P11.3 AN ASSESSMENT OF AUTOMATED BOUNDARY AND FRONT DETECTION TO SUPPORT CONVECTIVE INITIATION FORECASTS[†]

Paul E. Bieringer*, J. Morgan, J. Hurst, B. Martin, S. Winkler,
Massachusetts Institute of Technology Lincoln Laboratory
Lexington, MA 02420

Y. Xie, J. McGinley, S. Albers
NOAA Earth System Research Laboratory (ESRL)
Global Systems Division (GSD)
Boulder, CO 80305-3328

1. INTRODUCTION

Convective weather, and in particular the initiation of new thunderstorms, makes the efficient management of air traffic in the National Airspace System (NAS) difficult. To address this problem the Federal Aviation Administration (FAA) is currently developing an automated convective weather forecast (CWF) algorithm. CWF provides 0–2 hour convective weather forecasts tailored to meet the needs of air-traffic planners. A prototype of the Corridor Integrated Weather System (CIWS) provides continuous coverage over much of the northeastern third of the continental United States (Figure 1) and the 0-2 hour convective forecast is an element of this system. A detailed discussion of the CWF system can be found in Wolfson et al. (2004).

The CWF system currently produces forecasts of VIL based primarily on the characteristics of existing storms. Consequently, it significantly under forecasts precipitation coverage and intensity during the development of new storms. An example of this deficiency is illustrated in Figure 2, which shows a verification of the convective weather forecast from August 3, 2003. Here a thermally induced circulation initiated widespread precipitation around much of lower Lake Michigan that resulted in significant air traffic control delays. The images on the left side of Figure 2 depict a perfect forecast of the rapidly developing convection around Lake Michigan. The right side of Figure 2 illustrates the forecast from the operational CWF system over the same period. This case clearly illustrates how the CWF system will significantly under forecast precipitation due to its inability to capture the convective initiation that formed along the lake breeze convergence zone.

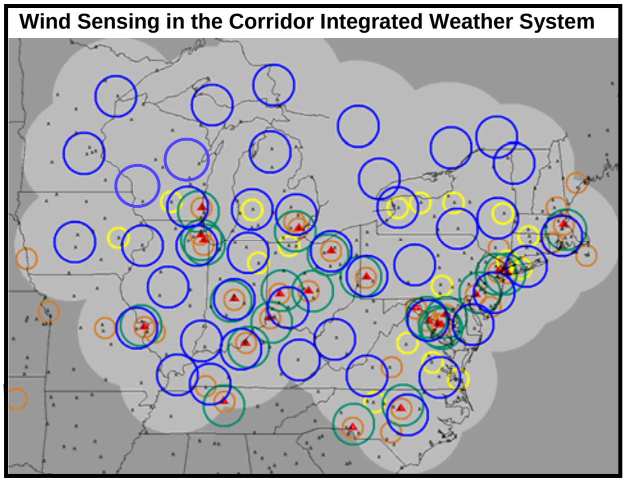

Figure 1. The 2005 Corridor Integrated Weather System domain and sensor locations. The ***A****'s denote the locations of the surface ASOS stations. The nominal surface layer wind sensing range of the WSR-88D (80 km), Canadian Doppler weather radars (80 km), TDWR (80 km), ASR-9 (40 km), and ASR-9 Weather System Processor (40 km) are denoted by the blue, aqua, green, yellow, and brown circles respectively. The red triangles denote the airports where the Integrated Terminal Weather System has been deployed by the FAA.*

In many situations, the development of new storms is preceded by zones of low altitude convergence in the horizontal winds (Wilson and Megenhardt, 1997) that range in size from the synoptic to meso scales. Gridded wind analyses that utilize Doppler weather radar, surface, and aircraft measurements are one of the best sources of low altitude winds that can be used to identify wind boundaries over large domains. Here a "large

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[*] *Corresponding author address*: Paul E. Bieringer, MIT Lincoln Laboratory, 244 Wood Street, Lexington, MA 02420-9185; e-mail: paulb@ll.mit.edu

domain" represents an area greater than or equal to the continental US east of the Mississippi river.

This research addresses the need to improve the CWF system performance during periods of convective initiation by pulling together the real-time gridded atmospheric analysis systems and image processing technologies to detect the boundaries along which the storms develop. The primary question to be answered is how to best identify the regions of convective initiation that lead to forecast failures in the CWF system. To answer this question this study examines the relevant types of objective analysis (OA) systems (systems using surface only versus surface and radar observations) that can produce analyses of low altitude winds. Several systems are currently in development and analysis products from two systems, the Space Time Mesoscale Analysis (STMAS) system (utilizes only surface observations) and the Corridor Boundary Layer Wind (CBOUND) analysis system (utilizes both surface observations and Doppler radar data) are examined by this study. Products from these real-time gridded wind analyses can then be post-processed to improve the signal-to-noise ratio of the fronts, thereby improving their detectability. Finally the gridded wind analyses and detection technologies need to be coupled in a real-time system with the low latency and high update rates necessary to make automated detections of boundaries and then pass them to the CWF system. The use of radar observations in the OA system requires significantly more computational and logistical resources than the surface observation only system. If both systems can provide gridded wind analyses from which comparable boundary/front detections can be made, then the surface observation only system would be the more cost effective means to improve the convective initiation forecast in the CWF system.

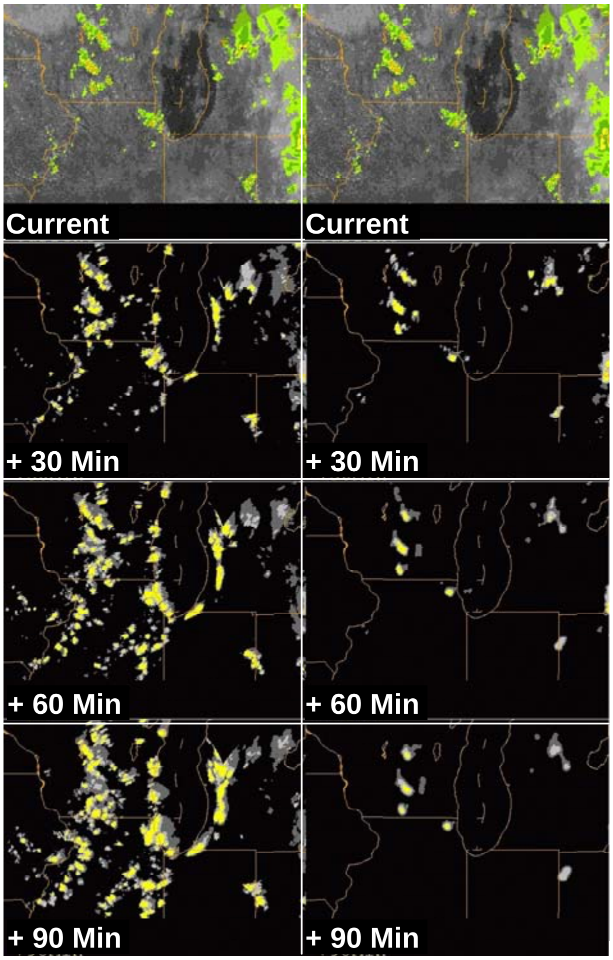


Figure 2. The CWF and "perfect" convective weather forecast for a lake breeze induced convection event that occurred around Lake Michigan on August 3rd, 2003. The "perfect" forecast is shown on the left, and the forecast from the 2003 CWF system is shown on the right.

This paper discusses this experiment and presents some preliminary results. It is organized as follows: Section 2 briefly describes the two gridded wind analysis systems and the analysis post-processing techniques used to detect the boundary/fronts. Section 3 contains the preliminary results of the analysis. A summary of the results and a discussion of future work are contained in section 4.

2. ATMOSPHERIC ANALYSIS SYSTEMS AND TECNIQUES

Recent improvements in communication and computing technology have made it possible to sample the atmosphere more frequently and transmit these observations to a central location to produce real-time atmospheric analyses over large domains. One-minute update observations from Automated Surface Observation Station (ASOS) networks are becoming available through the FAA communication network. Private and publicly owned surface weather sensor networks are being collected and redistributed through the Meteorological Assimilation Data Ingest System (MADIS) (MacDermaid et al. 2005) by National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory Global Systems Division (ESRL-GSD).

Five-minute update base-data products from the Weather Service Radar 1988 Doppler (WSR-88D) and Terminal Doppler Weather Radar (TDWR) are also now being networked. Together these sensor systems provide a mosaic of low-latency, high-update-rate observational coverage over much of the eastern United States. The two operational wind analysis systems considered for the automated boundary detection task, STMAS and CBOUND, were selected as examples of a surface observation only, and surface observation and radar OA systems. Both system were also capable of producing wind analyses over domains greater than 500 km while still meeting the high spatial resolution (1-5 km), high-update-rate (5-15 minute), and low-latency (5-30 minutes) requirements of the CWF boundary detection application.

2.1 CBOUND Wind Analysis System

The Corridor Boundary layer wind analysis system is a version of the Integrated Terminal Weather System (ITWS) Terminal Winds (TWINDS) system that was modified to run over a larger domain and accept observations from additional sources. TWINDS was developed for the FAA by Massachusetts Institute of Technology Lincoln Laboratory (MIT LL) and is capable of integrating the diverse set of observations listed above in real-time to produce a three-dimensional gridded wind analysis (Cole and Wilson, 1994). TWINDS is one of the products within the operational ITWS systems providing weather information to air traffic managers in the air traffic control (ATC) tower and Terminal Radar Control (TRACON) facilities.

Beginning in January of 2005 an experiment was initiated to demonstrate that high resolution (1-5 km) boundary layer wind analyses based on Doppler radar and surface observations can be generated in real time over large domains (i.e. 500 km or greater) to support automated boundary/front detection. For this demonstration a real-time prototype covering a 500 x 500 km domain centered over Chicago was assembled. The long-term goal of this development effort is to integrate data from all of the available FAA wind sensors in the CIWS domain into a single high-resolution low-latency wind analysis to detect the fronts that trigger new convection.

The prototype utilizes the winds from the 20 km Rapid Update Cycle model (RUC) as a background field and then uses a least squares optimal estimation technique to incorporate observational data. The CBOUND prototype currently accepts data in real-time from 12 WSR-88D and 3 TDWR radars, 23 ASOS sites that provide 1 minute update observations, and all of the remaining ASOS, maritime, and mesonet observations that are part of the ESRL-GSD Meteorological Assimilation Data Ingest System (MADIS). The Chicago prototype CBOUND system produces two 9-layer wind analyses that extend from the surface to 800 hPa at 1 and 5 km horizontal resolution with a 5 minute update rate and analysis latency. Figure 3 depicts the CBOUND domain, Doppler radar and surface sensor locations, and an example of the Doppler radar clear-air returns.

2.2 STMAS Wind Analysis System

A Space and Time Mesoscale Analysis System has been developed at Global System Division (GSD), Earth System Research Laboratory to generate a grid analysis of surface observations. It is a three-dimensional variational analysis (3DVAR) of horizontal space and time and provides an analysis with both space and time continuity. It is used to detect boundary-layer, frontal-zones, and various nonlinear mesoscale phenomena.

Surface observations are dense but usually inhomogeneous in not only space but also time. For example in time, the GSD Meteorological Assimilation Data Ingest System (MADIS) provides hourly, 15-minute, and 5-minute data. A single time frame analysis could result in some discontinuity in time due to this inhomogeneity in time. An analysis could yield better continuity both in space and time if it adds a time window into its analysis domain. STMAS uses the time information under a much more generally applicable variational framework and potentially could handle non-conventional observation datasets. STMAS not only fills in the observation gaps in time, but also help its analysis over data sparse regions.

To handle nonlinearity of different weather conditions, a sequential 3DVAR approach is adopted in STMAS to make the analysis gradually approximate the nonlinearity of the analyzed fields, which cannot be done by one single 3DVAR. Similar to a single Barnes iteration, a single 3DVAR analysis can only represent the atmospheric field over scales determined by the length scale of its covariance. Without an accurate error covariance, a 3DVAR system may not provide good analyses, particularly a 3DVAR using simple recursive filters (Hayden and Purser 1995) approximating the covariance. For conventional observation datasets, a 3DVAR analysis can be worse than a Barnes. Figure 4 shows the increments of the analyses from a single 3DVAR using a recursive filter, a two-correction Barnes, and STMAS, using an analytic observation innovation dataset derived from a highly nonlinear function over the real observation sites of MESONET. A bigger influence radius of the covariance for this single 3DVAR analysis can only produce a smoother field by removing the smaller scales from its analysis.

In a highly nonlinear and inhomogeneous data assimilation situation, STMAS is a better variational analysis system handling not only conventional data as well as Barnes analysis but also more complex data (radar and satellite data) like a 3DVAR system.

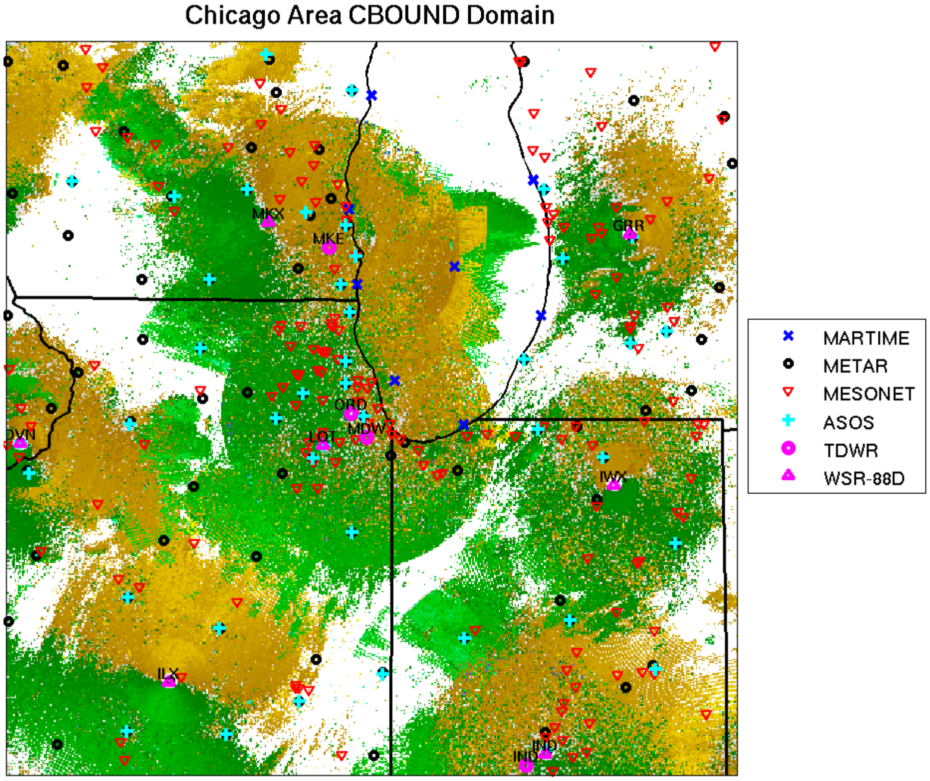


Figure 3. The domain for the CBOUND gridded wind analysis prototype demonstration. The locations of the surface-based sensors and radars used by the prototype CBOUND system are depicted on this map. The colored areas represent an example of the nominal clear-air Doppler radar coverage from the TDWR and NEXRAD radars in the region.

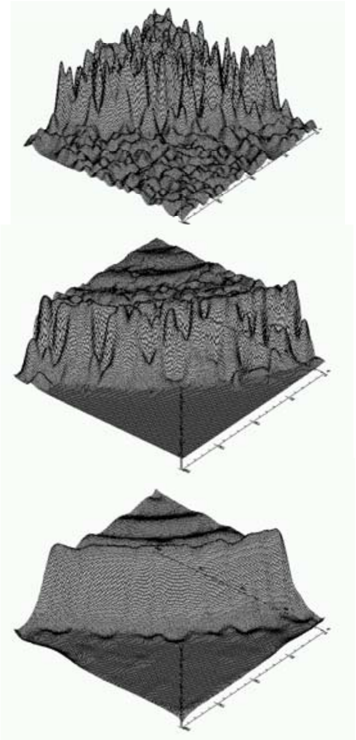


Figure 4. A single 3DVAR (top), Barnes (middle) and STMAS (bottom) analysis.

STMAS uses a sequence of 3DVARs to derive its analysis like Barnes. For each 3DVAR, the current implementation is to apply a one-dimensional recursive filter (Hayden and Purser 1995) to *x*, *y* and *t*, one after another. With this recursive filter approximating to the background covariance, ***B***, a single 3DVAR is:

$$\min \frac{1}{2}\left(x-x^{b}\right)^{T} B^{-1}\left(x-x^{b}\right)+\frac{1}{2}(Hx-y)^{T} O^{-1}(Hx-y)$$

where x^b is the background field, y is the observation, *O* is the observation error covariance, and *H* is the operator mapping grid values to observations.

STMAS starts its sequence of 3DVARs with a large influence radius parameter α value, say 0.999 (this parameter ranges from 0 to 1, (Hayden and Purser 1995). It solves the above 3DVAR problem with the observation data set and obtains a solution. This is similar to what a single 3DVAR does. In its following sequence of 3DVARs, it reduces the value of α from previous 3DVAR by τ, where $\tau \in$(1/2,1) is a constant, and solves the 3DVAR problem with a new set of observation, which is always generated by subtracting the previous 3DVAR analysis values at the observation sites from the observation values used by the previous 3DVAR analysis just like a telescoping successive correction Barnes analysis. This sequence of 3DVARs is repeatedly solved until the α value is small enough, where its corresponding influence radius is smaller than the scales that can be resolved by the observation network. The final STMAS analysis will be the summation of all of the previous analyses.

STMAS currently runs operationally every 15 minutes over US the eastern continental United States and generates 5-km grid analysis. Its analyzed fields include wind, temperature, dewpoint, pressure, pressure perturbation, divergence, moisture convergence. Its analysis can be viewed through the following website: http://laps.fsl.noaa.gov/ under the On-the-Fly page.

2.3 Lagrangian Scalar Integration

Automated techniques for the detection of synoptic scale fronts are also currently under development. The primary method used in the current work is Lagrangian Scalar Integration (LSI). Developed by MIT LL, LSI is a technique that can be applied to the gridded surface wind and scalar analyses (patent pending; Jones and Winkler, 2002).

LSI works as follows: A grid of tracers is specified over the wind analysis (results from the STMAS or CBOUND systems) at a resolution consistent with features of interest (synoptic or mesoscale) and advected following the horizontal winds. Data are gathered along each trajectory as a time series which is then time-averaged over some fixed integration period. This technique is akin to releasing “numerical weather balloons” and taking measurements along their paths.

In many applications, time integration of time series data provides a means of removing noise from the data while increasing the signal strength. In the case of atmospheric feature detection, meaningful time integration is difficult to achieve. The time interval between data updates can be long, meaning the feature of interest will be located in different places in each time slice of data. Even with relatively fast update rates, many features of interest (gust fronts) are in sufficiently different positions that time integration in the Eulerian reference frame can actually do more harm than good. In many cases, artifacts from the analysis process persist in similar locations from one time to the next and their signal is therefore enhanced by the time integration. Simultaneously, the feature of interest changes position and gets washed out by the integration process.

LSI is an attempt to overcome some of the difficulties of time integration by performing the integration in the Lagrangian reference frame. Air parcels moving with a feature tend to retain the dynamical properties of the feature over relatively long time intervals (relative to the update rate). Because the trajectories are calculated from the same wind field that is used to provide the relevant atmospheric scalars for the LSI technique, LSI can be thought of as a dynamically consistent time integration.

When tuned for the detection of boundaries, LSI effectively sharpens the gradients of the scalar quantity while at the same time reducing noise generated by an analysis. An example of this characteristic is illustrated in Figure 5 which compares a divergence field derived from a gridded Eulerian wind analysis (left image) to the LSI divergence field (right image). This case depicts a thunderstorm outflow event captured by the Dallas Ft. Worth International Airport (DFW) ITWS TWINDS system. A detailed discussion of this case can be found in DeLaura et. al. (2002). Here the time varying artifacts typically present in single time Eulerian divergence maps are minimized by the LSI technique, while the signature of the temporally coherent features (in this case the thunderstorm outflow) are enhanced. Furthermore, the frontal signatures in the LSI products tend to be more consistent from image to image making them more suitable for automated tracking.

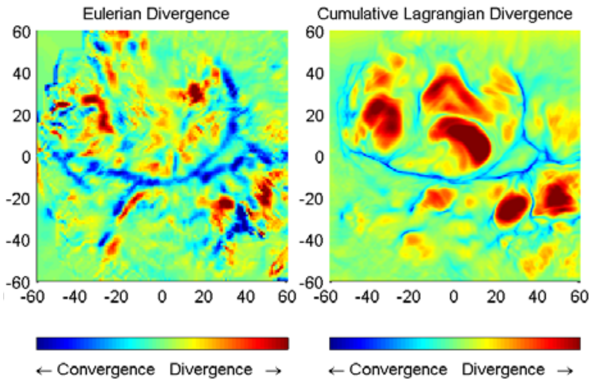


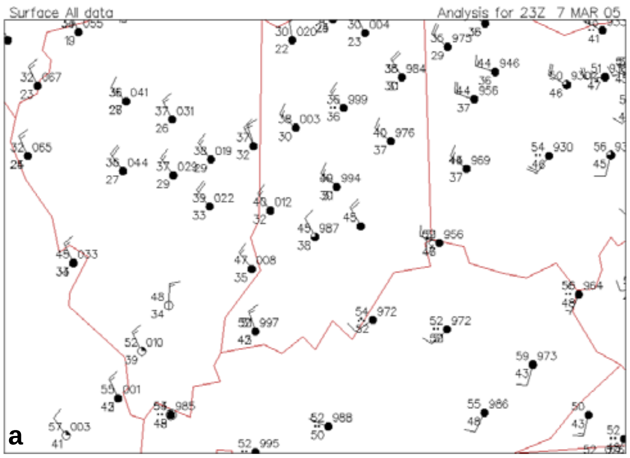
Figure 5. An example of an Eulerian and LSI analysis of wind divergence. Red colors represent diverging surface winds while the blue colors represent areas where the surface winds are converging.

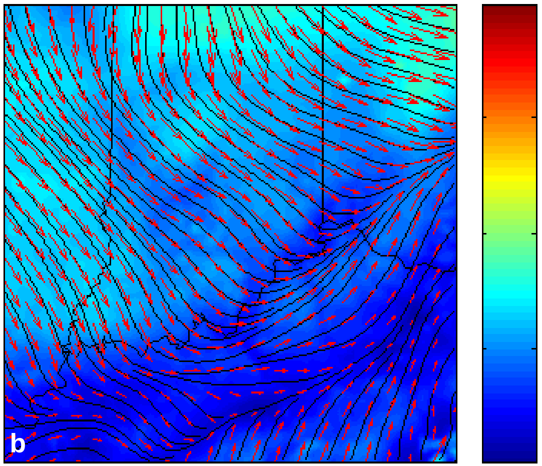
3. ANALYSIS AND RESULTS

The primary purpose of this study is to assess the feasibility of automated boundary detection using gridded wind analysis products from the STMAS and CBOUND systems. If boundary detection is feasible a secondary assessment will be made regarding the performance characteristics of the two systems. In particular this study will focus on the question of whether it is necessary to use high-update-rate analysis based on observations from Doppler weather radars or if a lower-update-rate system like STMAS is sufficient for the boundary detection.

For the purpose of frontal and boundary detection, the two primary scalars examined are vector divergence and relative dispersion. Vector divergence is a local measure of expansion or contraction along the parcel trajectory, and parcels exhibiting strong average local contraction tend to correlate with frontal features. Relative dispersion is a more global measure that compares the separation after some time of initially nearby air parcels. Large values of relative dispersion are often indicators of the strong gradients associated with fronts. While the focus of this work to date has been on vector divergence and relative dispersion, other scalar quantities can also be examined. For example, quantities such as temperature, moisture, wind direction changes, wind speed changes, etc., can be examined with the LSI technique, assuming that they are conserved following the wind flow over the specified period of time.

To answer the primary question of feasibility, separate cases were selected for STMAS and CBOUND. The STMAS case was a cold frontal passage event over southern Indiana at 23 UTC on March 7th 2005. The case was characterized by a distinct wind direction shift in the observations (Figure 6a), and in the STMAS analysis (Figure 6b).

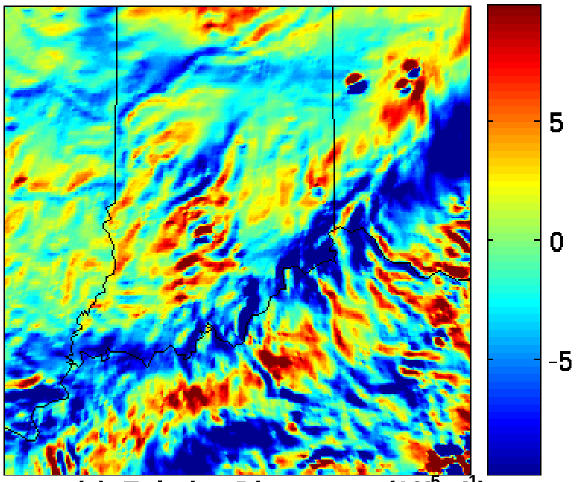




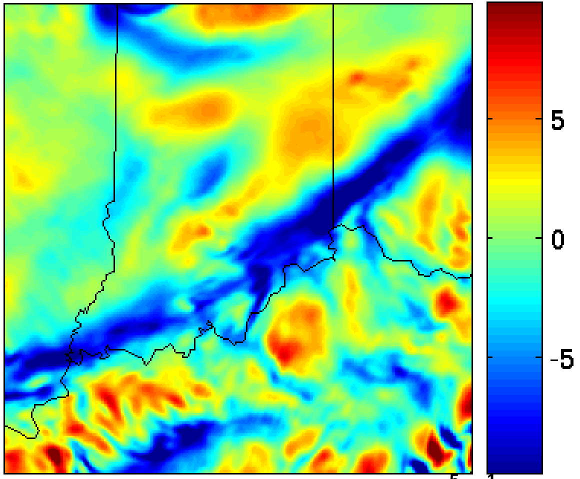
Vetors, Streamlines, and Magnitudes (ms^{-1})

Figure 6a and b. Surface wind observations (a) and the STMAS wind analysis (b) valid 23:00 UTC on March 7th 2005.

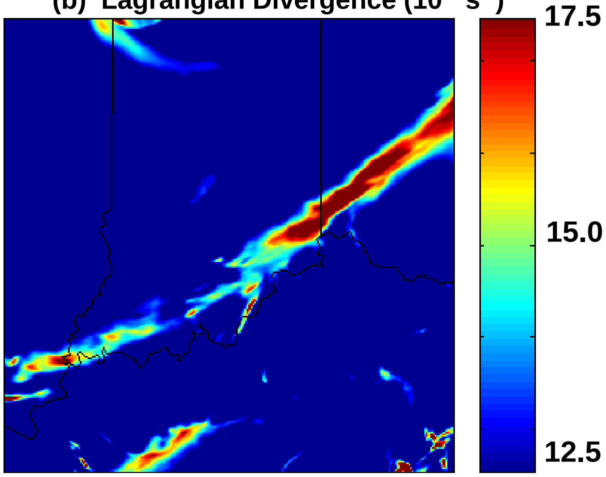
As expected the Eulerian divergence field derived from the STMAS field has a significant amount of high frequency noise (Figure 7a). For this reason it is difficult to make automated front/boundary detections with this image and a direct utilization by the 0-2 hour CWF system would be prone to excessive false alarms. A LSI relative dispersion and divergence tuned to amplify signatures coherent over a 2 hour period was then computed using the same wind field. The high frequency noise is significantly reduced in the LSI divergence field (Figure 7b). The LSI relative dispersion field can be thresholded to look for dispersion of a distance greater than 12.5 km but less than 25 km to isolate the front from the background fields (Figure 7c). This case suggests that it is feasible to identify synoptic scale cold fronts that are coherent over a period of greater than 2 hours with STMAS analyses.



(a) Eulerian Divergence (10^{-5} s^{-1})



(b) Lagrangian Divergence (10^{-5} s^{-1})



(c) Relative Dispersion (km)

Figure 7 a, b, and c. Eulerian (a) and the LSI divergence (b) LSI relative dispersion (c) derived from the STMAS wind analysis valid 23:00 UTC on March 7th 2005.

The evaluation of the CBOUND system was conducted using a thunderstorm outflow case that occurred over southern Lake Michigan on August 26th, 2003. In this case a strong isolated thunderstorm moved across the center of the CBOUND domain producing a curved outflow that was present in the CBOUND analysis (Figure 8). The Eulerian divergence field from the CBOUND gridded wind analysis field also contains high frequency noise, particularly in the regions where the radar observations are influencing the analysis (Figure 9a). The LSI relative dispersion and divergence technique was then applied to this same wind analysis. In this case the LSI filter was tuned to amplify signatures that were coherent over a 20 minute period. The shorter coherency period is possible with the CBOUND data since the 5 minute update rate provides 9 independent samples over a 20 minute period, while the 15 minute update rate of STMAS in its current configuration permits only 9 independent samples over a 2 hour period. The high amplitude noise is significantly reduced in the LSI relative dispersion field and the signal to noise ratio of the thunderstorm outflow is qualitatively improved (Figure 9b).

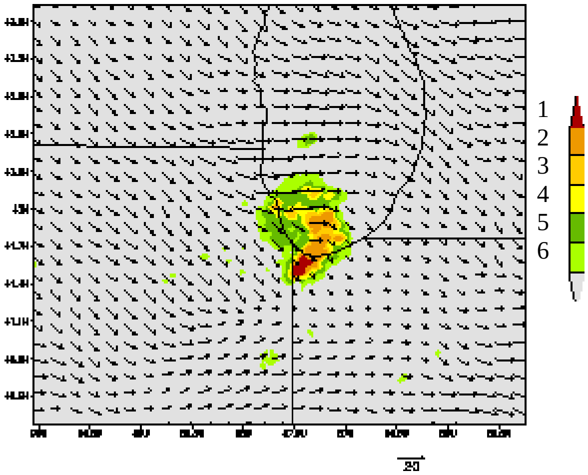


Figure 8. Six level radar precipitation and wind vector field from the CBOUND system valid 18:20 UTC on August 26th 2003.

One concern is that there will be an excessive number of false boundary detections if the output of the LSI filters is directly used in the CWF system. To address this concern the scalar fields produced by the LSI computations from both the STMAS and CBOUND cases were processed with a modified version of the Machine Intelligent Gust Front Algorithm (MIGFA) (Troxel et al., 2002) developed by MIT LL. The modified version of MIGFA utilizes multi-dimensional image processing and fuzzy logic techniques to identify synoptic fronts from the LSI data. In Figures 10a the STMAS-based LSI relative dispersion provides an interest field for the modified version of MIGFA to make a front detection. Overlying the interest field (black lines) is the location of the surface front as detected by the automated algorithm. While the position of front becomes discontinuous in the southwest quadrant of the grid, the detectable interest can be enhanced by layering other scalar quantities output by the LSI calculation, which can lead to a continuous fully automated detection. Figure 10b illustrates the LSI relative dispersion field derived from the 1 km resolution CBOUND wind analysis of a thunderstorm outflow. Here another successful, fully automated frontal detection of the thunderstorm outflow (overlaid as a black line) was made using MIGFA.

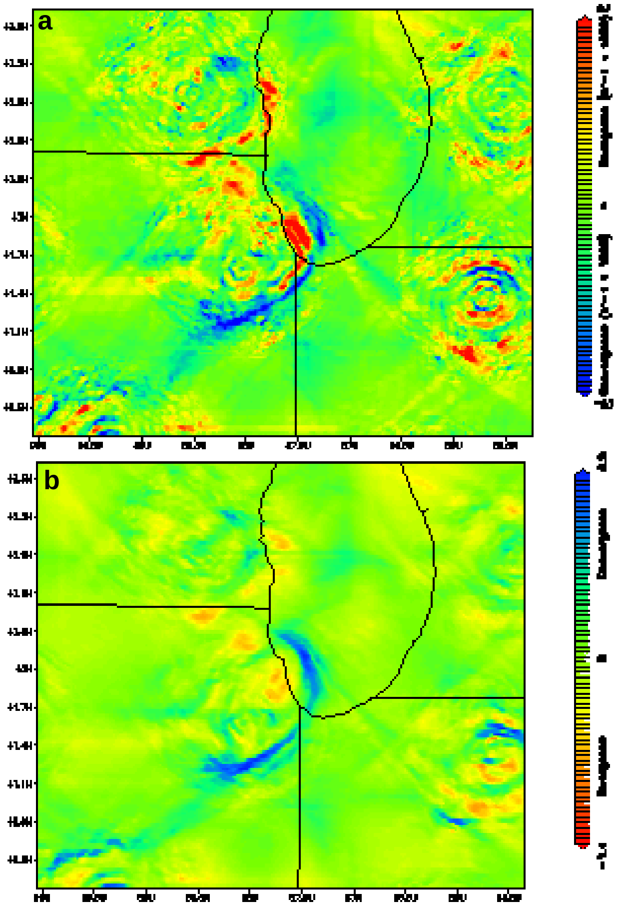


Figure 9a and b. Eulerian (a) and the LSI divergence (b) derived from the CBOUND wind analysis valid 18:20 UTC on August 3rd, 2005.

A data collection effort was undertaken from late August through mid October to assemble the data sets necessary contrast the boundary/front detection performance using STMAS and CBOUND wind analyses. Performance differences are anticipated due to the differences in grid resolution and update rates. This study will look at the performance relative to the operational requirement of the 0-2 hour CWF system to improve convective initiation forecasts. During this period data were collected from six cases where a front or wind shift boundary was present in the CBOUND domain (Table 1). Cases where new convection developed along the boundary are a priority in the analysis.

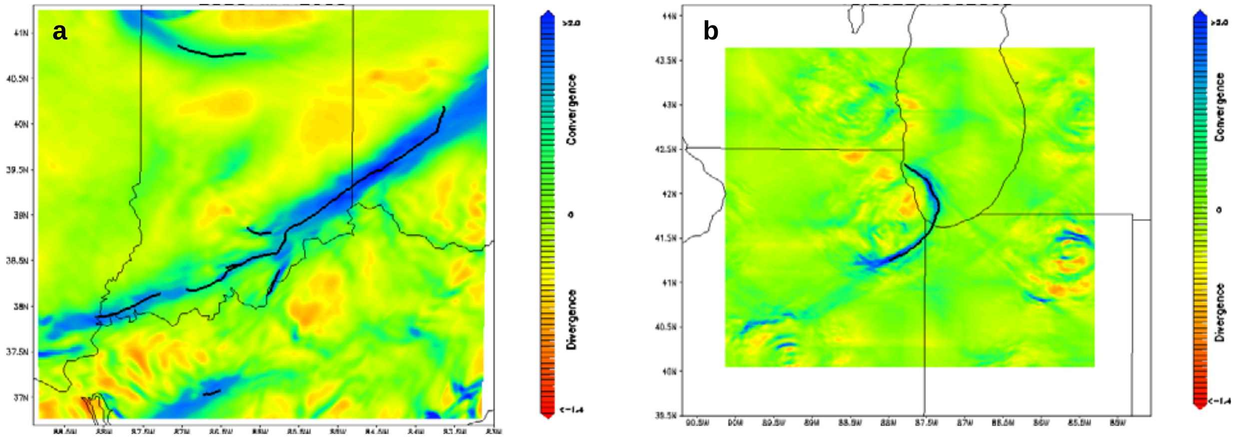


Figure 10a and b. The STMAS LSI dispersion field and MIGFA automated front detection (valid 23:00 UTC on March 7th, 2005) (a) and the CBOUND LSI dispersion field and MIGFA automated front detection (valid 18:20 UTC on August 26th, 2003) (b).

Table 1. Dates and descriptions of cases where corresponding data were collected from both the STMAS and CBOUND wind analysis systems.

Date	Convective Initiation	Description
8.27.2005	Yes	Convective development along a stationary front
9.14.2005	No	Cold front passage – Weak wind shift
9.19.2005	No	Cold front passage – Weak wind shift
9.22.2005	Yes	Cold front passage – Distinct wind shift
9.28.2005	No	Cold front passage – Distinct wind shift
10.6.2005	No	Cold front passage – Distinct wind shift

4. CONCLUSIONS AND FUTURE WORK

The inability to forecast the development of new convection is a significant deficiency in the current COWS 0-2 hour CWF system. It is well known that low altitude wind shift boundaries and synoptic scale fronts serve as a forcing mechanism along which new convection forms. This paper discusses an ongoing effort to address this deficiency through the automated detection of boundaries/fronts.

A key element necessary for this effort has been the development and refinement of gridded wind analysis systems. In order to effectively interface with the CWF system the wind analysis products will need to have the ability to run over large domains while maintaining high update rates and low latencies. Two wind analysis systems, STMAS and CBOUND, met these requirements and were evaluated in this study. The STMAS system has been operational for over a year and the prototype CBOUND system came fully online in mid August.

Often gridded wind analyses have artifacts that make automated detection of atmospheric phenomena difficult. For this reason this study has undertaken a parallel effort to develop techniques to improve the signal-to-noise ratio of the boundaries/fronts. The LSI technique has been shown to be an effective means to enhance temporally coherent features in a gridded wind analysis. This technique has been applied to both the CBOUND and STMAS gridded wind analyses and shown to be effective in producing images when frontal signatures are enhanced relative to the background. Output from the LSI filters were then passed to the MIGFA system which was able to make a fully automated detection of a cold front (STMAS) and a thunderstorm outflow (CBOUND). These preliminary results indicate that automated detection of synoptic and mesoscale wind shift boundaries and fronts is feasible.

Since CBOUND uses radar observations it requires significantly more computational and logistical resources than the STMAS system. If both systems can provide gridded wind analyses from which comparable boundary/front detections can be made, then the STMAS system would be the more cost effective means to improve the convective initiation forecast. Data are currently being analyzed to make this evaluation. This analysis will provide a recommendation of which system can best meet the boundary detection capability required to make successful automated convective initiation forecasts in the CWF system.

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