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Objective Predictions of Thunderstorm Location and Severity for Aviation

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This paper presents a computerized technique for medium-range (12-48 h) prediction of both the location and severity of thunderstorms, utilizing atmospheric predictions from the National Meteorological Center's limited-area fine mesh model. A regional-scale analysis scheme is first used to examine the spatial and temporal distribution of forecasted variables associated with the structure and dynamics of mesoscale systems over an area of approximately 10^6 km^2. The final prediction of thunderstorm location and severity is based upon an objective combination of these regionally analyzed variables. Medium-range thunderstorm predictions are presented for the late afternoon period of April 10, 1979, the day of the Wichita Falls, Texas tornado. The National Severe Storms Forecast Center's operational predictions are presented with the case study to demonstrate the possible application of this objective technique in improving 12-48-h thunderstorm forecasts for aviation.

Nomenclature

AVE/SESAME = atmospheric variability experiment/ severe environmental storm and mesoscale experiment
GMT = Greenwich mean time
GOES = geostationary operational environmental satellite
LI = lifted index
LFM = limited-area fine mesh
PBL = planetary boundary-layer
PBLMD = planetary boundary-layer moisture divergence
PBLVV = planetary boundary layer vertical velocity
TRWRI = thunderstorm relative index
TWS = 1000-500 mb thermal wind shear magnitude
VMF = vertical moisture flux
VMFCI = vertical moisture flux and convective instability in the lower troposphere
$\Delta\theta_e$ = vertical equivalent potential temperature difference term
θ_{ePBL} = equivalent potential temperature in the planetary boundary layer
θ_{e700} = equivalent potential temperature at 700 mb

Introduction

WEATHER forecasts issued by the major weather services in the world are primarily based upon results from numerical weather-prediction models, since they simulate, as accurately as possible, the dynamical and physical processes that govern the evolution of the synoptic and large mesoscale motions of the atmosphere. However, the prediction of moist convective activity and its intensity remains a serious problem, both in terms of our needs and our technological and scientific abilities. From a scientific viewpoint, thunderstorms are an integral part of the overall circulation of the atmosphere, since they vertically transport tremendous amounts of heat, moisture, and momentum and produce heavy precipitation. From the forecasting point of view, thunderstorm development is not so rare an event that it can be ignored, especially considering the rapid and extreme variations in both local and aviation weather that accompany convective activity.

With approximately 100,000 thunderstorms occurring within the contiguous United States each year, convective activity is, in fact, common in many parts of the U.S. More importantly, approximately 10% of these thunderstorms could be termed "severe" because the precipitation, hail, or winds accompanying these storms are sufficient to cause property damage and pose a threat to human life. A small percentage of the severe thunderstorms also spawn tornadoes that can destroy everything in their paths. Therefore severe convective activity represents one of the greatest geophysical hazards, both in terms of death and dollar-loss in damage.[1]

Although individual thunderstorms are too small to be completely resolved in the present observing and computing grids, the large mesoscale region within which such storms occur is hundreds of kilometers in size and is near the present limit of resolution of the continental U.S. radiosonde network and of numerical prediction models. Recent research has established good statistical and dynamical relationships between convective storms and the regional-scale disturbances that produce them, so that accurate medium-range prediction of large mesoscale systems should lead to improved forecast of thunderstorm location and intensity. While this approach is inherently probabilistic, it is currently the most viable method for medium-range objective thunderstorm forecasting since dynamically explicit prediction of most convection is not operationally feasible.

Therefore the purpose here is to present an objective technique, improved over the versions presented by Wilson and Marrs[2] and Wilson,[3] for medium-range prediction of the location and severity of thunderstorms. Predictions from the National Meteorological Center's LFM model are used to forecast those large mesoscale weather systems that often produce convection. Analysis of these forecasts is then performed by computer to generate the final thunderstorm predictions.

Sample results are presented for April 10, 1979, the day of the Wichita Falls, Texas tornado and Red River Valley tornado outbreak of severe weather.[4] This case is unique in that unusually complete verification data are available, including the first meso-α scale rawinsonde measurements of the at-

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mosphere made under NASA's AVE/SESAME program.[5] Verification of the forecasts is done with radar and satellite data and surface reports of severe weather. Final predictions are compared to short-range (2-6 h) severe weather forecasts made by the National Severe Storms Forecast Center to demonstrate the possible application of this technique in improving thunderstorm forecasts for aviation. Improvements and verification of this technique have been aided by operational testing and evaluation during recent months.

Background and Approach

Interaction processes between convective storms and both regional- and synoptic-scale systems have attracted considerable research interest in recent years. Thunderstorm-environment interactions of interest here are 1) stage-setting—the necessary and sufficient conditions for thunderstorm development, and 2) the synoptic- and regional-scale control of storm location, intensity, and movement. Good success has been realized in parameterizing the scale-interaction processes between snyoptic- and/or regional-scale systems and severe convection, since good severe weather forecasts are made from the current synoptic and surface weather observations.

These parameterized relationships indicate that the environmental flow field exerts a strong controlling influence over the intensity as well as the spatial and temporal distribution of the smaller mesoscale convective circulations. However, they do not explain the sequence of events which result in severe convection, nor do they account for the feedback processes between the convective storms and their environment.

Miller[6] has summarized the empirical relationships between mesoscale conditions and severe convective storm development. They include 1) a vertical temperature structure that is conditionally unstable, 2) large amounts of low-level moisture, 3) strong mid- and upper-tropospheric jets, and 4) a dynamical mechanism producing lifting and releasing convective instability. More quantitative synoptic and regional-scale relationships have been established by Hudson,[7] Chen and Orville,[8] and many other researchers, where cumulus cloud formation and populations have been parametrically and dynamically tied to macroscale and mesoscale moisture divergence, vertical velocity, and heat and moisture budgets.

Statistical correlation between observed convection and forecasted parameters from numerical models have helped in establishing the relationships between convective and synoptic-scale systems, but the inability of many models to resolve and forecast subsynoptic-scale systems has limited the accuracy of these predictions. However, some numerical models are now showing forecast skill on the regional scale, including the LFM model.

Combined dynamical and statistical methods[9] are currently being used by the National Weather Service (NWS) in operational forecasting of thunderstorms and severe weather up to 36 h in advance. Data for these forecasts come from different numerical models and current surface and upper-air observations to provide a wide choice of predictors. Some of the most important predictors are the numerical indices quantifying potential moist hydrostatic instability and include those operationally available at each synoptic observation period. Operational forecasting procedures developed in the Techniques Development Laboratory of the National Weather Service combine several of these indices with other predictors, using multiple screening regression, to provide a probability forecast of the location and severity of convection.

Short-range (2-6 h) forecasts have been developed by Charba[10] from predictors derived from observed surface variables, radar data, local climatic frequencies, and basic variables predicted by the LFM model. Reap and Foster[11] have produced 12-36-h probabilities of thunderstorms and severe weather using data from the National Meteorological Center's primitive equation models, a three-dimensional trajectory model, and the daily thunderstorm relative frequencies obtained from a small climatology of manually digitized radar data.

However, the forecasting technique to be described here relies only upon predicted variables from the LFM model, their accuracy, and the relationships between these predicted variables and the location and intensity of thunderstorm formation. The approach was to develop an objectively derived index, based generally upon the four empirical conditions of Miller[6] stated earlier, relating thunderstorm location and severity to the predicted state of the atmosphere determined by the LFM model.

Description of the Forecasting Technique

Predicted variables from the LFM model are operationally available from computer runs made at 0000 and 1200 GMT each day. Grid-point forecasts are available at 6-h intervals, out to 48 h, for all successful predictions. Since LFM forecasts cover approximately one-third of the Northern Hemisphere centered on the United States, a subset of this grid is chosen for making thunderstorm forecast (usually a square ~2000 km on a side). For each 6-h period of interest, grid-point fields of the following variables are retrieved or generated: planetary boundary layer (PBL) wind, mixing ratio, equivalent potential temperature, 1000-500 mb thickness, 700 mb equivalent potential temperature, and lifted index. Five basic terms in the final predicted index equation are transferred or computed from these fields. They include a) the lifted index (LI), b) the vertical velocity at the top of the PBL (PBLVV in μbar s^{-1}), c) the horizontal flux divergence of water vapor in the PBL (PBLMD in g $kg^{-1}s^{-1}$), d) the vertical moisture flux at the top of the PBL modified by convective instability between the PBL and ~700 mb (VMFCI in g $cm^{-2}s^{-1}$ times a constant representing convective instability), and e) the 1000-500 mb thermal wind magnitude (TWS in m s^{-1}).

In term d convective instability between the PBL and ~700 mb is parameterized by subtracting θ_{ePBL} from θ_{e700}. The grid field of vertical moisture flux is then multiplied by a field of the term

$$\Delta\theta_e = ((\theta_{ePBL} - \theta_{e700})/10) + 1.0 \qquad (1)$$

where $\Delta\theta_e \geq 1.0$ always. Therefore

$$\mathrm{VMFCI} = \mathrm{VMF}\,(\Delta\theta_e) \qquad (2)$$

so that vertical moisture flux is modulated by $\Delta\theta_e$, which usually ranges from 1.0-3.0 ($\Delta\theta_e$ defaults to 1.0 if the term is <1.0). The terms a-d are also multiplied by scale factors so that each usually ranges from about −10 to 10 and every term is considered equally in its contribution to the final prediction. Also, the signs of the scale factors are adjusted so that negative terms contribute to "yes" forecasts of thunderstorms. Negative ("yes") contributions to predictions of convective activity occur in each term when 1) term a, LI, becomes negative following the standard lifted index definition (scale factor = 1.0); 2) term b, PBLVV, shows upward air motion (i.e., negative value in pressure coordinates) at the top of the PBL that can lift and destabilize the atmosphere (scale factor = 4.0); 3) term c, PBL, indicates moisture is being concentrated in the PBL through wind convergence and/or advection of water vapor (scale factor $= 1.0 \times 10^4$); 4) term d, VMFCI, indicates moisture is being fluxed from the PBL into a lower troposphere that is convectively unstable (i.e., $\partial\theta_e/\partial_p > 0$) (scale factor $= -2.0 \times 10^5$). Term e, TWS, represents the magnitude of the 1000-500 mb thermal wind as a measure of the vertical wind shear throughout the low and middle troposphere. TWS is scaled by 4.0×10^{-2} so that a 1000-500 mb thermal wind magnitude of 25 and 100 m s^{-1} yields TWS values of 1.0 and 4.0, respectively.

The resulting prediction of thunderstorm location and severity is based upon an objective combination of these five terms into an index. The TWS term is used to modulate terms a-d when each individually contributes to a yes (i.e., negative) index prediction of convection. TWS is set to 1.0 when individual terms a-d are ≥ 0. The final thunderstorm forecast is actually a relative index ranging from about -20 to 20 with values less than about 5 reflecting yes predictions of thunderstorm location and severity. The index equation is

$$\begin{aligned} \mathrm{TRWRI} = {} & \underset{(a)}{\mathrm{LI}}\underset{(e)}{(\mathrm{TWS})} + \underset{(b)}{\mathrm{PBLVV}}\underset{(e)}{(\mathrm{TWS})} \\ & + \underset{(c)}{\mathrm{PBLMD}}\underset{(e)}{(\mathrm{TWS})} + \underset{(d)}{\mathrm{VMFCI}}\underset{(e)}{(\mathrm{TWS})} \end{aligned} \tag{3}$$

where TWS $= 1.0$ when terms a-d, individually, are ≥ 0.

In considering the relationships between thunderstorm location and intensity and the TRWRI values over the forecast area, we have tentatively determined from experience that thunderstorm formation rarely occurs when values are >5. With $-5 < \mathrm{TRWRI} < 5$, thunderstorms are likely but severe thunderstorms are rare while $-15 < \mathrm{TRWRI} < -5$ is accompanied with heavy thunderstorms and isolated severe thunderstorms. $\mathrm{TRWRI} < -15$ occurs with heavy thunderstorms and a few severe thunderstorms. Since each index field is available at 6-h intervals of the LFM forecast, predictions are generally considered valid for ± 3 h centered on the valid time of the TRWRI field. Limited objective verification results support these conclusions, but further research will optimize the "cut-off" index values for categorical predictions of "no thunderstorms," "thunderstorms," and "severe thunderstorms" as a function of season and geographical location. This work is currently under way.

Figure 1 summarizes schematically a hypothetical atmospheric condition predicted by the LFM that would lead to a "yes" forecast of convective activity by each of the terms a-e of Eq. (3), resulting in a highly negative TRWRI index value.

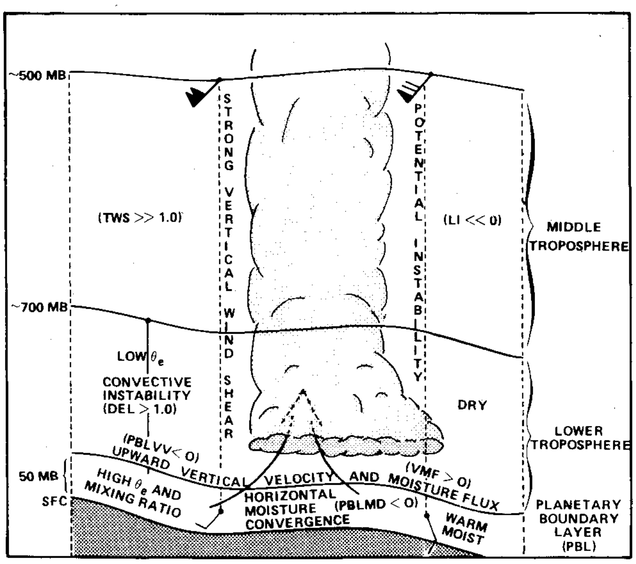


Fig. 1 Schematic representation of atmospheric structure and dynamics that would lead to a "yes" prediction of intense thunderstorm activity by every term in the TRWRI equation. Terms are depicted vertically as if they were predicted by the LFM model.

Forecast Results for April 10 and 11, 1979

Large-Scale LFM Forecasts

All forecast results presented here will come from the 12-h LFM prediction valid at 0000 GMT, April 11, 1979. Figure 2 is a National Weather Service product showing analyzed fields of numerous parameters from the 12-h LFM forecast over most of the model domain. The 500 mb height and absolute vorticity fields (Fig. 2a) depict a high amplitude wave pattern over North America with a particularly strong closed low and vortex circulation over the Southern Rocky Mountains. This system and its accompanying convective activity are examined closely in this paper.

A deep surface and 700-mb low was also predicted with this system over eastern Colorado. Water vapor, entering the storm from the southeast quadrant (Figs. 2b and 2c), was being lifted in a strong upward vertical velocity field over the Southern Plain States, resulting in a prediction of precipitation over the region (Fig. 2d). A 2000 × 2000-km box, located over the Southern Plain States (Fig. 2d), outlines the mesoscale region where predictions of atmospheric dynamics by the LFM are compared to those measured by NASA's AVE/SESAME I experiment. Included in the comparison are the TRWRI index fields that depend solely upon the atmospheric state either predicted by the LFM or diagnosed using AVE/SESAME I verification data.

AVE/SESAME Verification Data and Satellite Imagery

NASA Marshall Space Flight Center participated with its Atmospheric Variability Experiment in a large interagency mesoscale and severe storms experiment identified as AVE/SESAME '79 (Atmospheric Variability Experiment—Severe Environmental Storms and Mesoscale Experiment 1979). A primary objective of NASA was to support an effort to acquire carefully edited sets of rawinsonde data, during selected severe weather events, for use in correlative and diagnostic studies with satellite and radar data obtained at approximately the same time. Data were acquired during six individual 24-h experiments on both regional- and storm-scale networks located in the Central United States utilizing approximately 20 supplemental rawinsonde sites meshed among 23 standard National Weather Service sites. Included as the first among the six experiments is a data set obtained between 1200 GMT, April 10 and 1200 GMT, April 11, 1979, encompassing the formation and development period for the tornado-producing systems that devastated Wichita Falls, Texas and other sections of Oklahoma and Texas. Figure 3 shows the regional-scale rawinsonde network that provided complete and unique verification data for this case study.[12,13]

GOES satellite imagery for this period are shown in Fig. 4. The 1331 GMT visible picture on April 10 (Fig. 4a) depicts the cloud field conditions close to LFM initialization time. Extensive multilevel clouds covered most of the Central United States but no convective activity was present as determined from radar. However, by 2300 GMT (Fig. 2b), convective activity was common over many parts of the Central and Southern Plains, and severe convection was developing along a band from Southwest Texas to Northeast Oklahoma. The Wichita Falls storm is seen in North Texas along the Red River. The enhanced infrared image at 0000 GMT, April 11 (Fig. 4c), shows the cold cloud tops associated with this and other severe thunderstorms in Texas and Oklahoma.

Comparisons Between the Predicted and Observed Atmosphere

AVE/SESAME I data at 0000 GMT, April 11, 1979 were placed on the same grid used to examine the predicted LFM parameters so that a direct comparison could be made between the atmospheric structure and dynamics predicted by the model and that observed by the AVE/SESAME I network. AVE/SESAME I data were specially configured so that analyzed parameters would conform to the terrain-following

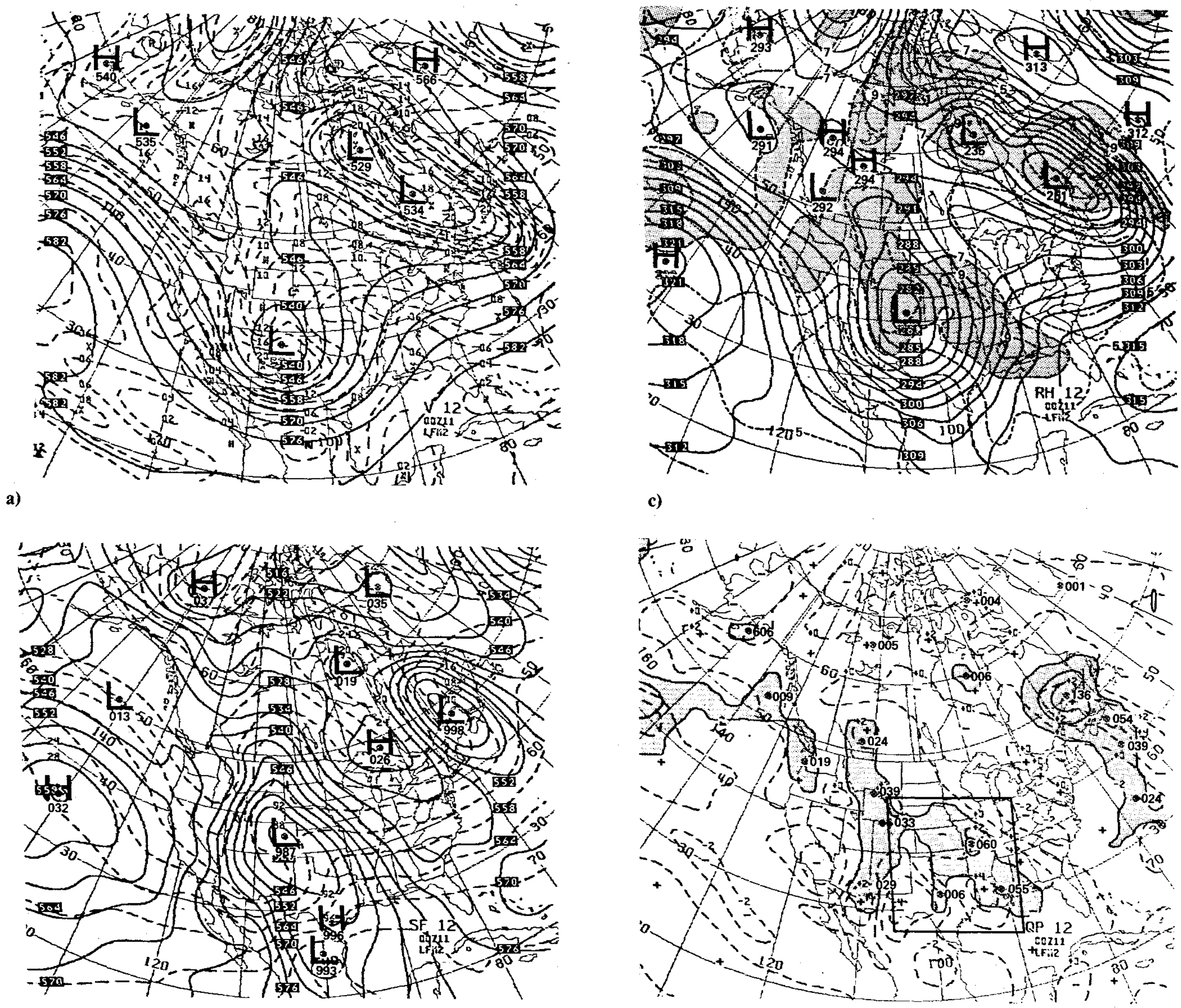


Fig. 2 National Weather Service LFM facsimile charts for a 12-h forecast valid at 0000 GMT, April 11, 1979. Included are a) 500-mb geopotential height and absolute vorticity, b) surface pressure and 1000-500 mb thickness, c) 700-mb geopotential height and surface-500 mb mean relative humidity (values > 70% shaded), and d) 700-mb vertical velocity (cm s^{-1}) and 12-h accumulated precipitation (in hundreds of inches and shaded).

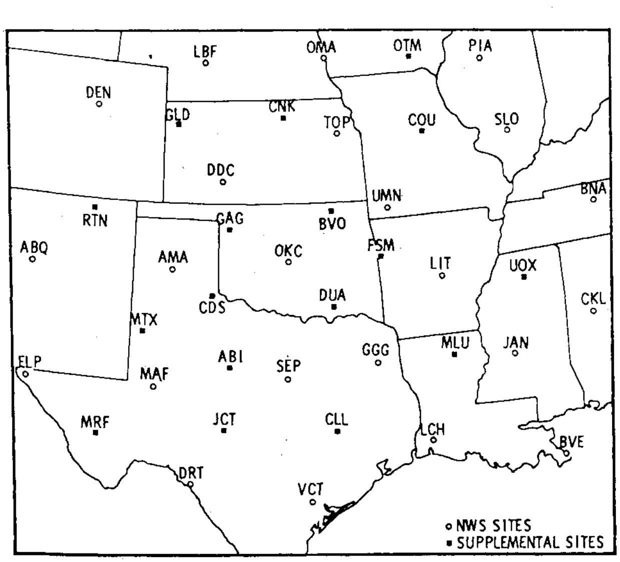
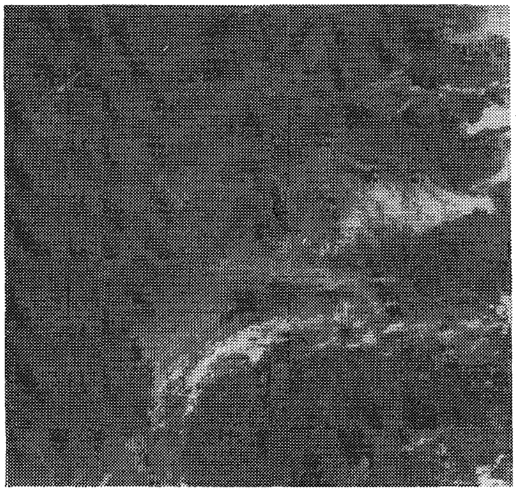


Fig. 3 Regional-scale rawinsonde network during April 10-11, 1979 (AVE/SESAME I).

coordinate system of the LFM model. The three atmospheric layers of interest were the PBL, lower-troposphere, and middle-toposphere shown in Fig. 1.

Figure 5 shows the predicted and observed PBL wind, mixing ratio, and surface pressure fields. These analyses are similar except in the southwest where actual winds are stronger in association with the poorly predicted wind shift along the cold front. This problem is related, in part, to the misplaced surface pressure trough that was predicted to lie from Colorado to Central Texas and contributed to under-forecasted mixing ratios southwest of the trough. Even so, the lifted index field (Fig. 6) was reasonably well predicted except in the southwest where water vapor forecasts were poor.

The PBL vertical velocity (PBLVV) forecast (Fig. 7) is exceptionally good in overall shape, but magnitudes of the centers are too small. Upward motion was accurately predicted along the frontal surfaces with a center close to the observed triple point in the Texas Panhandle. PBL moisture divergence (PBLMD) (Fig. 8) was poorly predicted only along the cold front in West Texas where wind and moisture forecast were poor. The same is true of the VMFCI term (Fig. 9).



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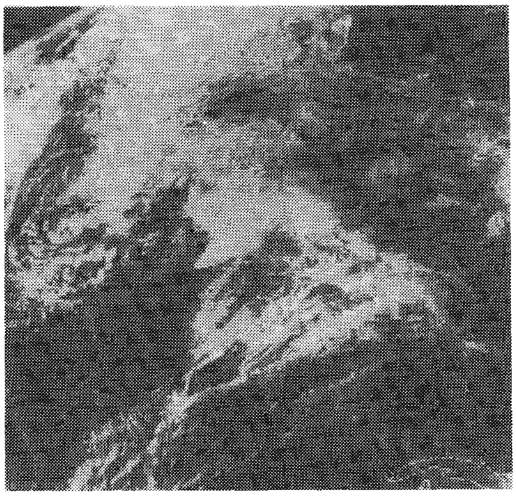

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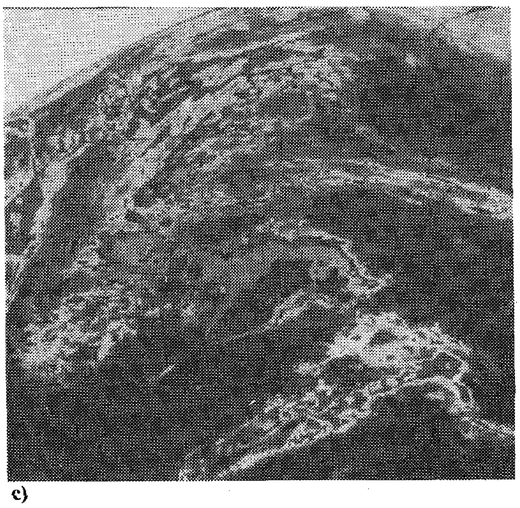
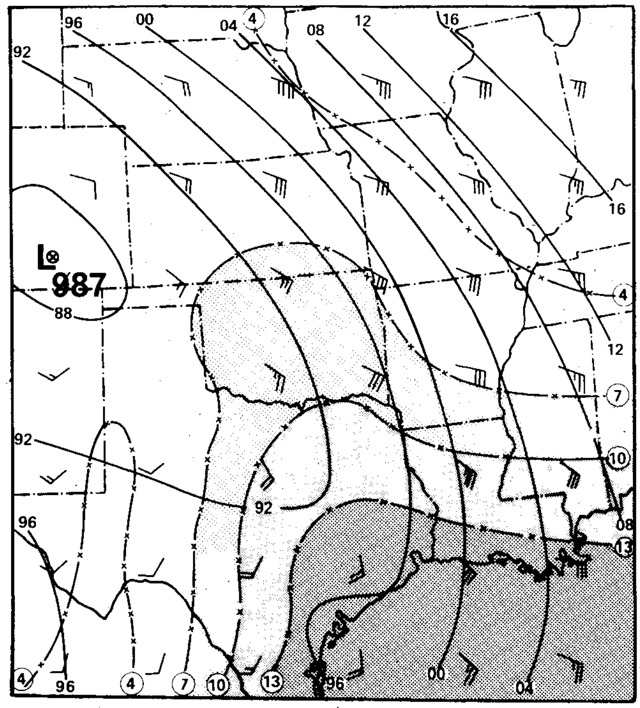


c)

Fig. 4 GOES satellite images during AVE/SESAME I. Included are a) visible image at 1331 GMT, April 10, 1979, b) visible image at 2300 GMT, April 10, 1979, and infrared image at 0000 GMT, April 11, 1979.



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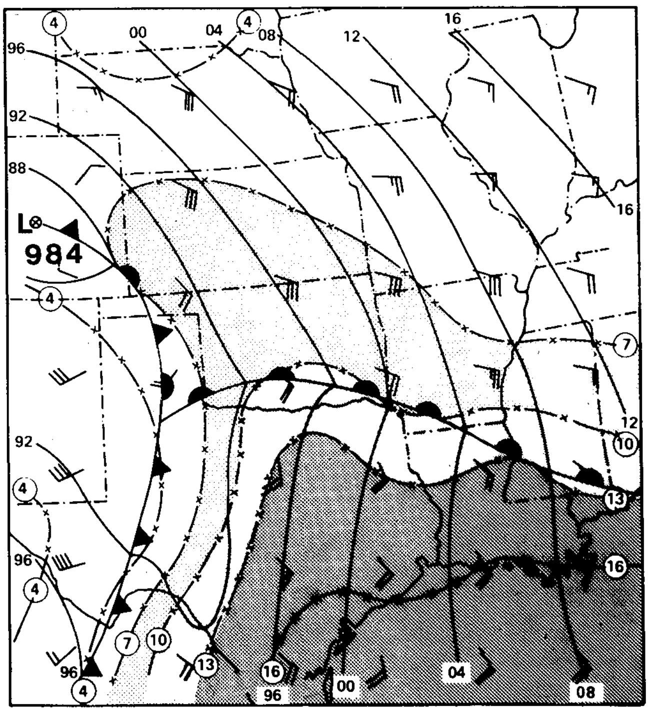


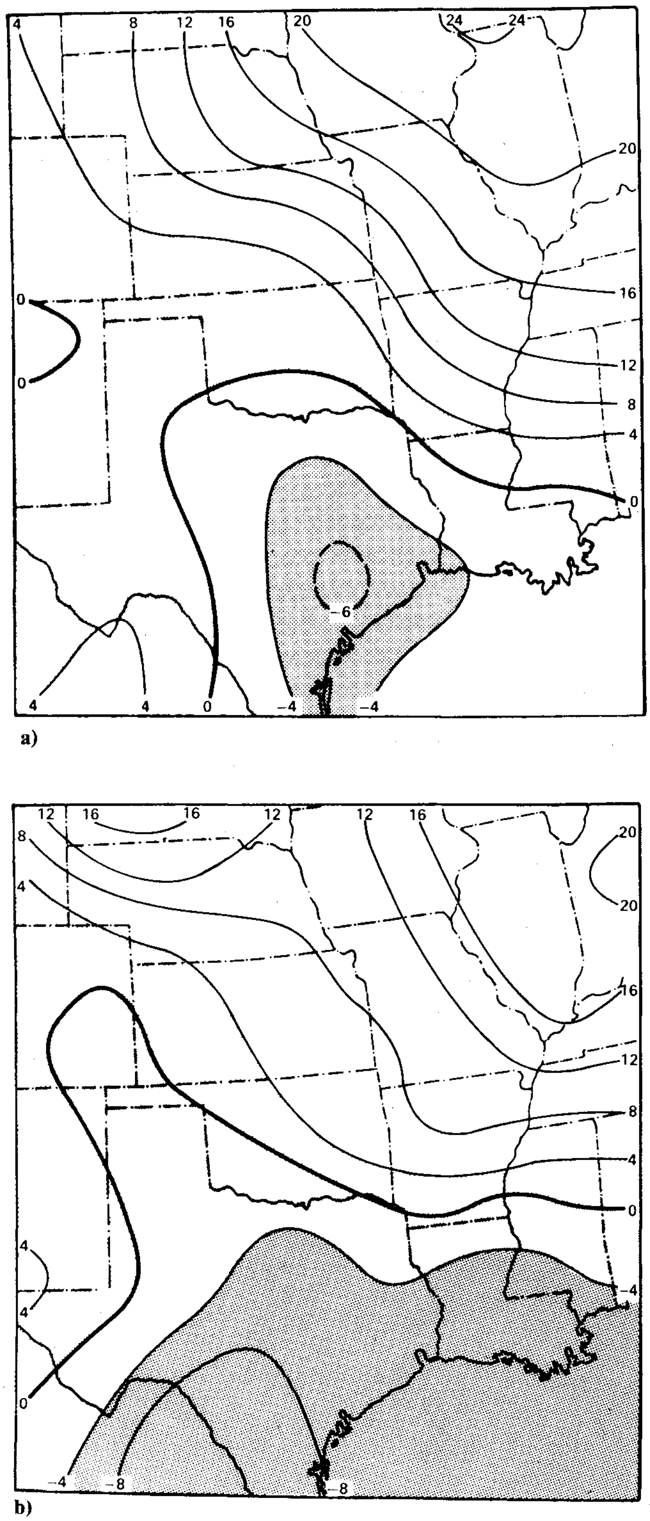
b)

Fig. 5 a) Predicted (12-h LFM) and b) observed (from AVE/SESAME I data) PBL wind (knots), PBL mixing ratio g kg^{-1}), and surface pressure (mbar) at 0000 GMT, April 11, 1979.

The thermal wind term (TWS) (Fig. 10) was reasonably well predicted, especially along the polar jet zone, but the LFM generated a secondary jet, similar in location to a subtropical jet, that was not verified by observation. Overall, however, the 12-h LFM model prediction faithfully reproduced the observed structure and dynamics of the atmosphere over this particular mesoscale region during a time of extreme baroclinic wave development. This produced good forecasts of the terms in the TRWRI equation even though magnitudes of field centers appeared to be smaller than observed conditions.

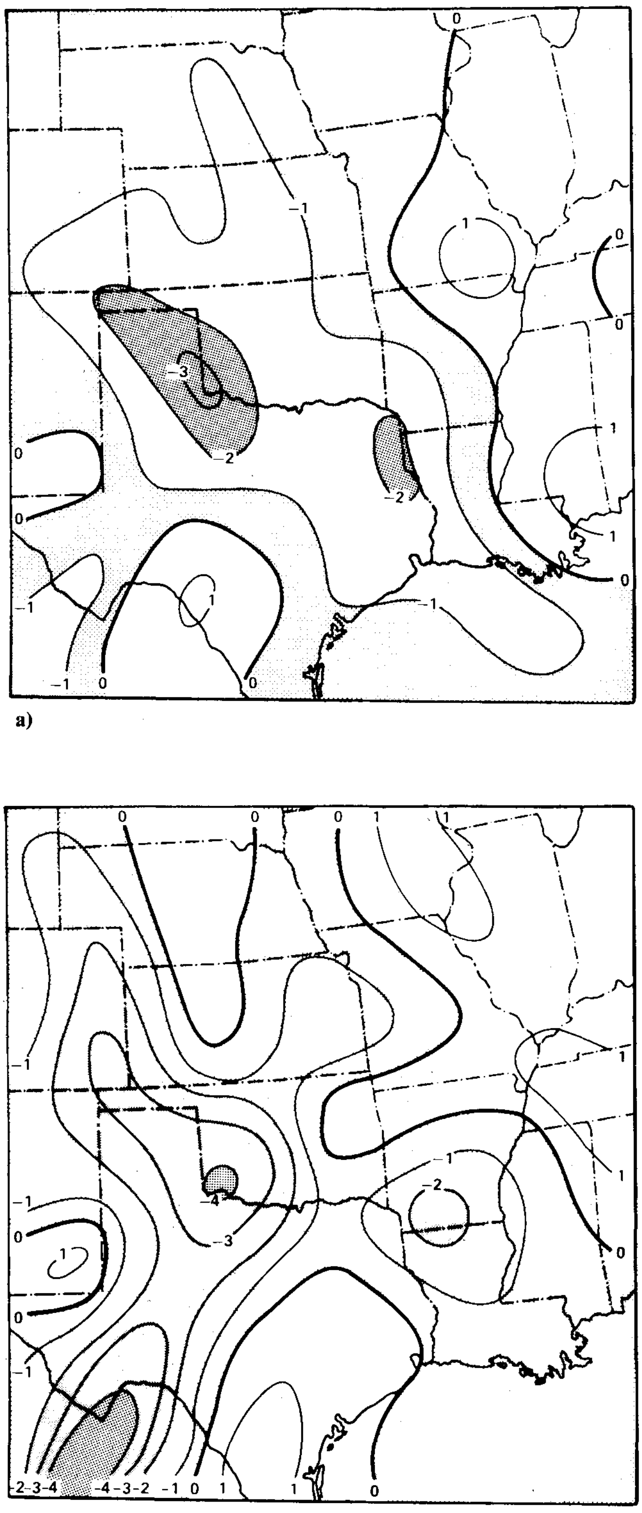
Thunderstorm Prediction and Verification

The predicted and observed TRWRI index fields are shown in Fig. 11. For verification, NWS hourly manually digitized radar measurements ≥3, from 2100 GMT, April 10 to 0300



a) b)

Fig. 6 a) Predicted (12-h LFM) and b) observed (from AVE/SESAME I data) lifted index (LI) fields at 0000 GMT, April 11, 1979.

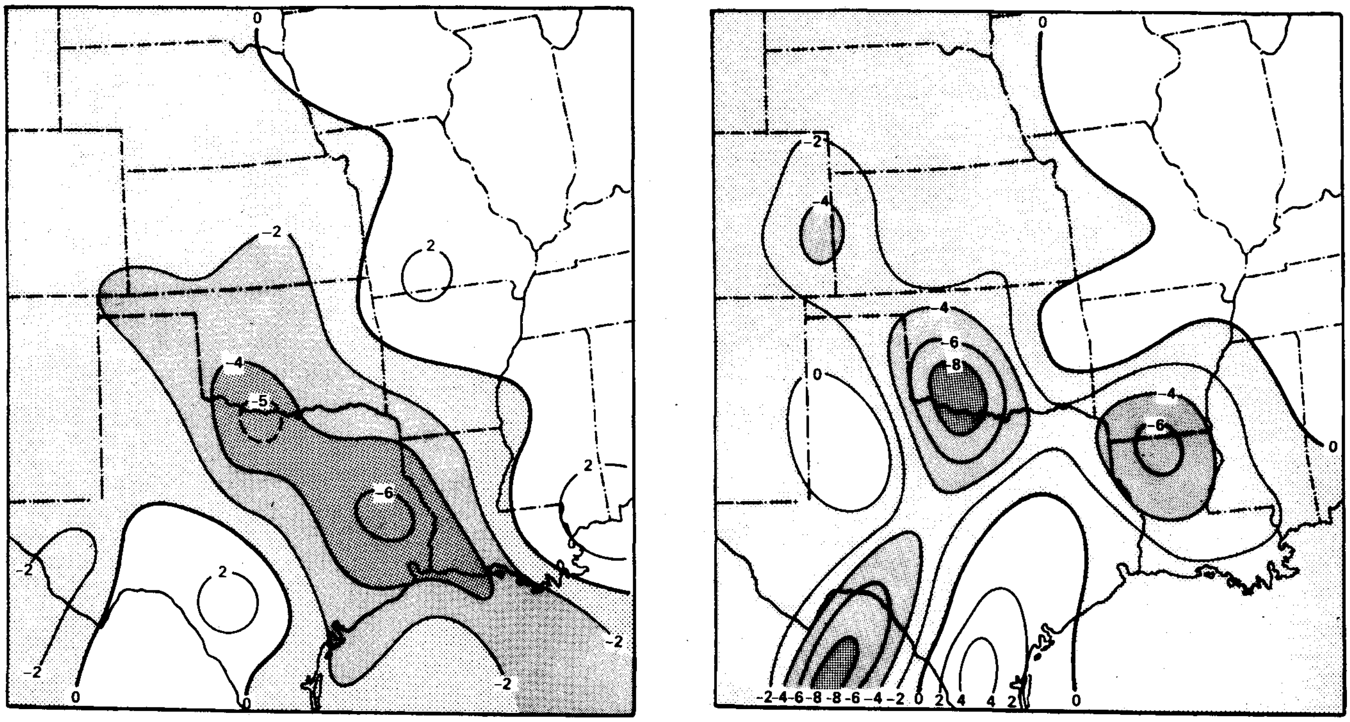


a) b)

Fig. 7 a) Predicted (12-h LFM) and b) observed (from AVE/SESAME I data) PBL vertical velocity fields (PBLVV in μbars s^{-1}) at 0000 GMT, April 11, 1979.

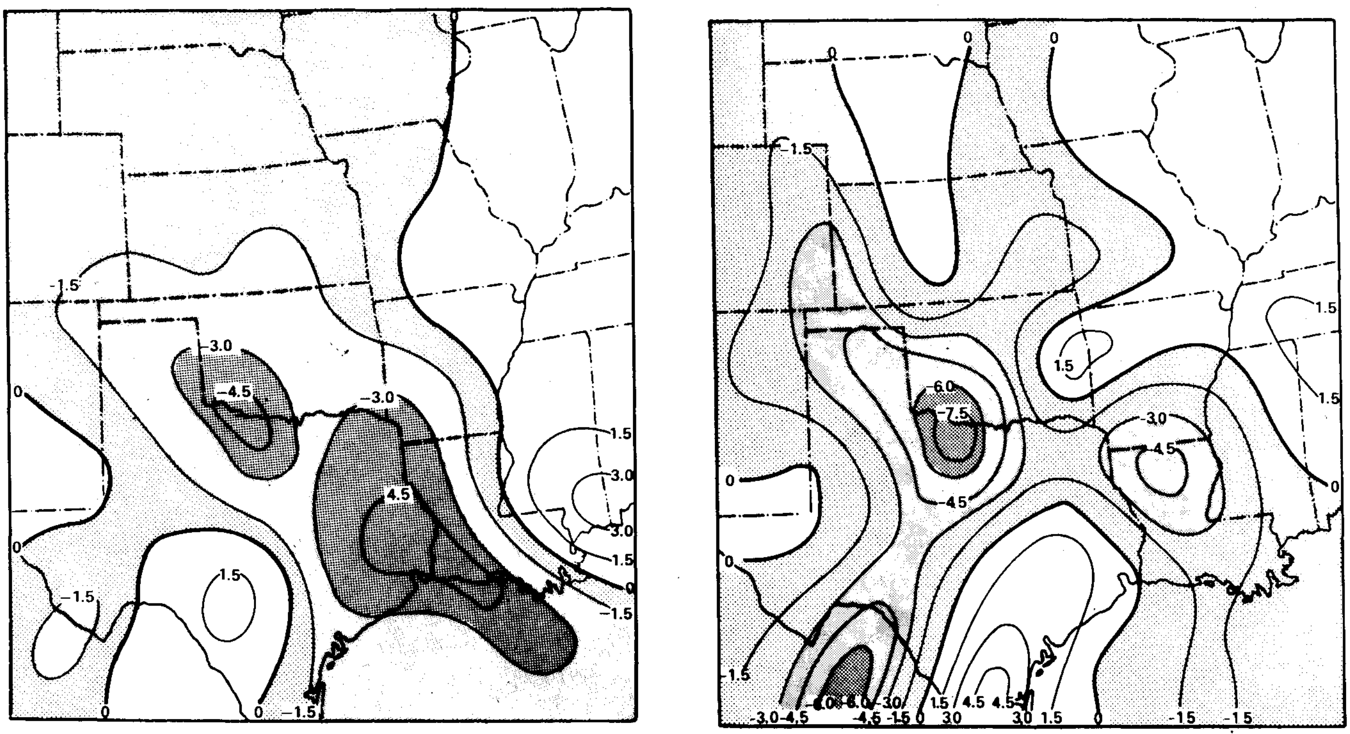
GMT, April 11, are darkly shaded in each chart along with radar tops (in hundreds of thousands of feet), severe weather observations (H = hail, C = funnel cloud, W = strong surface winds, and T = tornado) and short-range severe weather forecast "boxes." Negative index values are lightly shaded in each chart.

The predicted and observed TRWRI fields are reasonably similar in areal coverage of values <0 and in shape. Further, the observed TRWRI field shows a strong relationship to both the location and severity of thunderstorms except in the southwest where verification data are poor. Therefore thunderstorms were accurately predicted by the LFM 12-h TRWRI index field, with more intense convection expected in North Central Texas and Southwestern Oklahoma. This is verified by the severe weather observations. In addition, recent research has shown that consistent and comparable results were produced over the entire 12-48-h forecast period with some gradual degradation of the predictions after the 30-h period. Objective verification of the technique for various years and seasons is underway and should lead to modifications and improvements.



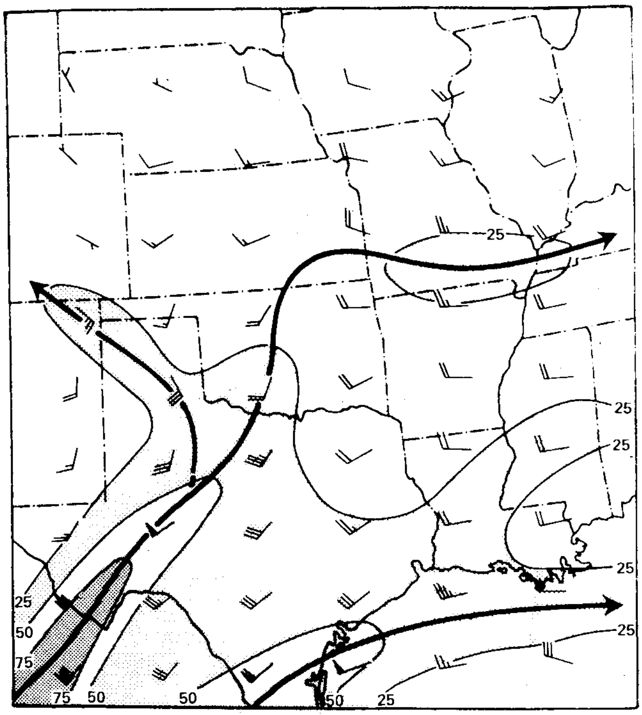
a) b)

Fig. 8 a) Predicted (12-h LFM) and b) observed (from AVE/SESAME I data) PBL moisture divergence fields (PBLMD in g kg $^{-1}$ s $^{-1}$ multiplied by 1.0×10^4) at 0000 GMT, April 11, 1979.



a) b)

Fig. 9 a) Predicted (12-h LFM) and b) observed (from AVE/SESAME I data) fields of vertical moisture flux at the PBL top modulated by convective instability between the PBL and ~700 mb (VMFCI in g cm $^{-2}$s $^{-1}$ multiplied by -2.0×10^5 multiplied by the constant $\Delta\theta_e$) at 0000 GMT, April 11, 1979.



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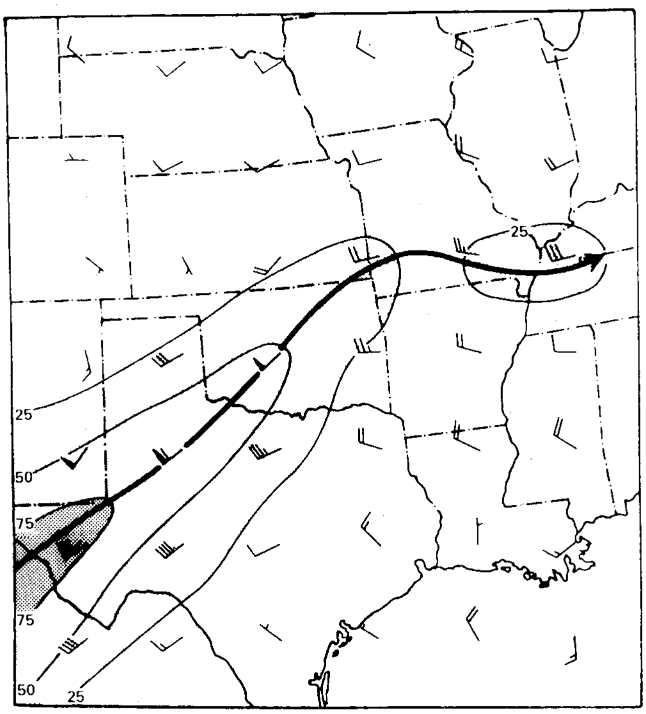
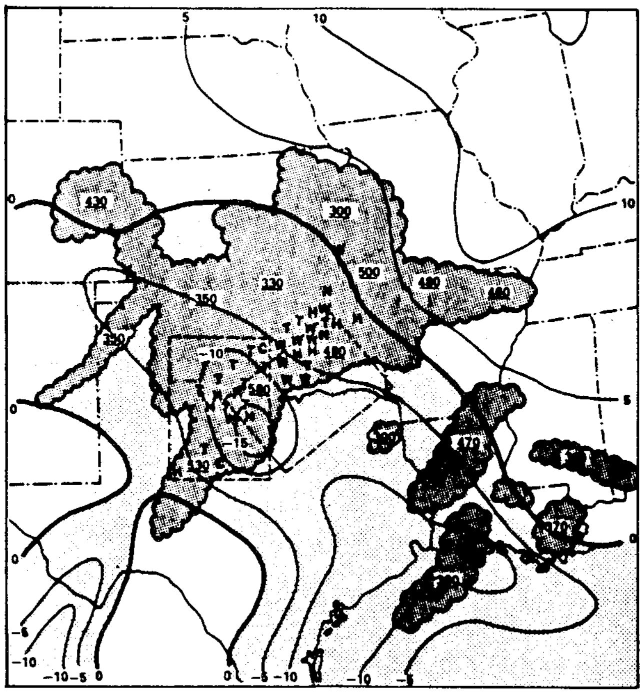


b)

Fig. 10 a) Predicted (12-h LFM) and b) observed (from AVE/SESAME I data) fields of 1000-500 mb thermal wind (m s^{-1}).



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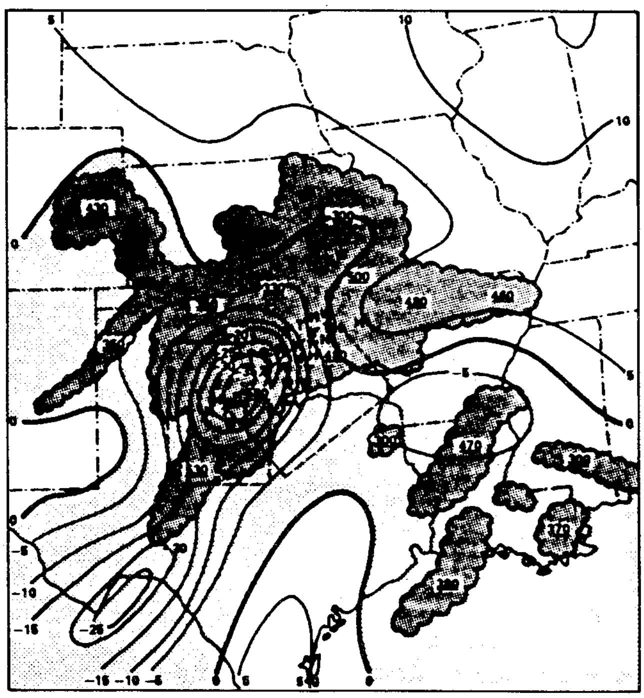

b)

Fig 11 a) Predicted (12-h LFM) and b) observed (from AVE/SESAME I data) TRWRI index fields. NWS hourly manually digitized radar measurements ≥3, from 2100 GMT, April 10 to 0300 GMT, April 11, are darkly shaded in each chart along with radar tops (in hundreds of thousands of feet), severe weather observations (H = hail, C = funnel cloud, W = strong surface winds, and T = tornado), and short-range severe weather forecast "boxes."

Conclusions

Using the relationships between thunderstorm formation and intensity and the regional-scale environment in which these storms form, the LFM model forecasts have been used to objectively predict the evolution of the regional-scale atmosphere in which thunderstorms and severe weather eventually formed during the AVE/SESAME I period of April 10-11, 1979. This study has demonstrated the usefulness of a medium-range objective forecast procedure, which uses only regionally forecasted variables and parameters from the LFM model, in making thunderstorm and severe weather forecasts.

Unique verification data for this case study has shown the LFM model capable of predicting the large mesoscale structure and dynamics needed to parameterize thunderstorm location and severity. Operational use of the TRWRI predictions should provide guidance to improve medium-range forecasts of thunderstorms for public and aviation users.

Acknowledgments

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