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A NEW APPROACH FOR MESOSCALE SURFACE ANALYSIS: THE SPACE-TIME MESOSCALE ANALYSIS SYSTEM (STMAS)

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1. Introduction

The importance of narrow zones of boundary layer convergence (or boundaries) for thunderstorm development and evolution has been recognized since the days of the Thunderstorm Project. Boundary detection and characterization are primary objectives of automated nowcasting systems, which employ surface data, radar and satellite observations of current storms and trends in their intensity to forecast thunderstorm initiation, growth, and dissipation (Golding 1998; Pierce and Hardaker 2000; Boldi et al. 2002). The National Center for Atmospheric Research (NCAR) Auto-Nowcast System, or ANCS (Mueller et al. 2003), utilizes a numerical model of the boundary layer and its adjoint, in addition to meteorological observations, to forecast the evolution of boundaries. Conceptual models for using boundaries to nowcast thunderstorms presented by Wilson and Mueller (1993) form the basis for the ANCS.

The skill of boundary detection algorithms falls off dramatically after 30 min because of the limit imposed by the life cycle of convection and the need for accurate knowledge of the boundary layer stability. The implication is that frequent updating of the nowcasting system is needed. Detailed analyses of sub-hourly mesonet surface observations are essential to nowcast severe convective storms. The ability to provide thermodynamic analyses on temporal and spatial scales appropriate for nowcasting severe local storms is also needed (Mueller et al. 2003). The ANCS relies on satellite cloud fields to imply the potential for convection, rather than direct observations of boundary layer stability. When high clouds obscure the underlying cumuli that are needed to infer potential instability, satellite data are of little use. Optimal use of mesonet surface data would seem to be a critical component of the solution to this problem.

This paper presents a new objective analysis system designed to maximize the information content inherent in surface mesonet observations, particularly the temporal information. We refer to this system as the Space-Time Mesoscale Analysis System (STMAS).

2. Requirements analysis

STMAS characteristics include quality control of all surface mesonet data available through the Meteorological Assimilation Data Ingest System (MADIS) at the NOAA Forecast Systems Laboratory, use of the highest temporal resolution inherent to each data set, a real-time 15-min analysis capability, derived product generation, and the incorporation of terrain features to provide additional detail.

Currently, observations from more than 13,000 stations are gathered by MADIS. The observations are collected from an assortment of operational and other federal, state, and private mesonetworks, with varying degrees of quality control, temporal resolution, spatial density and coverage. MADIS is described in greater detail at http://www-sdd.fsl.noaa.gov/MADIS. Despite the great number of stations, many gaps in coverage remain over the U.S., a feature that we refer to as data "deserts" interspersed with "oases." This problem is illustrated in Fig. 1 (this region is representative of the problem of inhomogeneous distribution of surface stations over the entire U.S.).

Fig. 1. Distribution of all surface stations over the CIWS domain (see text) available through MADIS.

Existing mesoscale analysis/nowcast systems employ either the method of successive corrections (SC), optimal interpolation (OI), or schemes that combine elements of both SC and OI (such as the

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Bratseth (1986) scheme). Popular examples of the SC approach are variations of the Barnes scheme used in GEMPAK (Koch et al. 1983) and in the Local Analysis and Prediction System (LAPS) available to National Weather Service (NWS) forecasters on AWIPS (Albers et al. 1996). MADIS uses the OI approach. The Advanced Regional Prediction System (ARPS) Data Analysis System (ADAS, Lazarus et al. 2002) uses the Bratseth technique. AWIPS–LAPS is designed in part to provide hourly nowcasts of the preconvective environment on a 10-km grid. The Bratseth technique acts more like OI approaches in that the analysis does not converge to the data in the presence of observation error, and because the scheme accounts for background errors.

All of the above objective analysis approaches suffer from problems caused by inhomogeneous data distributions. The SC schemes assume a fixed value for the radius of influence on the final pass through the data, whereas OI schemes assume a fixed scale for the gridpoint-to-observation and observation-to-observation spatial correlation functions. These assumptions are strictly valid only when the data are uniformly distributed. Attempts have been made in the ADAS version of the Bratseth scheme to mitigate the impact of spatial inhomogeneities in the data. Nevertheless, the governing principle is still the same – that these schemes will introduce noise in the deserts as an artifact of trying to maximize detail in the data oasis regions (due to the spatial invariability of the weighting and/or covariance functions).

Yet another limitation of existing SC, OI, and hybrid schemes is that they do not explicitly benefit from the detailed information contained in the high temporal resolution inherent to much of the mesonet data. For example, Oklahoma Mesonet data are readily available at 5-min resolution, and the Automated Surface Observing System (ASOS) data are produced at 1-min intervals (though access to this data is restricted and currently requires a slow modem to acquire the data). Unless surface mesoanalyses are performed every few minutes, the temporal information is basically lost. A notable exception to this deficiency is the Time-to-Space Conversion (TSC) modification of the Barnes scheme developed by Koch and O'Handley (1997) and Koch and Saleeby (2001). In the TSC Barnes scheme, off-time data are converted into spatial data using the TSC principle (i.e., using horizontal advection vectors). Comparison of the use of 5-min ASOS data in the TSC Barnes scheme to traditional Barnes analyses performed on a 15-min basis showed the TSC scheme to be far superior in terms of the time-space coherency of such mesoscale phenomena as gravity waves and pressure fields associated with mesoscale convective systems. However, the generality of this approach is questionable, since in this application, advection vectors were based on a simplification of linear gravity wave ducting theory. Such an assumption is not generally true for convective systems, frontal systems, lake breezes, and other mesoscale phenomena.

The above discussion motivates the following set of requirements for STMAS: (1) a demonstrated ability to analyze boundaries (such as thunderstorm outflows and lake breezes) at spatial and temporal scales appropriate for severe storm nowcasting; (2) general robustness for all kinds of mesoscale phenomena; (3) utilization of the highest available temporal resolution inherent to the various mesonetwork data; (4) quality control algorithms to identify temporal discontinuities, data biases, and inconsistencies with neighboring stations; and (5) production of fields consistent with planned AWIPS Linux capabilities and the need for NWS forecasters to populate the National Digital Forecast Database (NDFD) fields – thus, the ability for fields to be produced in real-time on a 5-km grid with an update frequency of 15 min.

The development of STMAS began in the spring of 2004, so it is not yet complete. The first demonstration of STMAS (version 1.0, described here) is an experiment in support of the Federal Aviation Administration's Corridor Integrated Weather System (CIWS). All fields shown below are those produced over the CIWS domain only (basically, this includes the Great Lakes states and much of the Northeast).

3. Description of STMAS

The three primary components of STMAS are a data quality control (QC) system, the objective analysis system, and product generation. Version 1.0 uses the LAPS QC procedures, but a Kalman filter QC procedure is nearing completion (McGinley 2001). The Kalman approach is designed to work in observation space, by modeling each observation as a weighted combination of a "self-trend," "buddy trends" (from neighboring stations), and external forcing (from a numerical weather prediction model). The net result is that each observation in the domain has a unique projection "engine" that provides a single data-cycle forecast value useful for QC and for filling in missing observations. This latter capability is a powerful aspect of Kalman filtering, which promises to optimize the use of the temporal information in the data.

The analysis step currently has two options undergoing testing and evaluation: (1) a space-time recursive filter, and (2) a spline wavelet technique. Both schemes utilize iterative approaches to sequentially add more detail on each pass through the data. Thus, the first pass defines the large-scale structure, and each successive pass adds more detail as the residual differences between the observations and the back-interpolated grid values from the prior pass provide the input to the analysis for the subsequent pass.

The recursive filter in STMAS differs from that in a conventional SC approach in that it uses a variational iteration method to minimize a global penalty function, which includes terms for optimal matching of the analysis with the observations. The iterations are continued until the analysis residuals are no larger than the observation error (typically, this takes 3–6 iterations). This same "telescopic" method is also applied in the time domain, a feature that distinguishes STMAS from all other SC, OI, and hybrid schemes, including the LAPS and TSC Barnes techniques.

The wavelet scheme uses a set of local basis functions to fit the observations. The approach here is to discretize the analysis domain into subregions of varying size depending on the *local* spatial data density. As in the case of the recursive approach, smoothness constraints may be applied. Non-isotropic searching is included in the wavelet method, unlike the telescopic recursive filter. Such an approach should, in principle, produce far better analyses in situations where the data is inhomogeneous and important meteorological systems exist across a broad spectrum of spatial and temporal scales. For example, one could easily imagine a situation involving a cold front, several prefrontal convective systems, gravity waves spawned by both the thunderstorms and the upper-level jet, and complications owing to local terrain influences like land-water boundaries and orography.

The characteristics of four different objective analysis methods are contrasted in Fig. 2 for an analytical function meant to represent a bore or soliton with imbedded waves. Bores are produced by gravity currents (such as from a convective outflow region) as they interact with a stably stratified boundary layer. Under some circumstances, bores can act as important boundaries for initiating convection (e.g., Smith 1988; Karyampudi et al. 1995; Koch and Clark 1999). This particular function is highly nonlinear, consisting of a major “hump” (arctanh) function and several amplitude-ordered waves, thus it offers a rigorous test of the objective analyses. The different objective analysis methods being compared here are: a) a traditional two-pass Barnes scheme, b) a standard recursive filter lacking the properties of telescopic data fitting in both the spatial and temporal domains, c) the STMAS telescopic recursive filter, and d) the spline wavelet technique. The advantages to be gained by use of either the space-time telescopic recursive filter, or even better, the spline wavelet technique, are apparent.

The last component of STMAS is the product generation system. STMAS adapts some of the current software of LAPS in this regard to be able to produce analyses of conventional meteorological fields (temperature, etc.), derived fields (equivalent potential temperature, moisture divergence, etc.), and specialized fields (such as reduced pressure). The method used to compute the reduced pressure is the same as that used in LAPS, which involves a specified terrain reference height. Our current plans are to add a “perturbation pressure” analysis based on bandpass filtering concepts, such as those presented by Koch and Saleeby (2001) to enable easy identification of gravity waves and storm mesolows and mesohighs , but this will require saving a much longer time series of data.

Other powerful attributes of STMAS were borrowed from LAPS. An especially important feature is the ability to use background “first-guess” fields from a model such as the Rapid Update Cycle (RUC) to be able to fill in the “data desert” regions with meaningful fields. Another important feature is the ability to modify these background fields to account for the influence of detailed terrain that cannot be resolved by the model (e.g., the operational RUC model uses a 20-km grid spacing). This capability can produce very detailed analyses of land-sea and mountain-valley temperature and wind contrasts, particularly when combined with a background field that includes lake and sea surface temperatures and a land-weighting scheme to prevent situations such as warm land grid points having an influence on cooler water areas.

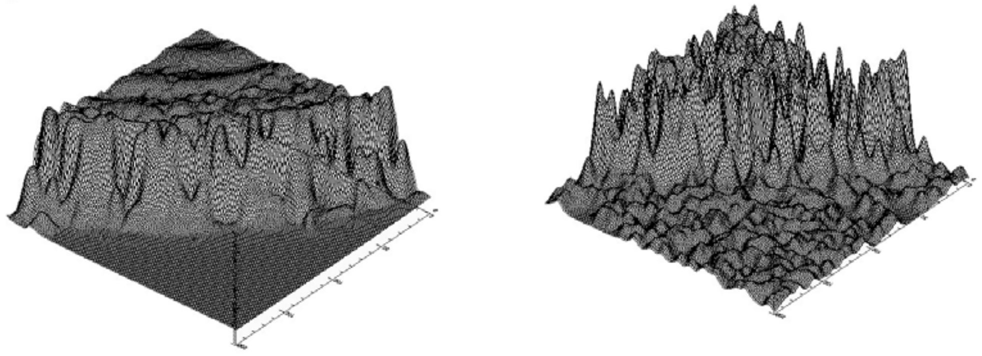
4. A sample of STMAS mesoanalyses for severe convective events

STMAS has been running regularly on a single-processor workstation at FSL since late May 2004. The analysis fields have been made available to NCAR and the MIT Lincoln Laboratory via ftp in NetCDF format on an experimental basis for evaluation. The analyses are produced every 15 minutes, and may be seen as images by selecting Domain = mw-rt-rcsv, Source = analysis, and Level = sfc/2d on the LAPS web page (http://laps.fsl.noaa.gov/request/nph-laps.cgi).

To demonstrate the capabilities of STMAS using the telescopic recursive filter, the severe weather event of 27 May 2004 is presented in Fig. 3. This event was one of several large outbreaks that ravaged the Ohio Valley and Great Lakes regions in the month of May. Although analyses were produced every 15 min, we show only one particular time here. At this time, a line of severe thunderstorms had just formed from the merger of two line segments – one over northern Missouri and the other over central Illinois (Fig. 3b). These systems eventually merged with a weaker system over Ohio, to produce strong storms extending along the Ohio River Valley from West Virginia to central Missouri by 0000 UTC 28 May. Subjectively analyzed outflow boundaries depicted on the synoptic surface map at 2200 UTC (Fig. 3c) include a strong boundary across northern Missouri (coincident with a synoptic cold front), a weaker and more complex boundary over central and eastern Illinois, and a separate outflow boundary over southeastern Indiana and southwestern Ohio. STMAS reveals all of these boundaries in both the wind and temperature fields. The strongest implied convergence and temperature gradient are in northern Missouri, consistent with the observations (note the 20°F temperature contrast there, as opposed to weaker gradients across the other boundaries). Finer-scale details in the shape and structure of the various outflow boundaries are seen in the analysis. Note the small “bubble-high” outflow over southeastern Illinois implied by the analyzed winds, and the thermal and wind fields supporting the separate outflow boundary entering western Ohio. Equivalent potential temperature and moisture convergence fields diagnosed from the STMAS analyses, both of which are often used as nowcasting tools, exhibited remarkable space-time continuity. These will be shown at the conference.

The influence of the background water data on the analysis of cool temperatures over the Great Lakes is quite evident. Temperature differences between the valleys and the mountain ridges in the Appalachians (not shown) are another result of the influence of the LAPS terrain data on the STMAS analyses. These surface features could help to generate boundaries.

a) Barnes b) Standard Recursive



c) Telescopic Recursive d) Spline Wavelet

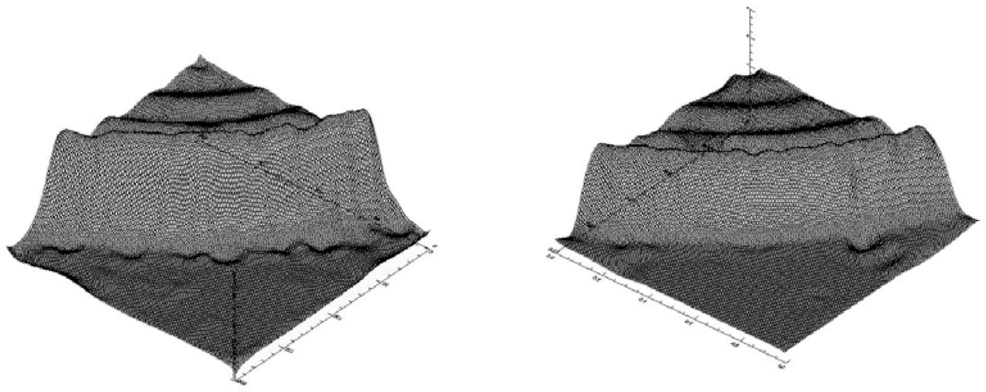


Fig.2. Comparison of four different objective analyses of an analytical propagating soliton function: a) traditional two-pass Barnes scheme, b) recursive filter lacking any spatial or temporal telescopic features, c) STMAS telescopic recursive filter, and d) spline wavelet technique. Actual analytical function is basically indistinguishable from the results in d), with the exception that the field in front of the soliton is totally flat, and the first wave crest should have absolutely no along-wave variability. Domain is that of the CIWS (Fig. 1). Speed of soliton is assumed to be 10 m s^{-1}, and sampling of the analytical function is performed at the locations of the MADIS stations (Fig. 1).

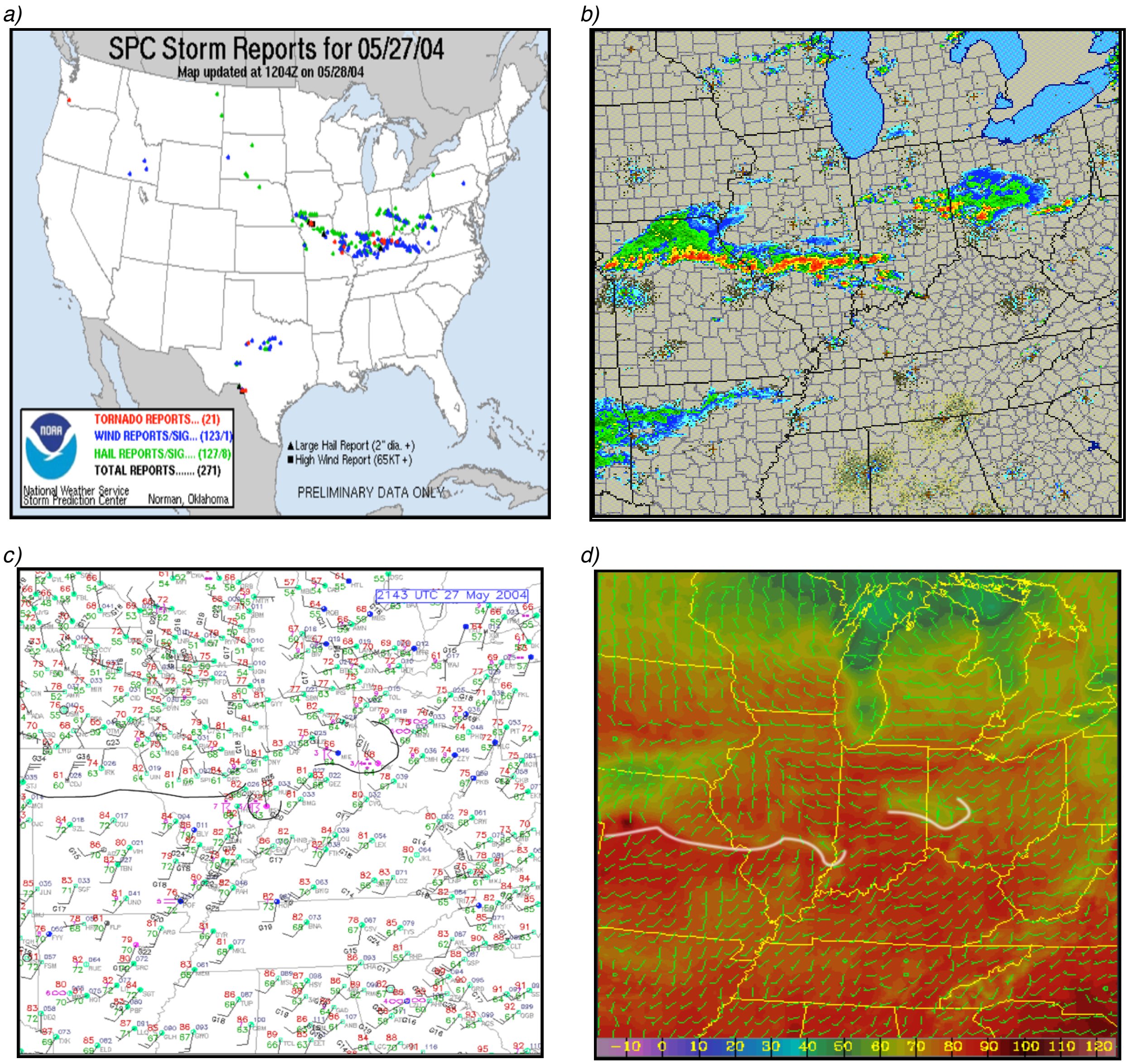


Fig. 3. Analysis of severe weather event of 27 May 2004 at 2200 UTC: a) preliminary reports of severe thunderstorms from the Storm Prediction Center, b) composite radar analysis, c) synoptic surface reports and subjectively analyzed outflow boundaries, and d) STMAS recursive filter analysis of temperature and winds with superimposed subjectively analyzed outflow boundaries. STMAS analysis is based on all the MADIS surface data, as shown in Fig. 1, not just that appearing in panel c).

A further demonstration of the capabilities of STMAS to resolve fine-scale details of direct relevance to the problem of predicting severe weather is given for the tornado event of 30–31 May 2004 (Fig. 4). Shown here are surface analyses of equivalent potential temperature (θ_e) and winds, and the corresponding tornado reports during each 30-min interval from 2300 to 0030 UTC. A wedge of very high θ_e values approaching 360K was present initially over eastern Illinois and western Indiana under strong southerly flow. Suddenly, at 2330 UTC a lobe of 25 C lower θ_e air intruded into the western side of this wedge from the area near St. Louis under west-southwesterly winds. This lobe then wrapped cyclonically around the northern part of the high θ_e wedge, eventually splitting it into two masses. Virtually every one of the tornado reports occurred in a region of strong θ_e gradient. The tornadoes became more numerous, concentrated, and (though not shown here), stronger as the low θ_e lobe made its way to the eastern side of the high θ_e wedge.

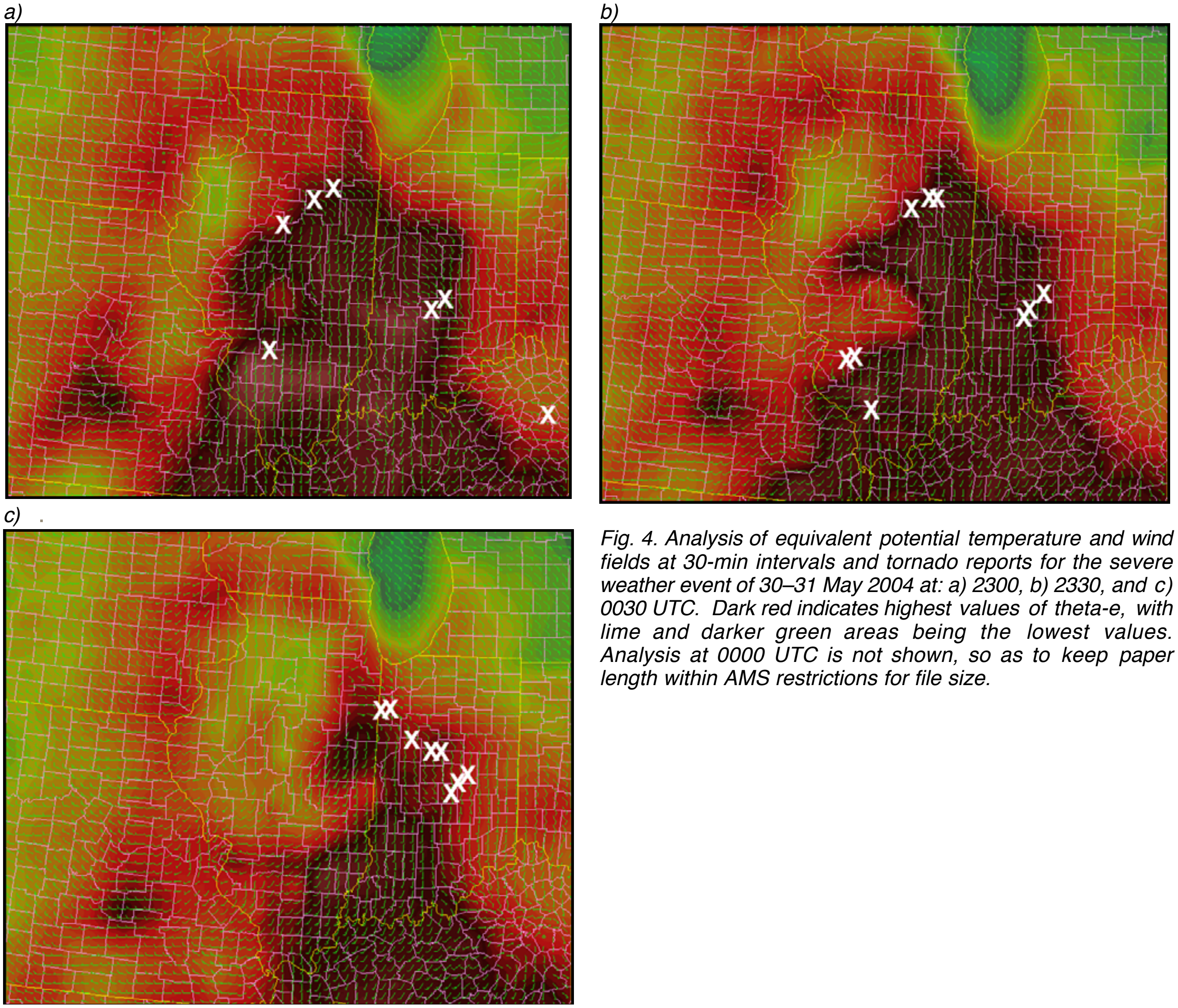


Fig. 4. Analysis of equivalent potential temperature and wind fields at 30-min intervals and tornado reports for the severe weather event of 30–31 May 2004 at: a) 2300, b) 2330, and c) 0030 UTC. Dark red indicates highest values of theta-e, with lime and darker green areas being the lowest values. Analysis at 0000 UTC is not shown, so as to keep paper length within AMS restrictions for file size.

4. Conclusions

A surface mesoanalysis system (STMAS) is being developed to take advantage of the high temporal and spatial resolution of mesonetwork data that are now becoming available in real-time for operational forecasting. STMAS is designed to provide maximum detail in the areas of highest data coverage, while not introducing undesirable noise in the regions of much sparser coverage – a problem that plagues all existing successive corrections, optimal interpolation, and hybrid analysis techniques. This paper gives a non-mathematical summary of this new scheme and provides several real-case examples showing how important mesoscale and storm-scale details can be obtained and how quickly important changes can occur (often in only 15 – 30 min).

Future plans for STMAS include the addition of a nearly completed Kalman filter for both quality control purposes and for filling in missing data. A pressure perturbation analysis will be added to supplement the reduced pressure analysis currently in STMAS, so as to make it much easier to visualize mesoscale pressure systems (Koch and Saleeby 2001). Consideration is also being given as to whether STMAS can play a role in helping to satisfy the need to populate the 5-km National Digital Forecast Database (NDFD) on AWIPS.

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