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NOWCASTING APPLICATIONS OF THE SPACE-TIME MESOSCALE ANALYSIS SYSTEM

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1. Introduction

Recently, the number of surface observations over the U.S. with spatially dense time and space coverage has grown rapidly. This has resulted in an essentially national mesonetwork offering the possibility of performing frequent monitoring of mesoscale features that may generate significant local weather, as well as hazards to aviation. Despite these advances, the density of these data remains highly variable across the country, literally being composed of "oases and deserts" of data. The distribution of surface mesonet stations currently available from the Meteorological Assimilation Data Ingest System (MADIS) at FSL shown in Fig. 1 illustrates this heterogeneous data issue (13,000 stations are currently in MADIS).

Detailed mesoanalyses can be obtained from the methods of successive corrections (SC), optimal interpolation (OI), or schemes that combine elements of both SC and OI (such as the 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 (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. The Bratseth and LAPS techniques act 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. However, all of these objective analysis approaches suffer from problems caused by inhomogeneous data.

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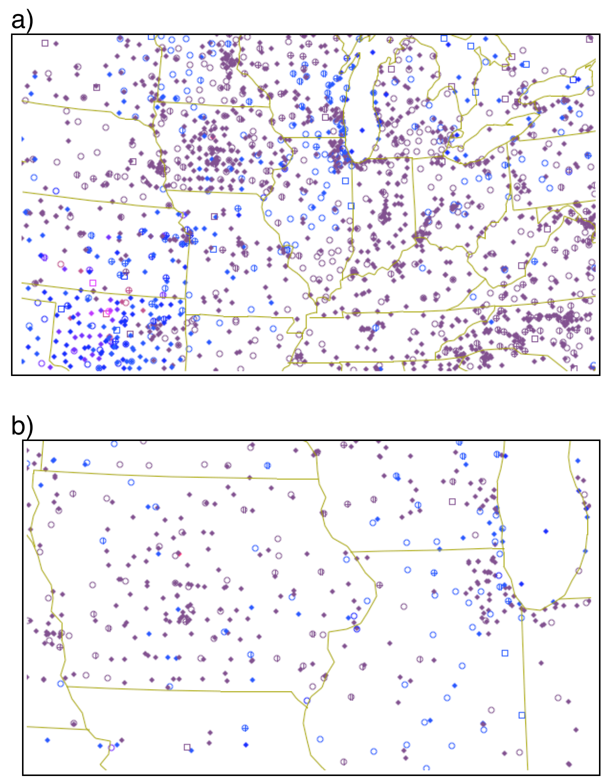


Fig. 1. Surface mesonet stations available from the MADIS system, illustrating the nonuniform spatial distribution of stations: a) larger scale perspective over the central U.S., b) zoomed-in portion of Fig. 1a showing how nonuniformity extends across scales. In addition, the networks offer a wide variety of temporal resolution varying from 1 to 60 min.

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 grid point-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 in 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. 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 (Koch and O'Handley (1997); 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.

In light of these needs, FSL has developed a 5-km resolution surface analysis scheme offering real-time products at 15-min intervals where the data support such detail, while avoiding noise in other parts of the analysis domain where only coarser-scale features can be resolved. This system is called the Space-Time Mesoscale Analysis System (STMAS) and is designed to analyze small-scale features such as thunderstorm gust fronts and lake breezes with excellent spatial-temporal coherence. STMAS is compatible with current AWIPS workstation display capabilities, includes a robust data quality control procedure, an iterative space-time recursive filter within a variational framework, and a product generation subsystem. The three-dimensional variational (3DVAR) framework underlying STMAS utilizes the two spatial dimensions and the time dimension in a sequential, multiple-pass recursive manner to handle the nonlinear, multi-scale characteristics of weather systems. In essence, STMAS is a variational extension of the Barnes recursive SC scheme.

Xie et al. (2005) present the theoretical description of STMAS and the results of analytical tests performed with the system. This paper discusses applications of STMAS for such purposes as nowcasting, verification of high-resolution numerical model forecasts, and aviation forecasting. We demonstrate the capability of STMAS to exploit the huge number of surface observations now available in order to reveal important mesoscale features that lead to hazardous local weather.

2. Technical description of STMAS

The analysis first pass in STMAS defines the large-scale structure. 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 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 recursive filter in STMAS also 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 product generation component of STMAS adapts some LAPS capabilities 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, which uses a specified terrain reference height).

A "perturbation pressure" analysis based on bandpass filtering concepts has also been added, which is similar in function to that in Koch and Saleeby (2001) used to enable easy identification of gravity waves, thunderstorm mesolows and mesohighs, mesoscale frontal disturbances, and other phenomena. Pressure perturbation is computed from the difference of two low-pass filters to analyze phenomena with wavelengths ranging between 120 and 330 km (~ 2 – 5.5 times the average station spacing) with a response greater than 0.5 (maximum of 0.7). This filter displays negligible "Gibbs oscillations" around the central peak (Fig. 2), thus undesirable phase shifts arising from use of the filter can be ignored.

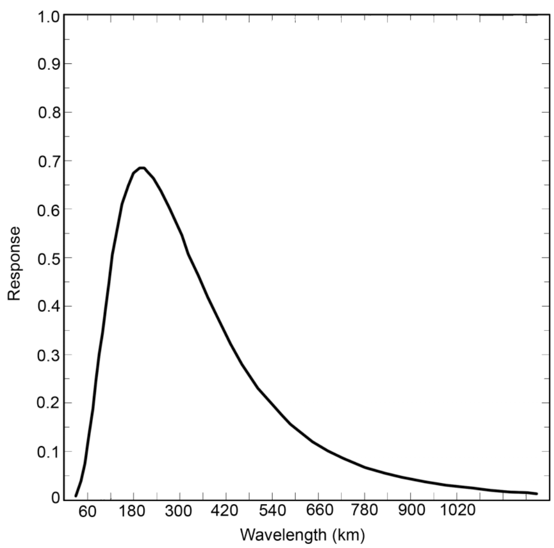


Fig. 2. Response function of Lanczos bandpass filter used to analyze pressure perturbations with resolved wavelengths between 120 and 330 km.

Another aspect of STMAS borrowed from LAPS is the ability to use background "first-guess" fields from a numerical weather prediction model. The default background for STMAS is a one-hour forecast produced from the 13-km resolution Rapid Update Cycle (RUC). This allows STMAS to fill in the "data desert" regions (including over the coastal waters and Great Lakes) with meaningful fields. It is also possible to modify these background fields to account for the influence of detailed terrain that cannot be resolved by the model. 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.

3. Some severe convective events analyzed by STMAS

STMAS has been running regularly on a single-processor workstation at FSL since late May 2004, producing analyses every 15 min on a 5-km grid over the U.S. east of ~115W longitude. Quality control consists of LAPS types of buddy checks, continuity checks, and use of the RUC background. Analyses may be viewed as images on the LAPS "on-the-fly" web page at

http://laps.fsl.noaa.gov/request/nph-laps.cgi.

Simply select Domain = dwfe-rcsv, Source = analysis, Level = sfc/2d, and then choose the field of interest (those in all caps are color-filled contour fields) and zoom factor. The X- and Y-coordinate choices allow the center of the display to vary from 0 to 1 in accordance with the selection of the zoom factor. Multiple fields may be superimposed, such as wind vectors ("wind"), a color-fill plot of pressure perturbation (P_PRIME), and a line contour plot of the same (pprime). An example of this particular plot appears in this paper (Fig. 4).

STMAS is serving several purposes currently, such as input to experimental convective weather nowcasting by NCAR and the MIT Lincoln Laboratory under support from the Federal Aviation Administration. The MIT/LL group has been developing a trajectory package for predicting air mass and other kinds of boundaries using the STMAS analyses, Doppler radar data, and satellite imagery. The considerable detail and temporal coherence afforded by the STMAS analyses over large regions is crucially important for this purpose, though analyses even more frequent than every 15 min would be desirable. Examples are presented next, showing the powerful multiple-scale analysis capabilities of STMAS for severe convection events, and how boundaries can be determined from these fields.

3a. Boundary analysis for the severe convection event of 30 June–1 July 2005

An outbreak of severe weather ravaged eastern Kansas and southern Missouri on this date, mostly in the form of damaging winds and hail as large as golf balls. Additionally, several tornadoes were spawned in southeastern Kansas during the interval 0100–0215 UTC 01 July 2005 (Fig. 3c). The event began as a convective storm cluster over northeastern Kansas and northern Missouri in the early afternoon (Fig. 3a). This cluster maintained itself to the north of a quasi-stationary frontal boundary draped from west-northwest to east-southeast. STMAS depicts a very strong horizontal gradient in the equivalent potential temperature field exceeding 40 K in only 100 km, with values of nearly 365 K in northeast Oklahoma (Fig. 3d). In addition to this cluster, nontornadic storms formed along an outflow boundary over the Missouri-Arkansas border analyzed in the STMAS fields. Also, by early evening, tornadic storms developed at the extreme western end of the convective complex north of Chanute, Kansas (Fig. 3b). STMAS reveals what is a likely cause for this local tornadic activity: a strong cyclonic circulation that developed in the late afternoon near an intensifying small-scale mesolow pressure system along the front (Fig. 4). It is intriguing to see how the pressure perturbation field reveals a change in the structure from that of a simple cool mesohigh – warm mesolow system at 1900 UTC (Fig. 4a) to that of a cyclonically wrapped-up mesohigh structure with a westward extension just north of the frontal mesolow in east-central Kansas (Fig. 4b).

3b. Tornado outbreak of 30–31 May 2004

A further demonstration of the capabilities of STMAS to resolve fine-scale details of direct relevance to the challenge of predicting severe weather is presented for a tornado event that occurred in the Ohio Valley on 30–31 May 2004. Shown in Fig. 5 are surface fields of equivalent potential temperature Θ_e and winds from analyses conducted every 15 min, plus the corresponding tornado reports, at 2300 UTC 30 May 2004 and 0030 UTC 31 May 2004. A wedge of very high Θ_e approaching 360 K 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 began to intrude into the western side of this wedge under west-southwesterly winds from the area near St. Louis. This lobe then wrapped cyclonically around the northern part of the high Θ_e wedge, eventually splitting the wedge into two pieces. Virtually every tornado report occurred in a region of strong Θ_e gradient at the nose of this intrusion. The tornadoes became more numerous, concentrated, and stronger as the low Θ_e lobe rotated around to the eastern side of the high Θ_e wedge.

3c. Lake breeze convection

The next example illustrates the ability of STMAS to provide abundant detail in local analysis of lake breeze convergence boundaries. Visible satellite imagery and STMAS analyses of temperature and winds in the Great Lakes area at 2100 UTC 06 July 2005 are displayed in Fig. 6. Lake breezes are quite evident in the lines of cumulus convection encompassing Lake Michigan and in north-central Ohio. Animation of the satellite imagery revealed that the latter line of convection developed along the southern shores of Lake Erie and became more distinct as the line traveled southward. STMAS reveals convergence boundaries and associated temperature gradients along both of these cloud boundaries. In addition, STMAS suggests an asymmetric nature to the Lake Michigan breeze front, which propagated farther westward than eastward – again consistent with the satellite imagery. A third lake breeze front is apparent to a lesser degree in the isotherm analysis over eastern Michigan, though very little wind convergence is apparent with this front. The lack of convergence helps to explain the lack of deep cumulus convection along this westward-propagating lake breeze emanating from Lake Huron. Note in Fig. 6a the lack of any cumulus development over northeastern Michigan and Lake Huron; these areas are under the influence of the cool, stable air from the lake. In fact, all three lakes (Huron, Michigan, and Erie) are cloud-free, and the STMAS temperature analysis of cooler air over the lakes is consistent with this observation. Such close association between analyzed boundaries and satellite imagery seen at this one time was present throughout the entire day.

4. Use of STMAS for verification studies

STMAS was used this past winter during the Developmental Testbed Center (DTC) Winter Forecast Experiment (DWFE) to verify 5-km resolution forecasts produced by two different configurations of the Weather Research and Forecasting (WRF) model (Bernardet et al. 2005). An example of this use of STMAS is provided in Fig. 7, which shows a mesoscale vortex over Lake Erie displaced from the main synoptic-scale low pressure system over western Pennsylvania. The WRF model 18-h forecast shows a similar phenomenon in nearly the same location. Many other examples of such use of STMAS for model verification during DWFE can be shown.

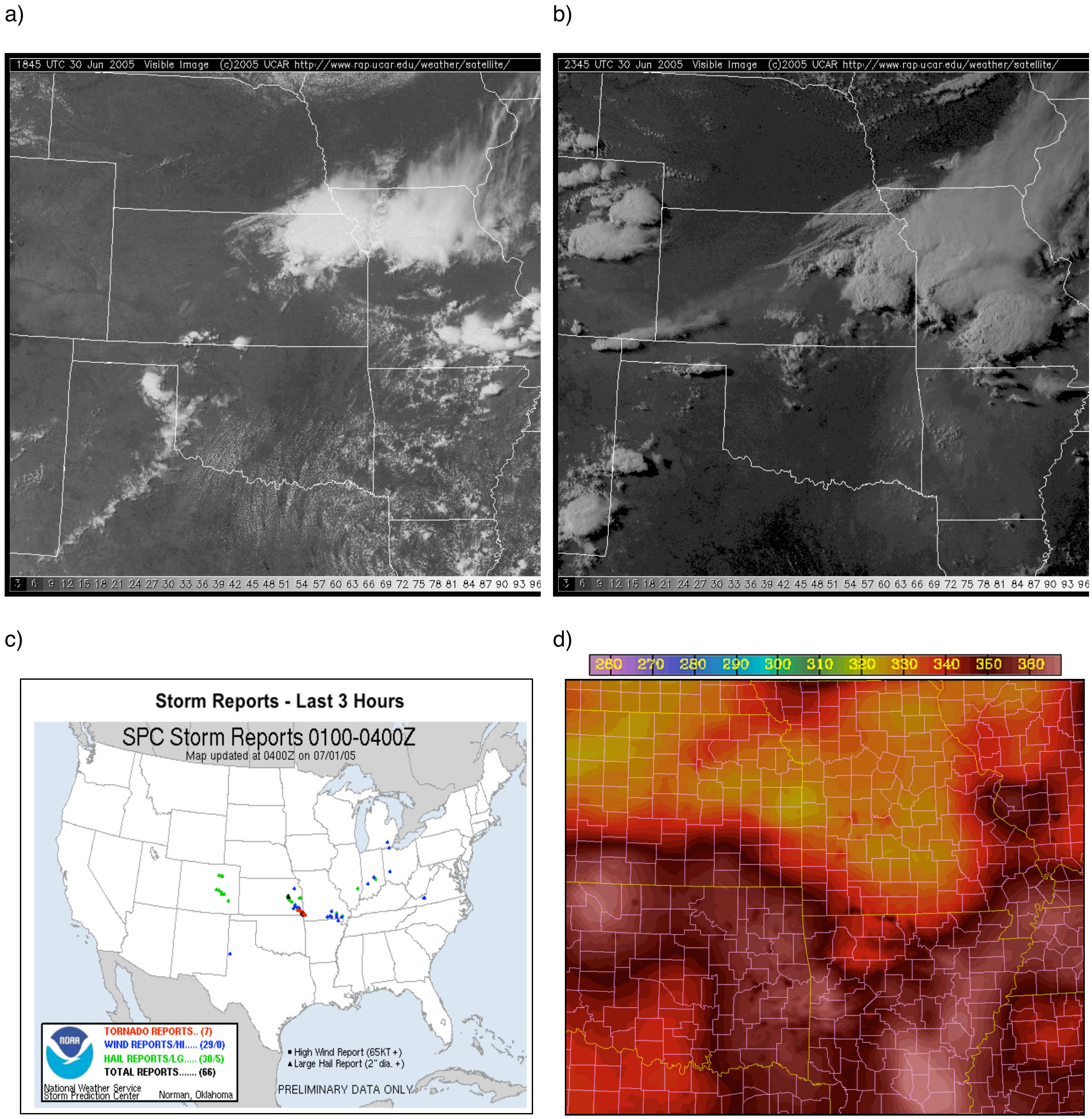


Fig.3. Visible satellite imagery for a) 1900 UTC 30 June 2005 and b) 0000 UTC 01 July 2005, c) Storm Prediction Center reports of severe weather for 0100 – 0400 UTC 01 July 2005, and d) STMAS analysis of surface equivalent potential temperature (K, note colorbar) at 0000 UTC 01 July.

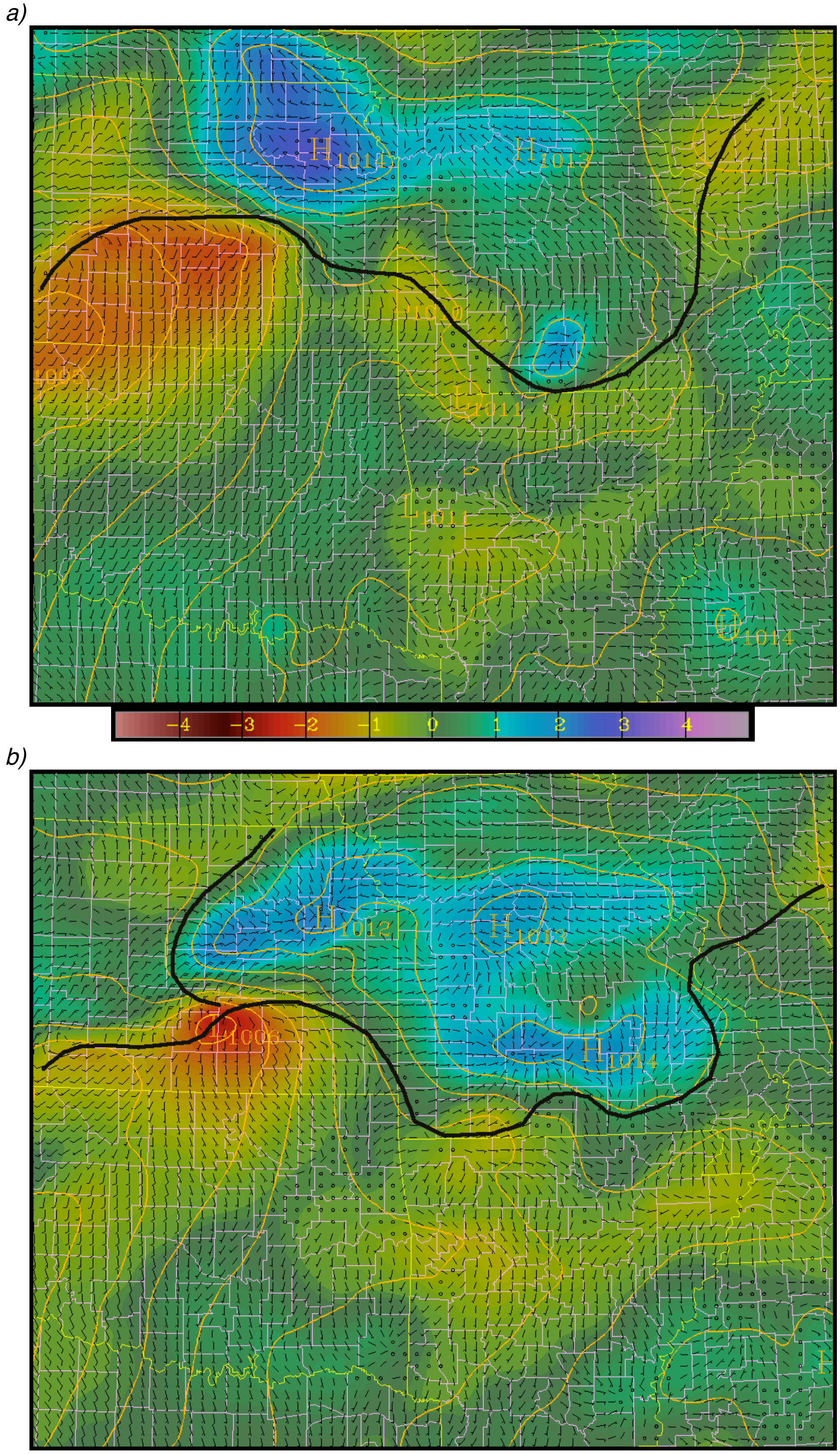
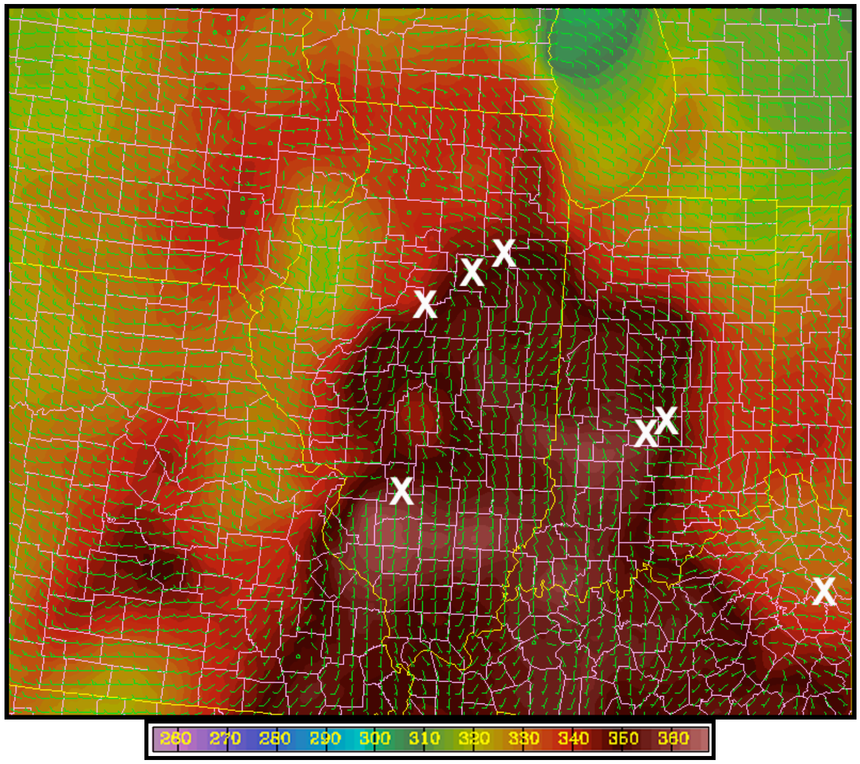


Fig. 4. STMAS analysis of pressure perturbation (hPa, note colorbar), reduced pressure (1 hPa isobars), and surface wind fields with superimposed subjectively analyzed boundaries at a) 1900 UTC 30 June and b) 0000 UTC 01 July 2005.

a)



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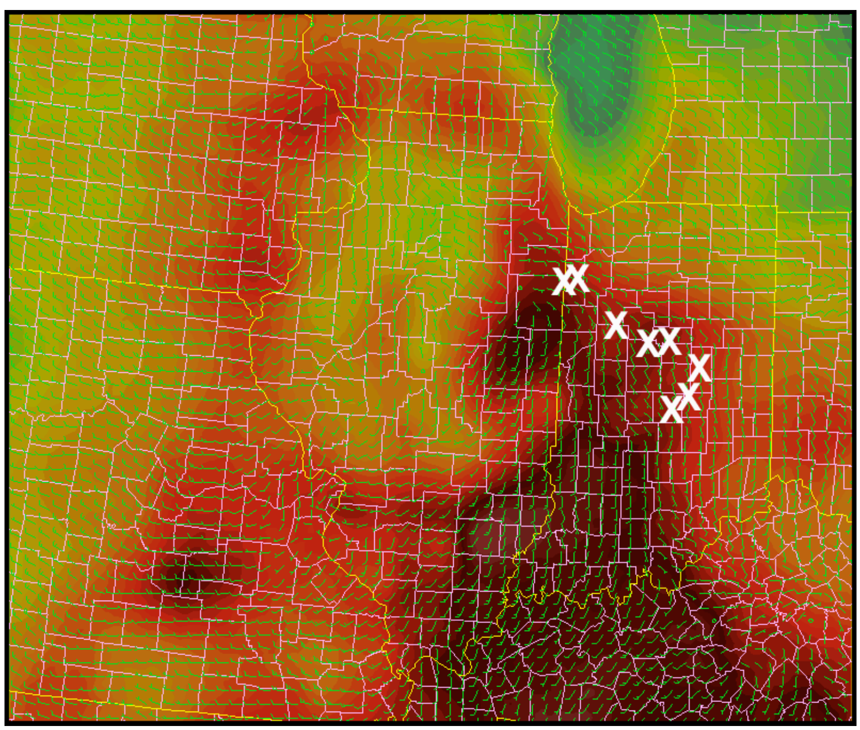


Fig. 5. STMAS analysis of equivalent potential temperature (K) and winds (kt) at a) 2300 30 May 2004 and b) 0030 UTC 31 May 2004. Dark red indicates highest values of theta-e, with lime and darker green areas representing the lowest values (see colorbar). Reports of tornadoes within ±15 min shown by "X".

a)

b)

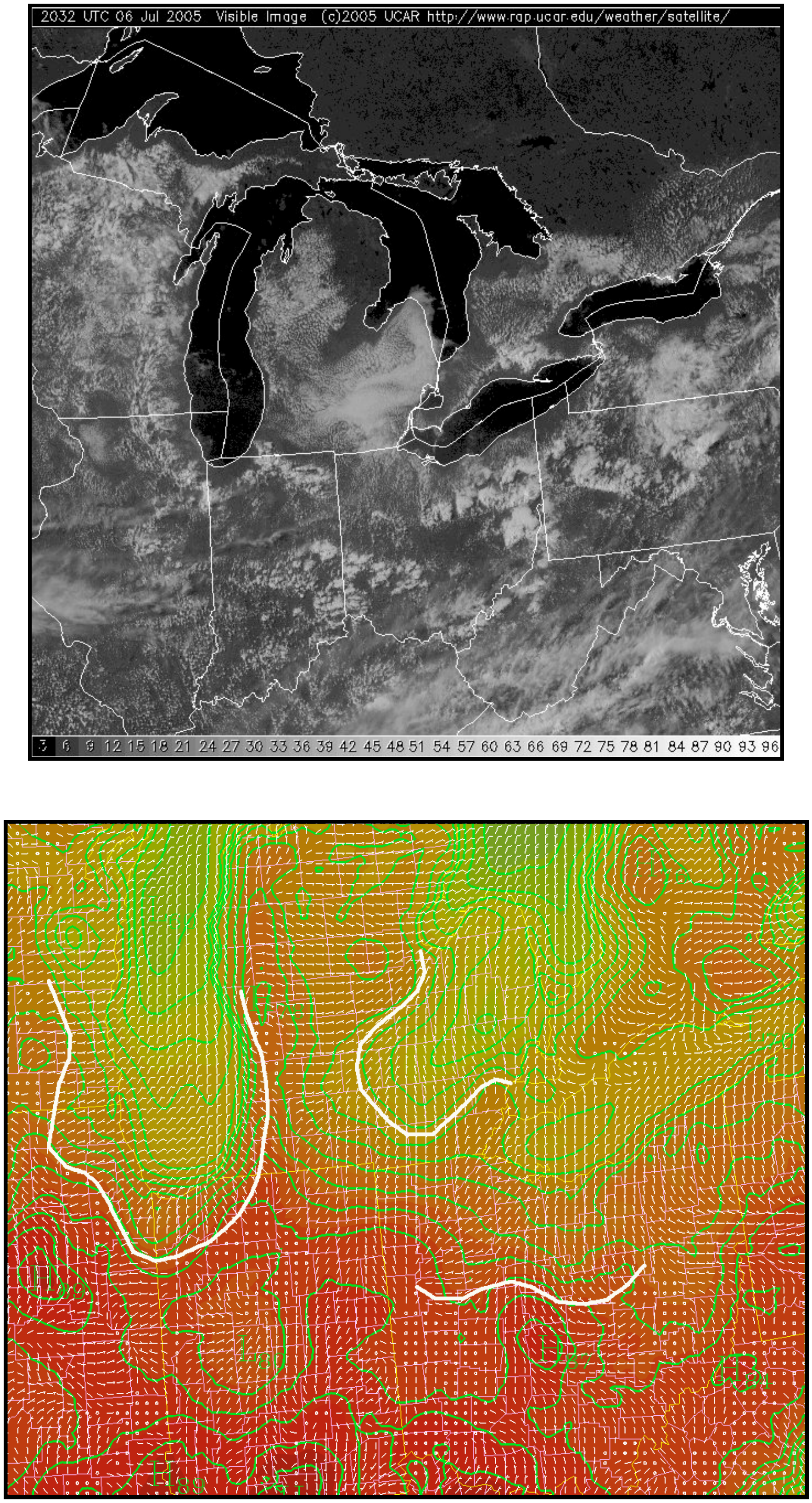
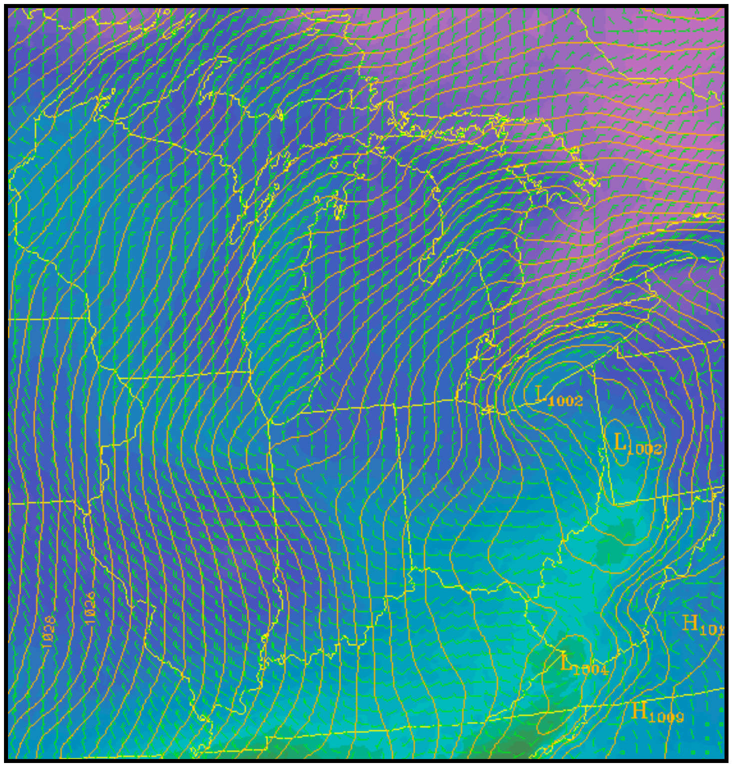


Fig. 6. Lake breeze convergence boundaries detected in a) visible satellite imagery and b) STMAS analysis of temperature and wind fields at 2100 UTC 06 July 2005. Isotherm interval is 2°F (1°C).

a)



b)

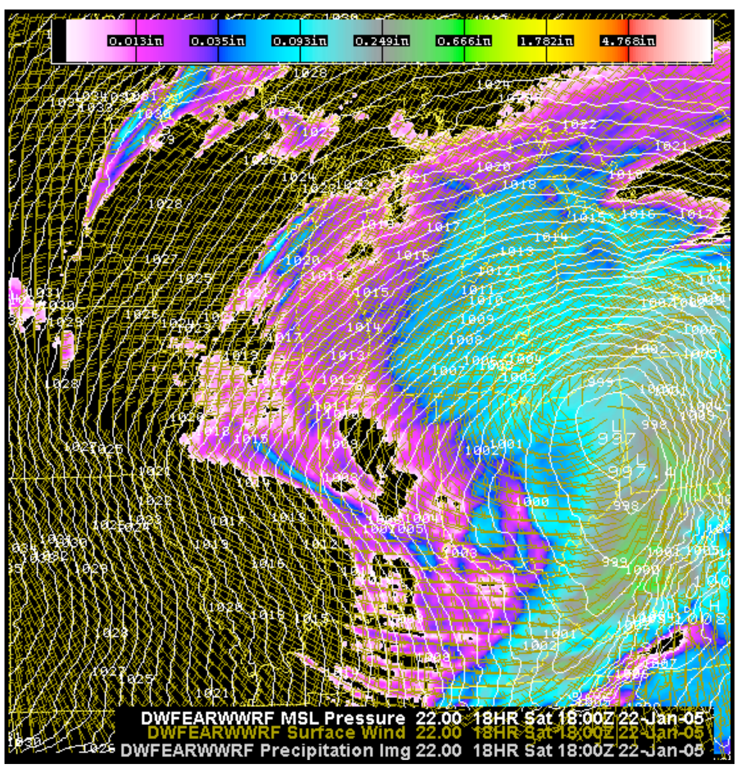


Fig. 7. Mesovortex over Lake Erie a) analyzed in 5-km resolution STMAS surface winds and reduced pressure field and b) forecast by the 5-km WRF ARW model valid for 1800 UTC 22 January 2005. Color-shaded fields in b) are 3-hourly forecast precipitation (inches).

5. Summary

A surface space-time mesoanalysis system (STMAS) has been developed to take advantage of the high temporal and spatial resolution of mesonetwork data that are becoming available in real-time for operational nowcasting. 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 nonmathematical summary of this new scheme and provides several real-case examples showing how important mesoscale 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 improved quality control purposes and for filling in missing data. Also, an objective boundary detection algorithm is being developed. Finally, we are moving the STMAS processing to a massively-parallel computer and testing a multigrid technique to replace the recursive filter. Initial results suggest that multigrid not only is more efficient but also provides better analyses of analytic functions than the recursive and wavelet techniques.

6. Acknowledgments

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