5.5 FORECASTING CONVECTIVE WEATHER USING MULTI-SCALE DETECTORS AND WEATHER CLASSIFICATION – ENHANCEMENTS TO THE MIT LINCOLN LABORATORY TERMINAL CONVECTIVE WEATHER FORECAST

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1. INTRODUCTION[†]

Over the past decade the United States has seen drastic increases in air traffic delays resulting in enormous economic loses. Analysis shows that more then 50% of air traffic delays are due to convective weather. In response the FAA has assembled scientific and engineering teams from MIT Lincoln Laboratory, NCAR, NSSL, FSL and several universities to develop convective weather forecast systems to aid air traffic managers in delay reduction. A user-needs study conducted by Lincoln Laboratory identified that a major source of air traffic delay was due to line thunderstorms (Forman et al., 1999).

Recognizing that the line storm envelope motion was distinct from the local cell motion was the impetus for developing the Growth and Decay Storm Tracker[1] (Wolfson et al., 1999). The algorithm produces forecasts by extracting large-scale features from two dimensional precipitation images. These images are tracked, using either correlation techniques (Terminal Convective Weather Forecast or TCWF) or centroid techniques (National Convective Weather Forecast or NCWF). IN TCWF, the track vector field is used to advect the current precipitation images forward to produce a series of forecasts in 10-minute increments up to 60 minutes.

The TCWF forecasts are highly skilled for large-scale persistent line storms. However, detailed performance analysis of the algorithm has shown that in cases dominated by airmass storms, the algorithm occasionally performed poorly (Theriault et al., 2001). In this paper we describe the sources of error discovered in the TCWF algorithm during the Memphis 2000 performance evaluation, and describe recent enhancements designed to address these problems.

2. TCWF 2000 PERFORMANCE EVALUATION

In 2000, the FAA funded a formal assessment of the TCWF algorithm at the Memphis ITWS prototype site. The FAA Technical Center provided unbiased user feedback, MCR Federal, Inc. provided the cost/benefit analysis and Lincoln Laboratory provided an evaluation of algorithm performance. The main causes of the incorrect forecasts were found to be a) the use of a vector quality control constraint based on the direction of the global correlation vector, b) tracking artifact arising from over-filtering of small cells in the precipitation images, and c) the lack of explicit growth and decay in the forecast.

The primary quality control on the track vectors in TCWF is to compare each raw vector with the “global vector,” calculated by cross-correlating 75% of the total precipitation image to determine the overall motion of all storms in the image. In cases where storms in the image are forced by the same synoptic forcing, the global vector is an effective tool in removing errant vectors. In airmass situations, storm movement can often be controlled by meso- and micro-scale forces that vary in direction throughout the forecast region, thus making the use of a global quality control constraint inappropriate.

Use of a 13x69 km filter, optimized for line storms, created transient spur-like artifacts in filtered images of small airmass storms. The jagged over-filter artifact is picked up in the correlation tracker and leads to contaminated motion estimates in locations with heavy artifact, resulting in degraded performance.

We attack these problems by classifying weather into distinct regions (line, airmass, and stratiform) via image processing techniques. Using the resulting weather classification image in conjunction with vectors derived from separate matched filtering/tracking of large-scale persistent features (lines) and small-scale regions (cells), we are able to produce a better quality vector field. The addition of growth and decay trending, while not completely addressing the lack of explicit growth and decay, does help considerably in some cases. These enhancements to the TCWF algorithm are described more fully below.

3. WEATHER CLASSIFICATION AND MULTI-SCALE TRACKING

Storm classification is a well studied problem in meteorology. For this study we assume line storms are well organized, multi-cellular, and persistent on

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[1] US Patent # 5,959,567 issued 28 September 1999.

approximately hour-long time scales and can be tracked using their envelope motion. We assume airmass storms have life cycles of approximately 20-30 minutes and are disorganized, in that individual airmass storms can move in any direction and are best forecasted by extrapolating cell motion.

Algorithm Overview

The enhanced TCWF algorithm is shown schematically in Figure 1. Three main processing steps are depicted. Interest image detection and vector extraction are done in the large "Detectors" box at the top, where four images and two sets of track vectors (envelope and cell) are generated. The images are: weather classification, 13x69 km rotated elliptical-kernel-filtered image (envelope image), 13 km circular-kernel-filtered image (cell image), and a set of growth and decay trend interest images. The vector fields are generated by tracking the envelope and cell images to form the envelope and cell vector fields. Vector conditioning is performed next where vectors are removed based on weather type and a set of conditioning rules. The final step is the advecting of either the original VIL image or a set of images modified by growth and decay trends that are prepared specific to each advection time. Following is more detail on each step.

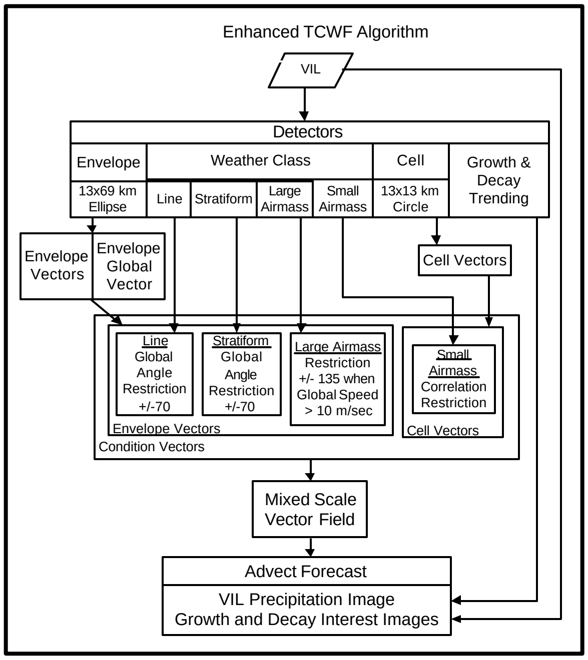

Figure 1. Enhanced TCWF algorithm with Multi-scale tracking and growth and decay trending.

Storm Classifier

Weather classification is derived using Functional Template Correlation (FTC), a matched filtering technique developed at MIT Lincoln Laboratory (Delanoy et al., 1992). Distinct weather types are detected from vertical integrated liquid water (VIL) images using FTC feature detectors. Figure 2 is an example of the weather classification image from one VIL image.

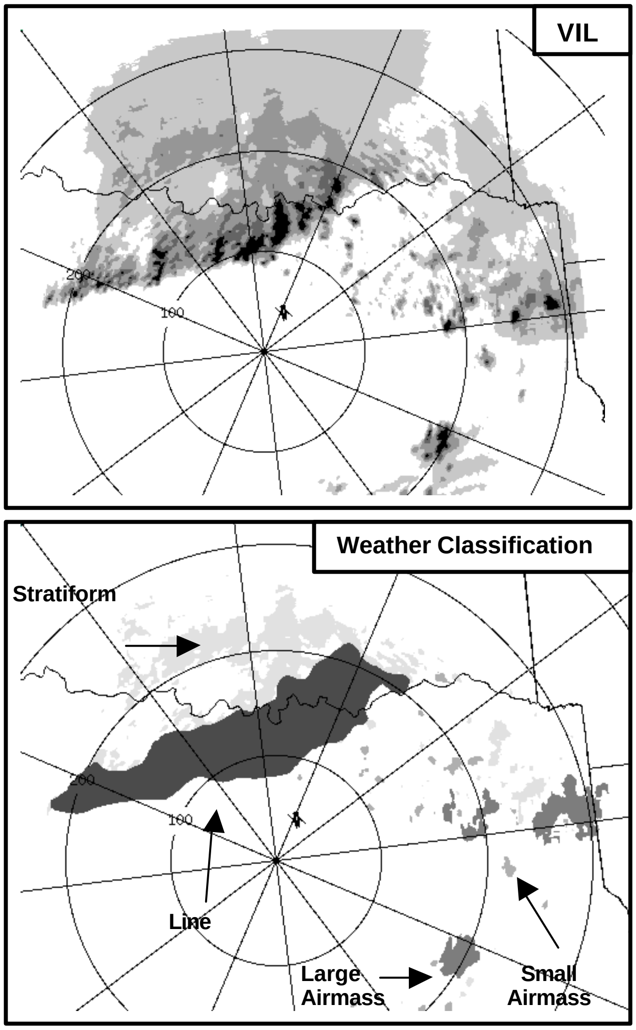

Figure 2. The upper figure is vertical integrated liquid water (VIL) image. The lower figure is the Weather Classification Image derived from VIL. Darkest gray = line storms, dark gray = large airmass, gray = small airmass (cell), and light gray = stratiform detections.

The weather classification feature detectors work as follows. First a line storm detector is run to highlight large linear features. This consists of removing low level weather from the precipitation image by thresholding and filtering with a rotated elongated elliptical mean filter. In parallel, the standard deviation of the precipitation image is calculated using a small kernel, scored and smoothed to produce a 'variability image'. Regions with highly variable VIL and strong linear features are identified as lines.

For areas that are not classified as line interest we use the variability image to distinguish airmass from stratiform regions. Regions with high variability are considered airmass storms. We further divide airmass cells into large complexes and small single cell units, using a simple size threshold criteria. The precipitation image is clipped at level 2, the regions are circumscribed with a bounding box, and the length of the diagonal of the bounding box is used as a measure of storm size criteria. If the diagonal is less then 70 km then the storm is small airmass, otherwise it is large airmass. The stratiform detections are the remaining regions with low variability.

Tracking Filtered Images

Research conducted during the initial development of TCWF showed that the best performance was obtained when a track vector field was derived from a VIL image filtered with a 13x69 km rotated elliptical kernel mean filter (Cartwright et al., 1999), and conditioned by keeping only vectors that were within a ± 70 degree angle from the global correlation vector. Later research (Theriault et al., 2001) showed that the tracking of airmass storms could be improved if the global correlation conditioning was removed; the track vector field was derived from a 13 km diameter circular filter, and a new correlation restriction (described in the following section) was applied.

Vector Conditioning

Once the detection step is completed the vector fields are conditioned by a set of phenomenological derived rules. The envelope image is created from a single VIL image and the results are tracked, outputting a field of raw unconditioned local vectors and a global correlation vector. In parallel, a cell image is created and tracked outputting a raw unconditioned vector field. These two vector fields are then combined in conjunction with the use of the weather classification image, a set of vector constraint rules specific to the type of weather within a region, and the global vector direction and magnitude. For regions with line interest, a global angle restriction is applied to the envelope vector field. If the vectors are not within ± 70 degrees of the global they are removed. Likewise regions tagged as stratiform are also conditioned with ± 70 degrees from the global vector.

For the large airmass regions, a ± 135 degree constraint from the global is applied to vectors when the global vector magnitude is > 10 m/sec, indicating synoptic motion, or line storm behavior. This restriction was introduced to remove back growth vectors that are occasionally observed for line cases. When the global image is < 10 m/sec we assume predominantly airmass weather and do not apply an angle constraint, since motion of large storms can be opposite to the global motion.

For small airmass regions we use vectors derived from the 13 km diameter circular filtered image (cell image) conditioned with a new local ‘correlation restriction’. In airmass cases small popup storms often occur in the correlation area. This can contaminate the raw vector field with unlikely large magnitude track vectors. An implicit assumption used in the correlation restriction rule is that small airmass storms move slowly. From this, a vector is only assigned to a correlation point when it exceeds a threshold that is a function of its distance from the last found correlation point. This effectively favors the closer correlations, but also may introduce a slow bias to the track velocities. The ‘correlation restriction’ vector field is not constrained in any way by the global vector.

After the constraints are applied, the vectors are combined to form a mixed vector field. Areas with weather that don’t have vectors are interpolated using a 1/r weighted average at a 7 km resolution. Finally bilinear interpolation to a 1 km grid resolution in regions containing weather is performed. This vector field is used to advect either a VIL precipitation image or growth and decay trend interest images.

Growth and Decay Trends

The “Detectors” part of the algorithm also creates a set of interest images that are used for detecting regions of growth and decay trends. These images are created using the VIL precipitation image, the weather classification image, a derived trending interest image and a set of weighting functions specific to the weather classification and forecast time. The trending interest image is built by differencing prior precipitation images, and combining/averaging these difference images. This yields a trend image that highlights likely areas of persistent growth and/or decay. The weather classification image is used along with the trending image and the weight functions to modify the input VIL precipitation image into forecast images specific to each advection time. For example, a small airmass storm that shows decay can be gradually dissipated over approximately 20-30 minutes. Defining the time/trend weighting functions is an active area of research.

4. RESULTS AND DISCUSSION

In this section we discuss the enhanced forecast derived from multi-scale tracking and growth and decay trend enhancements and compare the new algorithm with previous performance of TCWF. To demonstrate the improvements gained by the enhancements we analyze NEXRAD radar data from July 20, 2000 in Orlando, FL. This case is interesting because it contains examples of small single cell storms, large independent multi-cell airmass complexes, as well a large line that propagates opposite to the airmass cell motion.

Figure 3 demonstrates the clear improvement when using multi-scale vectors. Old TCWF correctly moves the line storm to the south, but the large airmass storms were also moved (incorrectly) to the south. The northern large airmass storm actually moved to the northeast and later impacted the Orlando Airport (MCO), causing delays. The enhanced version of TCWF captures the motion of the large airmass cell moving to the northeast (showing the impact on MCO), as well as the southward motion of the line.

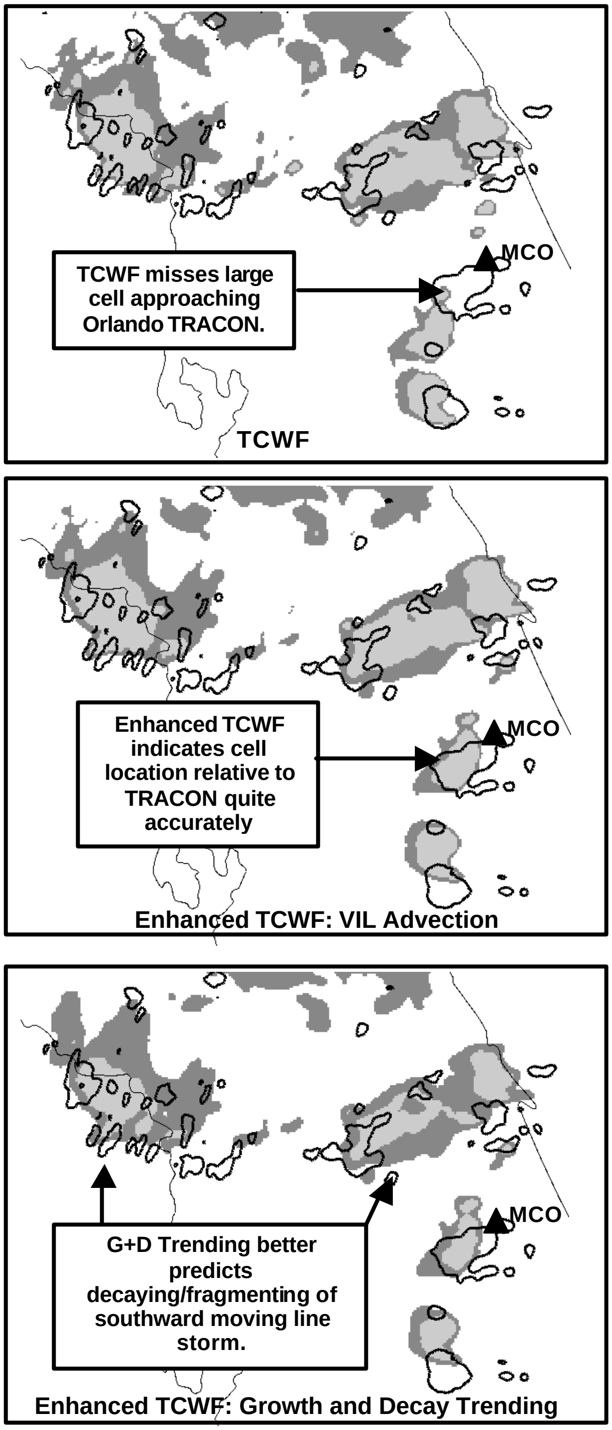

Figure 3. Comparison of TCWF, Enhanced TCWF using VIL Advection, and Enhanced TCWF using growth and decay trending on 20 July 2000 at 23:27 GMT. 30 Minute Forecasts are shown with Level 3 contours from the actual weather (truth) overlaid. Solid triangle is the Orlando Airport (MCO).

Figures 4 demonstrates the performance of the algorithm in forecasting weather to 30 minutes. Plotted in Figure 4 is the binary Critical Success Index (CSI) which is a statistic that is defined by the number of hits per total of hits, misses, and false alarms above level 3 and thereby quantifies not only successful forecasts but degrades performance if the weather is over-forecast. Clearly the enhanced multi-scale tracker shows increased performance.

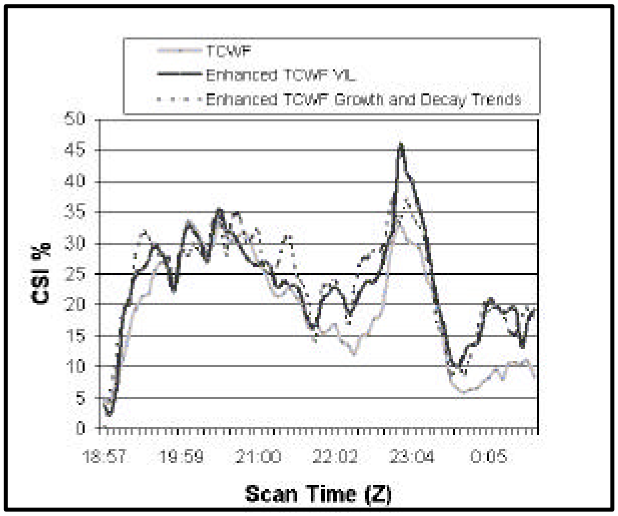

Figure 4. 30 Minute Forecasts on 20 July 2000 MCO case. Critical Success Index (CSI) for TCWF, Enhanced TCWF with VIL Advection, and TCWF with Growth and Decay Trending Advection is shown.

5. CONCLUSIONS

Enhanced TCWF has shown significant improvement for airmass storms without loss of performance on line storm cases where TCWF has historically done very well. The use of a weather classification image generated by image processing of the precipitation images is a powerful tool for the generation of short term convective weather forecasts. Future work will be to refine the growth and decay trending algorithm.

6. REFERENCES:

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