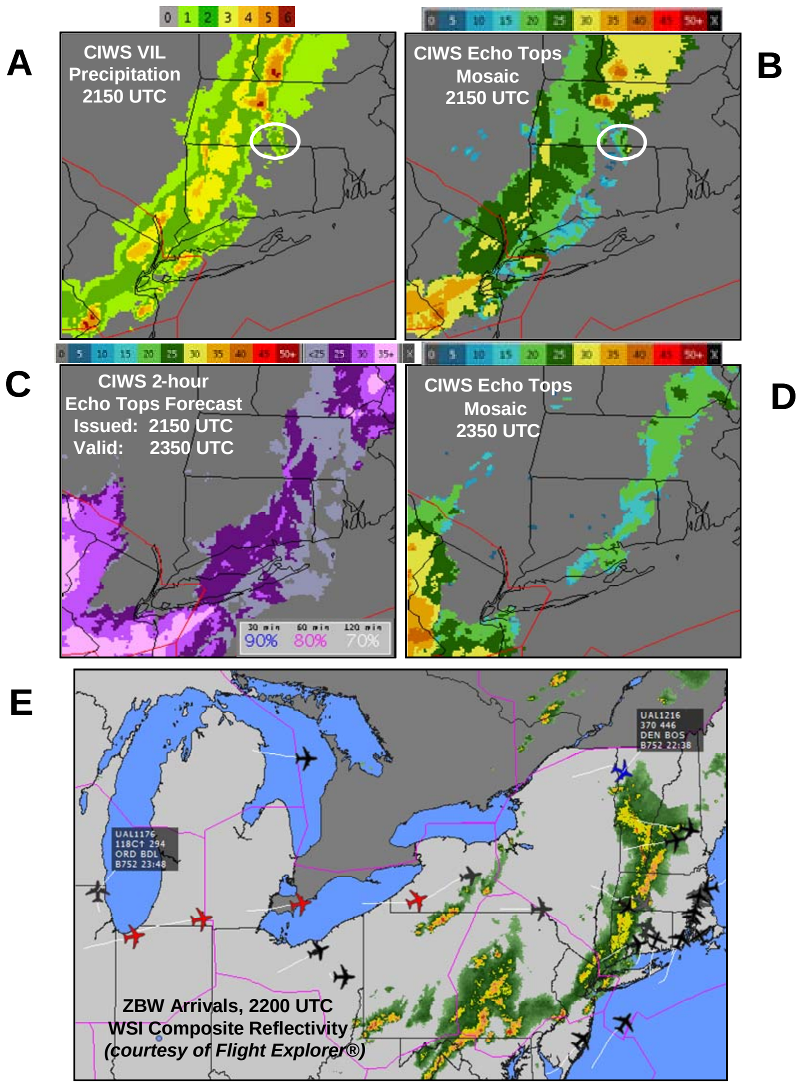


Figure 9: (A) CIWS NEXRAD VIL Precipitation on 6 June 2005 at 2150 UTC, (B) CIWS Echo Tops Mosaic at 2150 UTC, (C) CIWS 2-hour Echo Tops Forecast issued at 2150 UTC, (D) CIWS Echo Tops Mosaic at 2350 UTC, time of Echo Tops Forecast verification, and (E) FlightExplorer® flight tracks and Weather Services Inc. (WSI) composite reflectivity showing flights en route to Boston (MA), Providence (RI), Hartford (CT), and Manchester (NH) airports. At 2150 UTC, a near solid line of level 3+ convection, with embedded echo tops exceeding 30 kft, continued to significantly impact air traffic operations in the Boston (ZBW) ARTCC (see A and B). Despite near-term storm severity, and the threat of new storm development (circled region in A and B) ZBW traffic managers used the 2-hour Echo Tops Forecast (see C) and the looping past Echo Top Mosaic to determine that storm heights were decreasing and key airways blocked by weather would be available to ease capacity constraints. Forecast accuracy scores for predicting 30 kft+ echo tops at 30, 60, and 120 min were 90%, 80%, and 70%, respectively (See C – inset). Using this Echo Tops Forecast, ZBW traffic managers, in collaboration with neighboring ARTCCs, allowed en route transcontinental flights to ZBW (see E – aircraft colored red) to discontinue longer, more complex reroutes around the north end of the squall line (see E – aircraft colored blue in northern VT is last flight to use extended reroute) and return to normal routes through central NY. Additionally, the ground stop for Chicago O'Hare (ORD) flights to ZBW airports was discontinued early based upon the Echo Tops Forecast (see E – flight departing from ORD to Hartford). Inspection of the Echo Tops Mosaic at the time of forecast verification (See C and D) demonstrates the accuracy of the 2-hour Echo Tops Forecast.

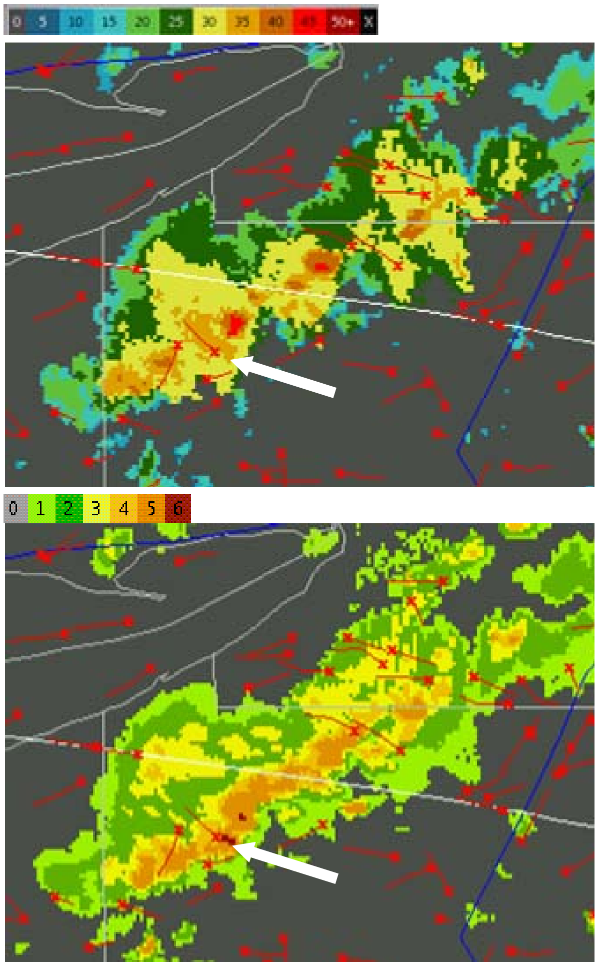


Figure 10: Echo Tops Mosaic in kft (top) and 6-level VIL precipitation (bottom). The red 'x' and tail denotes flight tracks ≥ 16 kft. The white arrows show an area where planes are flying in the vicinity high tops (>35 kft) and high VIL (≥ level 3). This figure demonstrates that depictions of high tops (>35kft) and high VIL (≥ level 3) are not necessarily adequate indictors of no-fly zones as shown in the ETFs and PFs.

5. FUTURE DIRECTIONS

Now that the ETF is operational we seek to maximize its utility through product enhancements and improvements. Two main areas are identified:

1) Forecast algorithm enhancements
2) User interface improvements

Through conversations with ATM users we have learned that the Echo Tops past weather loop is used extensively to identify growing or decaying trends in storm top heights. Currently, long-term (>20 min) storm top decay trends are not captured in the ETF model. Based upon observations of ATC operations and CIWS product usage, we suspect that reliable predictions of long-term storm top evolution trends will provide significant assistance to ATM when developing weather impact mitigation plans.

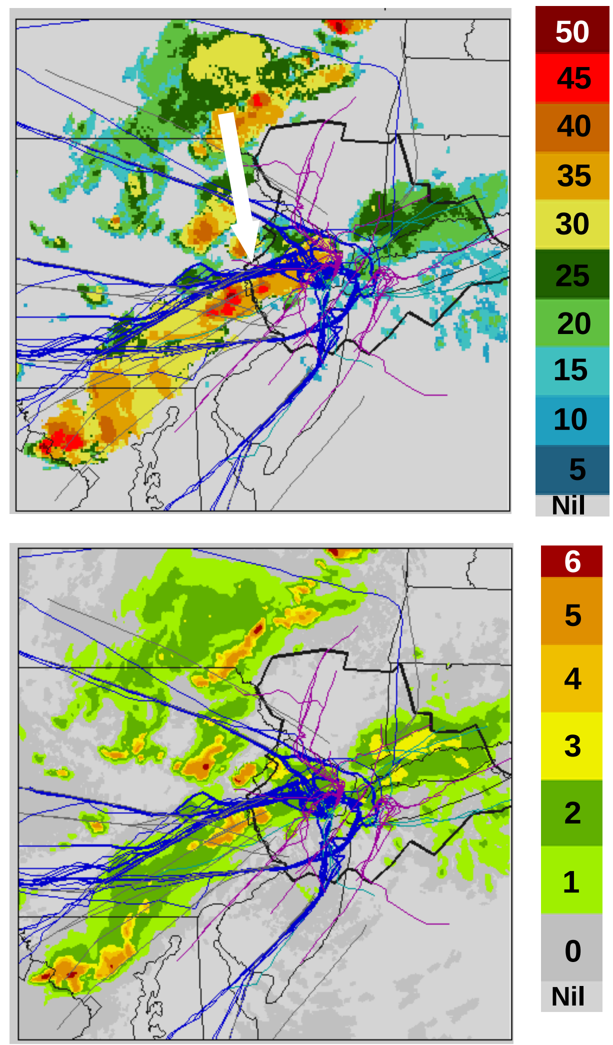


Figure 11: This figure shows Echo Tops in kft in the top image and 6-level VIL in the bottom with cumulative departures (dark blue and cyan) and arrivals (magenta) in New York Terminal Radar Approach Control (TRACON) (heavy black line) over a 30 minute period centered on 2245Z on June 29, 2005. Note westbound traffic flow around 50 kft convective cell (white arrow) on the TRACON boundary, where aircraft are still climbing to cruise altitudes.

The ETF display currently shows all tops >35 kft with a single color, in some cases this results in large broad forecast areas where it is difficult to discern storm structure in the forecast. An example of this can be seen in Figure 1, where a broad, rather featureless area of >35 kft exists over Indiana. In addition, observations of flight track data suggests that 5 kft is an important dimension scale for top over flights, illustrating a need for a product that can show greater storm detail. A few enhancements under consideration are:

1) Finer resolution in the forecast color maps
2) Product representing a combination of Precipitation (VIL) and Echo Tops Forecasts for use in identifying structure
3) Development of novel overlays for the forecasts that depict storm structure

Observations with ATM users at the facilities have also shown a preference for the contour overlay of the PF on the current weather precipitation window. This method is preferred because information about current storms and predicted areas of level 3 and above can be gained at a glance allowing quick decisions to be made. It has also been noted that observing the animation loop can be time consuming. Based on this feedback, the users might benefit from having an ETF contour on the current weather displays.

In order to address forecasting of tops beyond the 2 hour time horizon, MIT LL is currently evaluating an echo tops forecast product derived from the fifth-generation Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model (MM5, Grell et al. 1994) reflectivity forecasts. Shown in Figure 12 is an example of an MM5 8.5 hour Echo Tops Forecast verified against the CIWS Echo Tops Mosaic product at time of validation. The MM5 captures the location and nature of the echo tops even at this relatively long lead time. The MM5 ETFs are promising; however more work is required to fully evaluate the model's performance and utility to forecasts beyond 2 hours. Data fusion methods are also being evaluated to blend extrapolation and numerical weather prediction forecasts.

6. SUMMARY

In this paper we have presented a novel Echo Tops Forecast product that forecasts the position, height, motion, and growth trends of the cloud tops out to 2 hour lead times. The ETF product was introduced to the CIWS prototype in May 2005 and is currently being evaluated in the NAS. The ETF shows consistently good performance over long periods of operation and during periods of convective growth (Dupree et al. 2005).

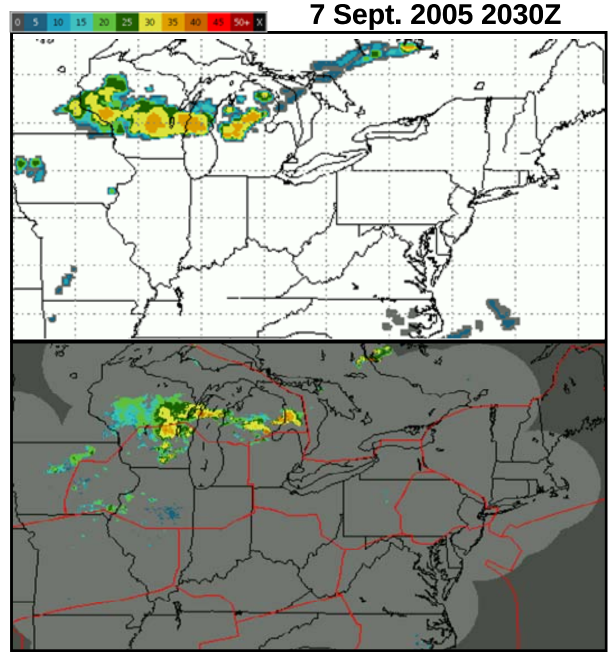


Figure 12: MM5 Echo Tops Forecast: Shown are the 8.5 hour lead time MM5-generated Echo Top Forecast in kft (top) and the CIWS Echo Tops Mosaic in kft at the time of forecast validation (bottom). The spatial resolutions are 9 km and 1 km for the MM5 ETF and the Echo Tops Mosaic respectively.

In the summer of 2005, MIT LL conducted a field use assessment that involved direct field observations of operations and post-event interviews with ATM. The results show that the most significant benefits of the ETF to ATM were improved convective weather impact mitigation plans, reduced airspace complexity, and improved inter/intra-facility coordination. As a result of these benefits, the CIWS ETF product has assisted in avoiding air traffic delays and hence helped in maximizing airspace capacity. This paper also discusses observations from a MIT LL analysis of flight track data that was undertaken to provide insight into how planes are flying in convective weather. The results from the field use assessment and flight track analysis are being used to guide future enhancements to the ETF product. The future enhancements, which include algorithm and display improvements, are also discussed in this paper.

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