SUPPLEMENT

THE VALUE OF WIND PROFILER DATA IN U.S. WEATHER FORECASTING:

Case Studies

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This document is a supplement to "The Value of Wind Profiler Data in U.S. Weather Forecasting," by Stanley G. Benjamin, Barry E. Schwartz, Edward J. Szoke, and Steven E. Koch (*Bull. Amer. Meteor. Soc.*, **85,** 1871-1886) • ©2004 American Meteorological Society
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Oklahoma tornado outbreak, 3 May 1999. Numerous papers (including the May 2002 issue of *Weather and Forecasting*) describe the significance of the 3 May 1999 Oklahoma City tornado outbreak. Edwards et al. (2002) and Thompson and Edwards (2000), writing from the standpoint of operational forecasting, specifically mention the profiler data as an important data source that helped in the diagnosis of the prestorm convective environment. The introduction of the main paper includes remarks of forecasters from the National Oceanic and Atmospheric Administration's (NOAA's) Storm Prediction Center (SPC) about the importance of profiler data on this day. The 20-km Rapid Uptake Cycle (RUC) with a 1-h assimilation cycle was rerun for the 24-h period (0000 UTC 3 May–0000 UTC 4 May 1999) with (CNTL) and without (EXP) the profiler data to assess their impact on forecasts of preconvective environment parameters and precipitation over Oklahoma. [Profiler observations were not available for operational forecasts from the then-40-km RUC due to computer timing issues for predictions actually run on 3 May 1999. Velocity azimuth display (VAD) winds from the Weather Surveillance Radar-1988 Doppler (WSR-88D) were neither used in the actual RUC predictions for this event nor in this case study due to quality issues identified at the National Centers for Environmental Prediction (NCEP).]

Prompted by the remarks of Thompson and Edwards (2000), we first examined the difference between the wind analyses and forecasts in the CNTL and EXP runs beginning at about 1500 UTC. The authors describe an embedded jet streak associated with a deepening trough that was approaching Oklahoma from the west, and how the NCEP Eta Model from the 0000 UTC 3 May 1999 run underforecast the intensity of the wind speed maximum aloft (see "Discussion and conclusions" of Benjamin et al. 2004b for their complete remarks). They based their assessment on the Tucumcari, New Mexico, profiler time–height time series (Fig. S1), showing increasing winds in the 4–10-km layer. The high-frequency profiler data showed 300-hPa winds increasing from 30 m s^{-1} at 1200 UTC to 50 m s^{-1} within 7 h. In the RUC 6-h forecasts initialized at 1800 UTC, the winds are stronger at 300 hPa in the CNTL experiment compared to the EXP run by about 4–6 m s^{-1} over a broad area, including western Oklahoma and north-central Texas (Fig. S2). According to the verifying CNTL analysis at 0000 UTC (Fig. S2c), the profiler data improve the accuracy of the short-range RUC upper-level wind forecast by better capturing the jet streak noted in the

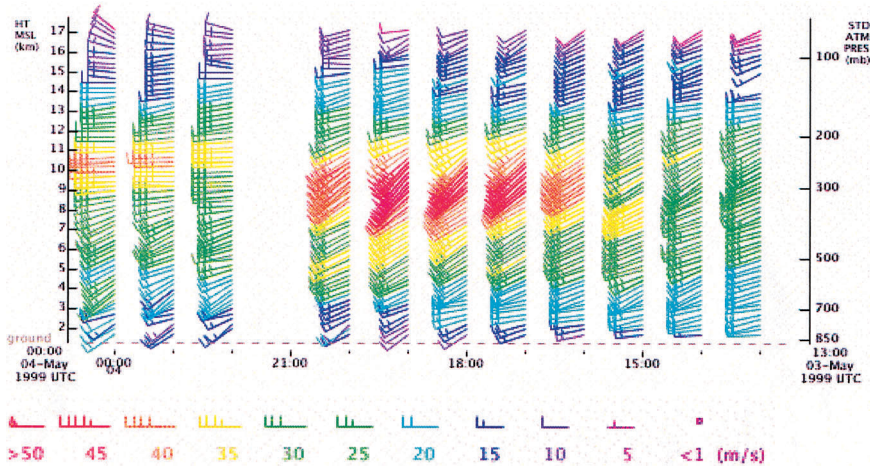

FIG. S1. Tucumcari, NM (TCUM5), profiler time series valid for 1300 UTC 3 May–0000 UTC 4 May 1999. Wind speed (m s^{-1}) is coded by color in the legend at the bottom.

Tucumcari profiler observations and its subsequent effect on the upper-level winds over the area of convective development in Oklahoma.

The difference between CNTL and EXP 6-h 850-hPa wind forecasts (Fig. S3a) shows an enhancement of the southeasterly flow at low levels related to the convective available potential energy (CAPE) shift evident in Fig. S4a. The general flow at 850 hPa (CNTL analysis at 0000 UTC) is south-southwesterly. The 0–3-km helicity

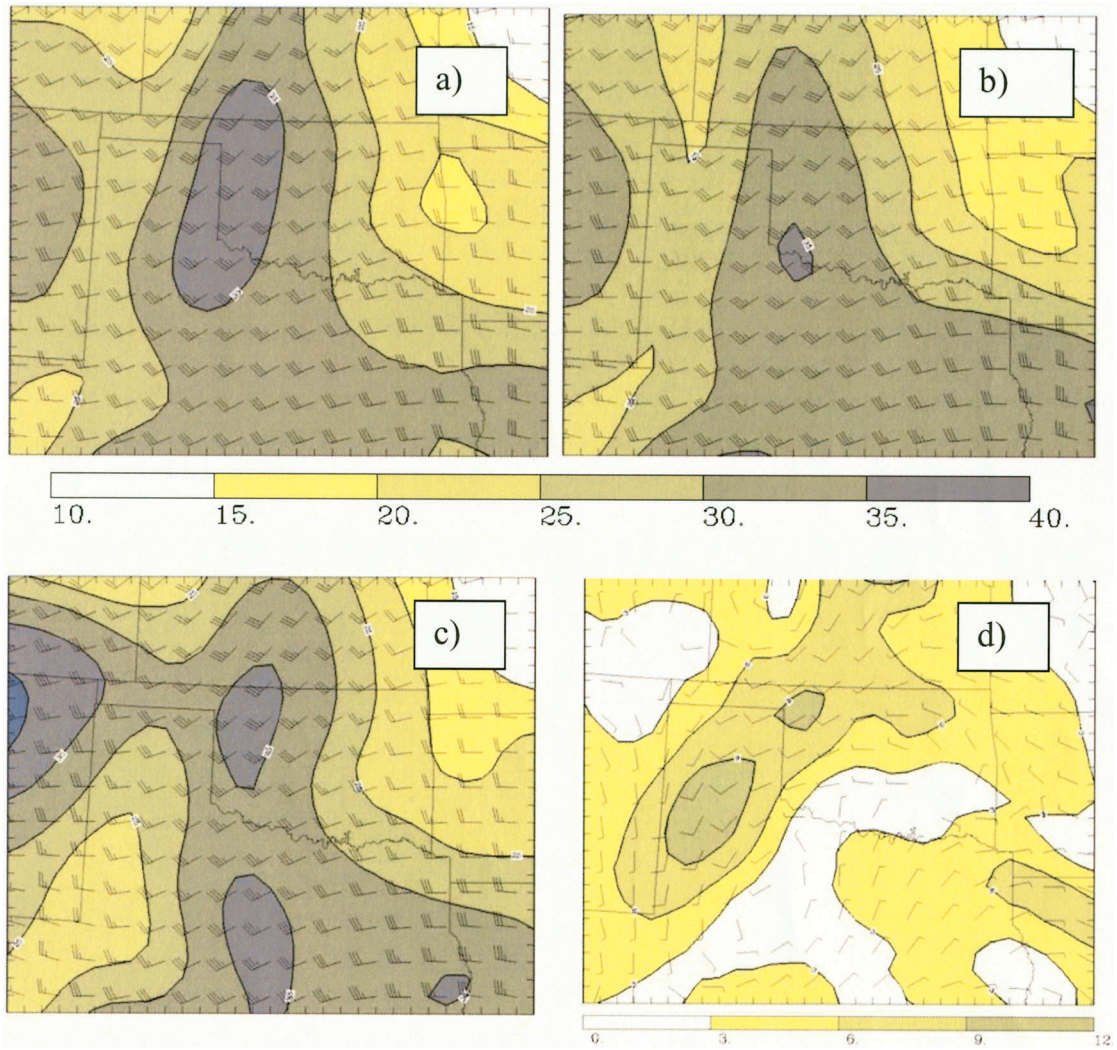

FIG. S2. The 6-h forecasts of 3000-hPa wind (m s^{-1}) for (a) CNTL and (b) EXP initialized at 1800 UTC 3 May 1999 and valid at 0000 UTC 4 May 1999; (c) verifying (CNTL) analysis at 0000 UTC 4 May 1999 and (d) CNTL – EXP difference between 6-h forecasts [(a) – (b)].

from the CNTL and EXP 3-h forecasts did not show significant difference (not shown). However, the area of maximum helicity (Fig. S4c) from both CNTL and EXP runs was predicted to be centered over the area in southwestern Oklahoma where tornadic storms first formed (Fig. S5).

In addition to wind fields, CAPE forecasts derived from the RUC (with averaging of potential temperature and water vapor mixing ratio in the lowest 40 hPa) were also examined from the CNTL and EXP experiments. Figure S4a shows the difference between CNTL and EXP 6-h forecast CAPE forecasts valid at 2100 UTC 3 May 1999. Observed CAPE values (Fig. S4b) were generally large (> 4000 J kg^{-1}) in the area where the first storms formed (see supercell track summary; Fig. S5, upper left inset) in southwestern Oklahoma. The increase in CAPE values (by 1000 J kg^{-1}) in this area in the CNTL run is primarily the result of an improved location of the axis of maximum CAPE (i.e., a reduction in the phase error). The CAPE forecast improvement from assimilation of profiler data was largely related to an enhanced southeasterly flow of moisture into the area of convective initiation and a westward shift of dryline position, both changes closer to the observations. The 3-h CAPE forecast error fields for 2100 UTC (not shown) were similar except that the EXP and CNTL errors were not as large as their 6-h forecast counterparts.

The 3- and 6-h surface dewpoint forecast error fields

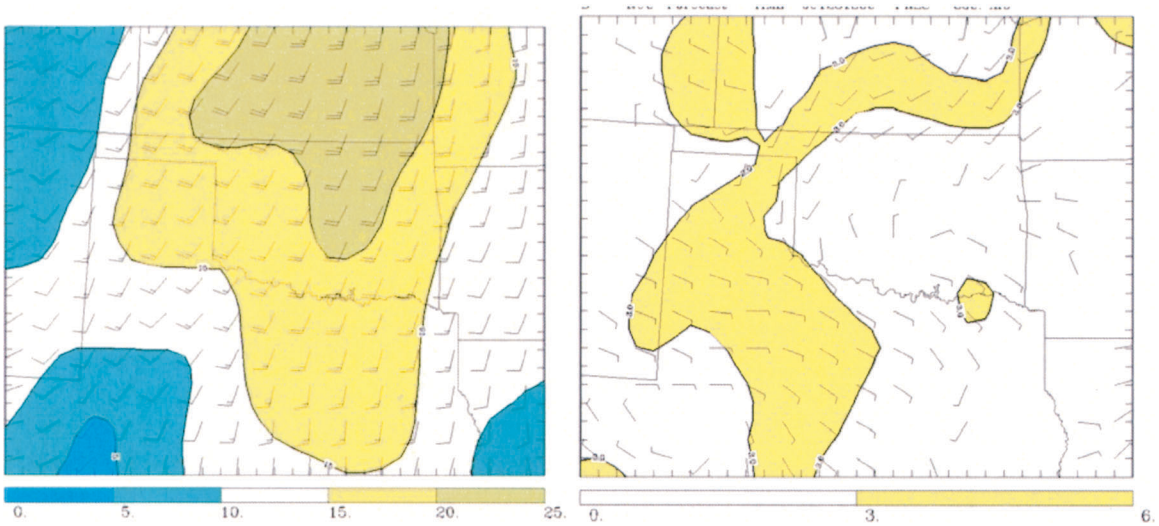

Fig. S3. (a) The 850-hPa (CNTL) wind analysis valid at 0000 UTC 4 May 1999, (b) CNTL – EXP difference between 6-h 850-hPa wind forecasts valid at 0000 UTC 4 May 1999.

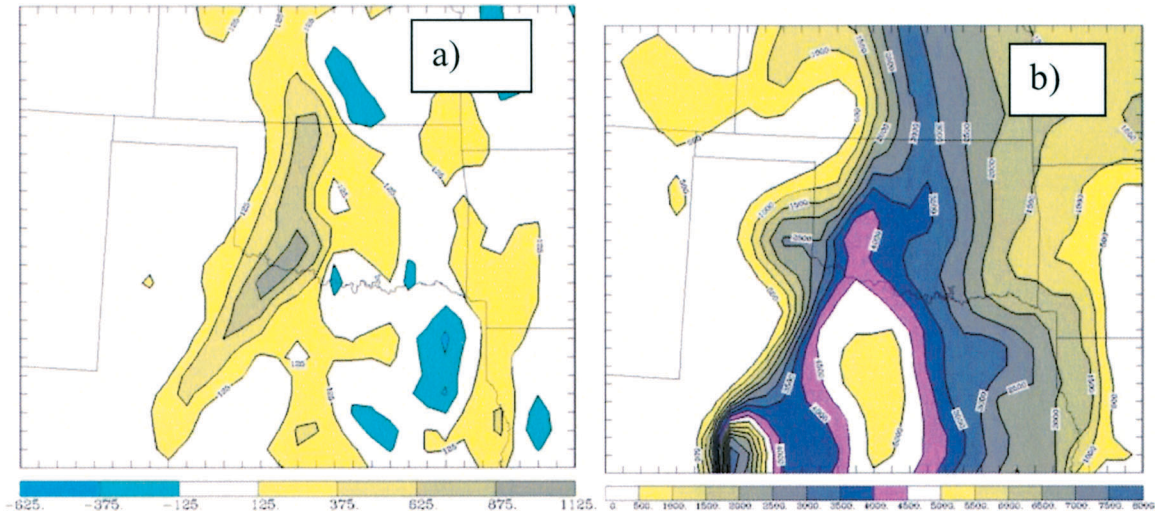

Fig. S4. (a) CNTL – EXP difference for 6-h CAPE forecast and (b) CAPE values from analysis (CNTL) valid at 2100 UTC 3 May 1999.

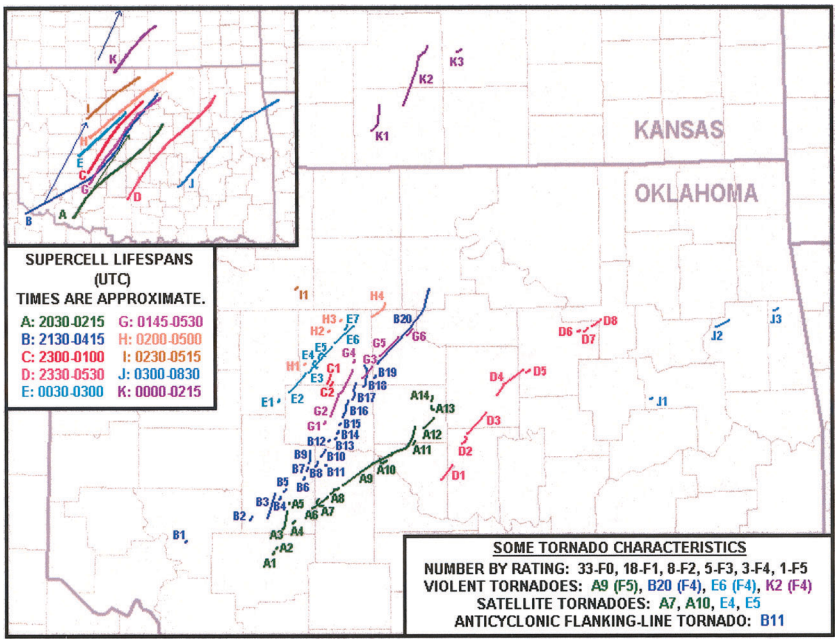

Fig. S5. (upper left) Tornado and supercell track summary for 3 May 1999 storms. (Provided by NWS Forecast Office, Norman, OK.)

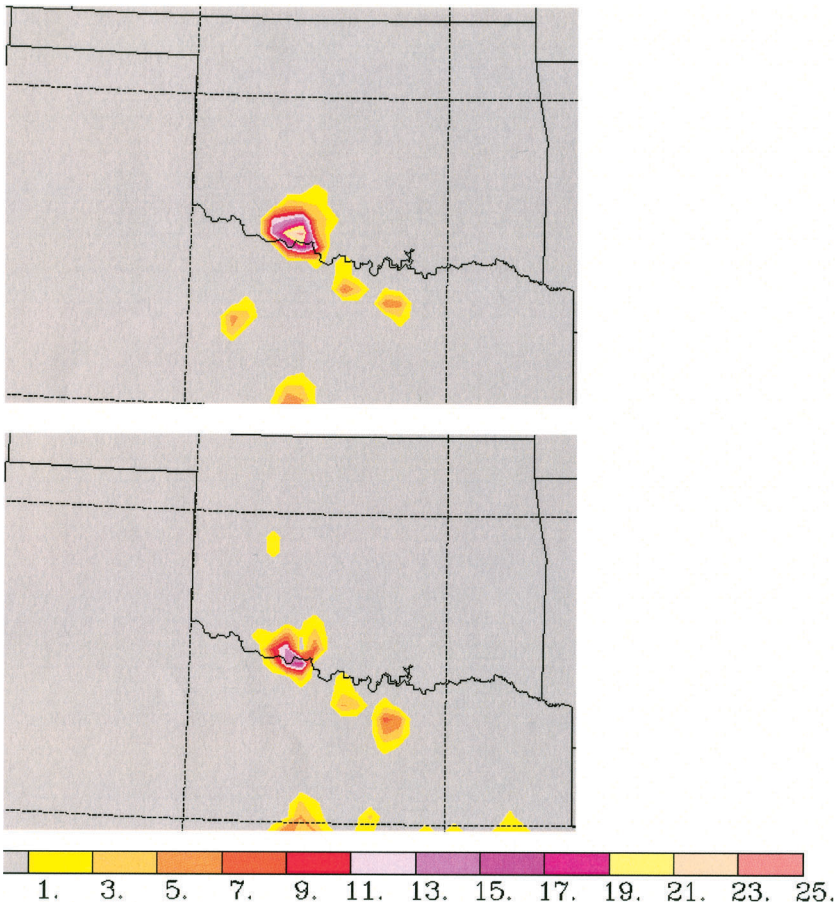

Fig. S6. The 6-h predictions of 3-h-accumulated precipitation for the period 2100 UTC 3 May–0000 UTC 4 May 1999 from (top) CNTL and (bottom) EXP forecasts initialized at 1800 UTC. Contour interval is 2 mm (0.08 in.) starting at 1 mm.

(not shown) were consistent with the CAPE error fields, and indicated that dewpoints in the area of the underforecast CAPE in the EXP were as much as 3°C lower than in the CNTL run within the area of large EXP CAPE error. A comparison of 850-hPa wind forecasts from the two experiments (Fig. S3) indicated that assimilation of profiler data caused a slight backing of flow in north and central Texas. The modified 850-hPa flow in the CNTL run with profiler data appeared to cause the extra moisture transport and a westward shift in the dryline position. The resulting phase shift of the maximum CAPE in the control run with profiler data brought it closer to the region where the storms initiated.

Finally, the supercell track and tornado track summary (Fig. S5) may be compared with the 6-h forecasts of 3-h-accumulated precipitation valid at 0000 UTC 4 May from the CNTL and EXP runs (Fig. S6). The initial position of the first supercell (supercell A, see upper left inset in Fig. S5) near the Oklahoma–Texas border is fairly well forecast by both the CNTL and EXP experiments. The intensity of the convective precipitation is somewhat stronger in the CNTL experiment, evidently a result of the higher CAPE associated with the shift in dryline position and backing of low-level flow shown in Figs. S4 and S3.

Severe snow and ice storm of 8–9 February 2001. The 20-km RUC was also used to examine the impact of profiler data for a winter storm that brought a variety of weather to the plains and Midwest on 8–9 February 2001.

This event fell within the retrospective test period used for the data-denial experiments described in Benjamin et al. (2004b, "Data-denial experiments using the RUC model" section). Although this storm system was fairly typical of winter storms in this area, some locations experienced an impressive storm, with portions of Kansas receiving 25–40 cm (10–16 in.) total snowfall (24-h snowfall amounts shown in Fig. S7) and with heavy sleet and freezing rain from south-central into eastern Kansas. Short-range (3 h) forecasts from RUC CNTL and EXP experimental profiler data extracted for a 3-h period of intensifying precipitation (0300–0600 UTC 9 February 2001) from the 13-day experiment described in Benjamin et al. (2004b, "Case studies" section) were examined to determine how the profiler data affected the precipitation forecasts. For comparison with 3-h precipitation forecasts, 3-h Meteorological Aviation Report (METAR) precipitation observations and radar reflectivity were examined. Several profiler stations in Oklahoma and southern Kansas (see Fig. 1 in Benjamin et al. 2004b) were well located to capture the flow above and below a frontal zone located in this region, with isentropic lift resulting from overrunning of the frontal zone being a key mechanism for precipitation in the cold sector in this case. By 0000 UTC 9 February, a band of heavier snow was located across west-central Kansas, while sleet and freezing rain intensified over south-central Kansas. This intensification continued over the next 6 h.

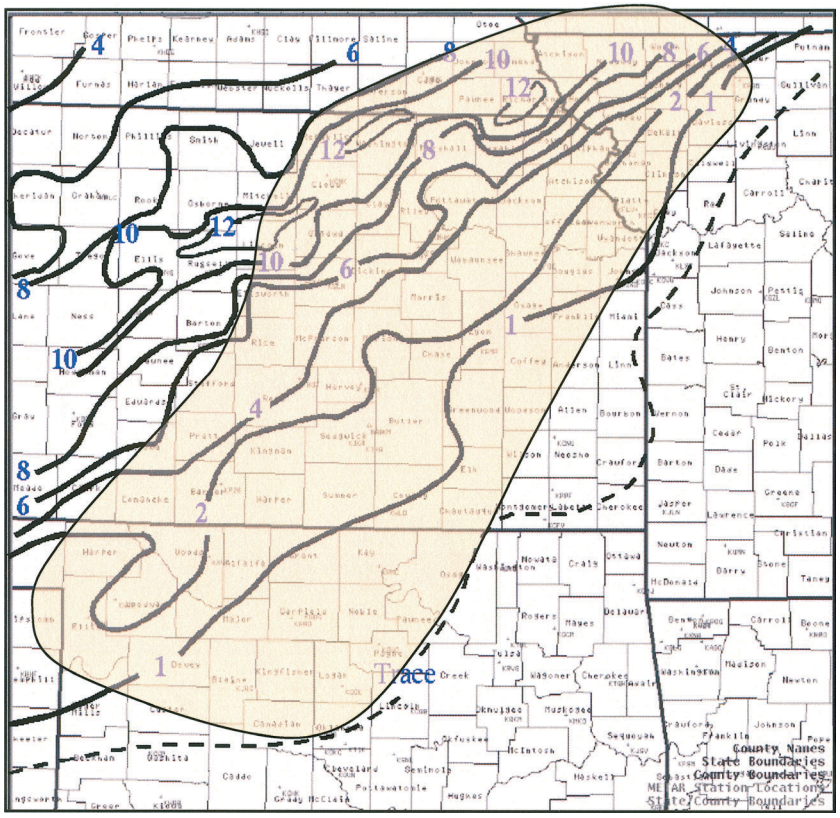

FIG. S7. Snowfall (in.) for 24-h period ending at 1200 UTC 9 Feb 2001. Shading indicates areas of sleet or freezing rain accumulation.

A synoptic overview of the storm is given in Fig. S8. A full-latitude trough moving out of the Rockies placed the Kansas–Oklahoma area in a region of upper-level forcing ahead of the approaching trough. Strong southerly flow was found at the surface south of a sharp, slow-moving cold front located from Kansas City, Kansas, to just west of Oklahoma City, Oklahoma, at 0000 UTC, stretching back to a surface low in western Texas. Several profiler stations in Oklahoma and southern Kansas (Fig. 1 of Benjamin et al. 2004b) were located in a good position to capture the southerly flow advecting moisture northward over the front, with overrunning of the frontal zone being a key mechanism for precipitation in the cold sector in this case.

Several waves of precipitation occurred during the daytime hours on 8 February, but snowfall was limited to northern and western portions of Kansas (and Iowa and Nebraska), and the Oklahoma Panhandle. Most of the precipitation over central Kansas fell as freezing rain or sleet before 0000 UTC 9 February, while rain fell over eastern Kansas and southward across most of Oklahoma (except for the panhandle). By 0000 UTC 9 February, the areas of heavy snow were moving east, with a band of heavier snow across west-central Kansas, while sleet and freezing rain intensified over south-central Kansas. Radar reflectivity at 0600 UTC indicated a band of heavier precipitation extending from west-central Oklahoma to northeastern Kansas (including widespread reflectivity > 40 dBZ), with many 3-h METAR precipitation reports from 7 to 14 mm (0.28–0.56 in.) in this zone (Fig. S9).

The RUC forecasts (Fig. S10) for this 3-h period show that the CNTL precipitation was more intense (7–12 mm) throughout this frontal zone than the EXP experiment (4–9 mm). The CNTL forecast more

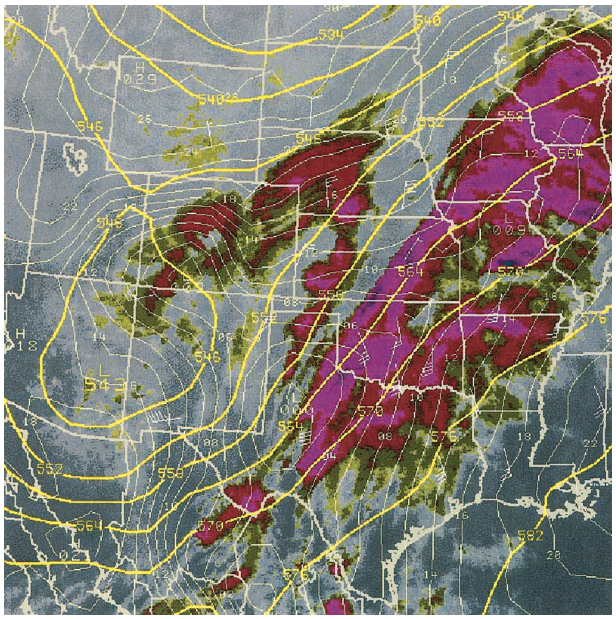

Fig. S8. RUC 500-hPa height (dam) and sea level pressure (hPa) analyses and 500-m AGL profiler observations with infrared satellite image for 0000 UTC 9 Feb 2001. (From AWIPS.)

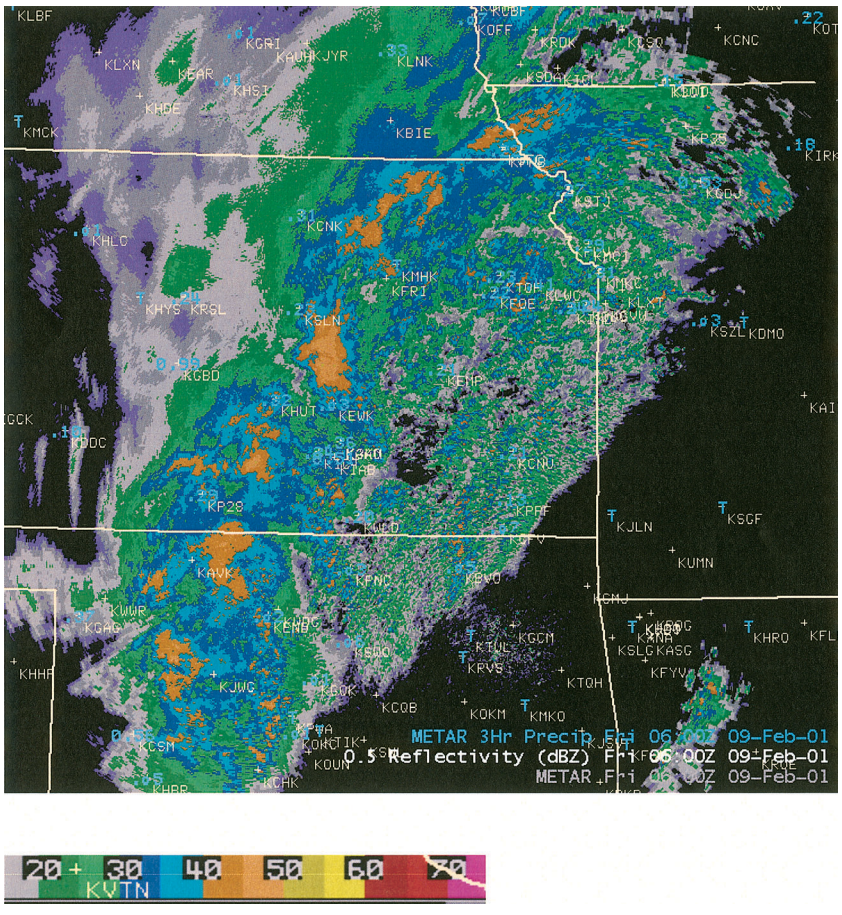

Fig. S9. Radar reflectivity (0.5° elevation scan, dBZ color scale shown at bottom) valid at 0600 UTC 9 Feb 2001 and METAR precipitation (in.) totals for 3-h period ending 0600 UTC. (From AWIPS.)

closely matched observed 3-h precipitation and radar reflectivity, especially from western Oklahoma into south-central Kansas. The difference in precipitation between the two experiments was apparently related to the lower-tropospheric frontal position, more accurately depicted in the CNTL experiment with profiler data.

A comparison of the analyzed 900-hPa wind fields at 0300 UTC from the CNTL and EXP experiments (Fig. S11) helps to explain why the CNTL experiment predicted more precipitation in southern Kansas than the EXP run. The strength of the southerly flow at this level south of the strong cold front, evident as a wind shift, was approximately the same in both experiments. However, the location and curvature of the front is different. The front in the CNTL experiment is rotated slightly to more of an east–west orientation, giving a sharper ascent to the southerly flow overrunning it. This difference in orientation extends from southwestern Oklahoma into eastern Kansas, including the vertical cross sections to be shown in Figs. S12–S14. Although these differences are not exceptional, they are important enough to result in heavier forecast precipitation to the north with the CNTL experiment, showing better overall agreement with the observations.

Vertical cross sections from each experiment oriented north–south across the front (Fig. S12), from the 3-h forecast valid at 0600 UTC, show the relationship of the along-flow wind component of 30–35 m s^{-1} south of the front, and sloping upward above the front over Kansas. Close inspection reveals the slight shift in frontal position noted in the 900-hPa wind fields in Fig. S12, with a position further north and a sharper ascent of the southerly flow > 30 m s^{-1} north of the surface front in the CNTL experiment. The approximate position of the axis of heavy precipitation in south-central Kansas north of the surface front is denoted by an arrow in Fig. S12. The flow over the frontal zone ascends more steeply in the CNTL experi-

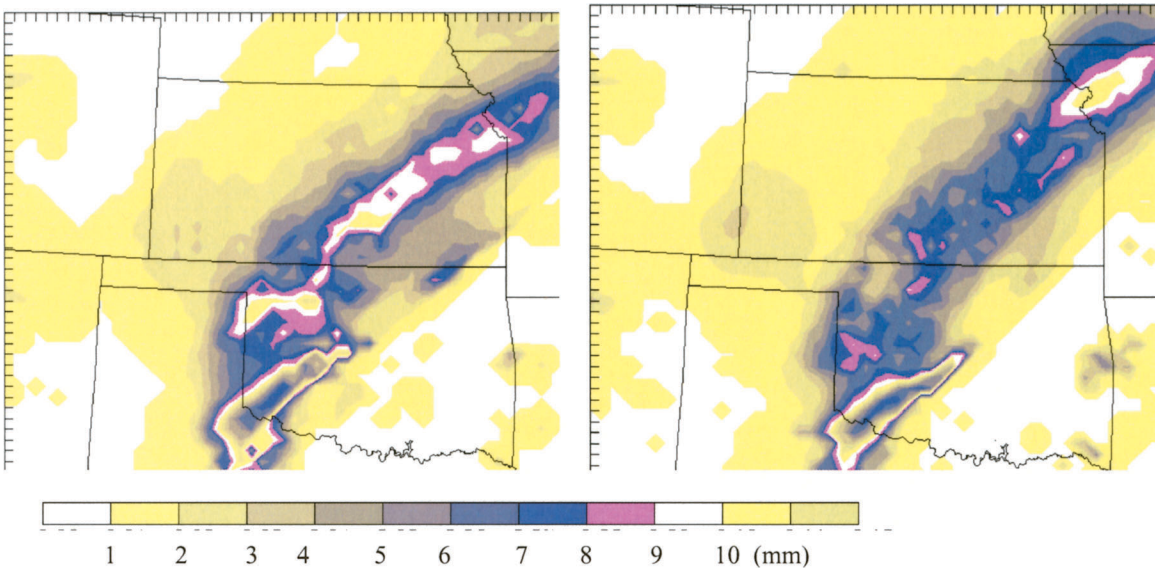

Fig. S10. Forecast 3-h precipitation (mm) for 0300–0600 UTC 9 Feb 2001 (left) CNTL and (right) EXP experiments; forecasts are initialized at 0300 UTC.

ment, a consequence of the more east–west orientation of the front noted in Fig. S11. The steeper ascent in the CNTL experiment is evident in a stronger and deeper plume of vertical velocity (Fig. S13) associated with the heavier precipitation over southern Kansas (about 200 km north of the surface front). The upward vertical motion (diagnosed in the RUC model as described by Benjamin et al. 2004a) producing this precipitation is much broader and deeper in the CNTL experiment (note extensive area with greater than 30 μb s^{-1}). Finally, a comparison (Fig. S14) between the CNTL and EXP experiments is presented for vertical cross sections of combined hydrometeor mixing ratio from rain, snow, and graupel, which are all forecast explicitly in the RUC model microphysics. The CNTL experiment shows an area of 0.12–0.14 g kg^{-1} in the cold air north of the surface front associated with the heavier precipitation depicted in Fig. S10. The precipitation condensate mixing ratio in the EXP experiment is about 20% less. These differences in the three-dimensional flow from assimilating profiler observations appear to be responsible for the improved precipitation forecast in the CNTL experiment. This example of profiler impact in a difficult forecast situation is typical of those cited by NWS operational forecasters in the sidebar in the main article.

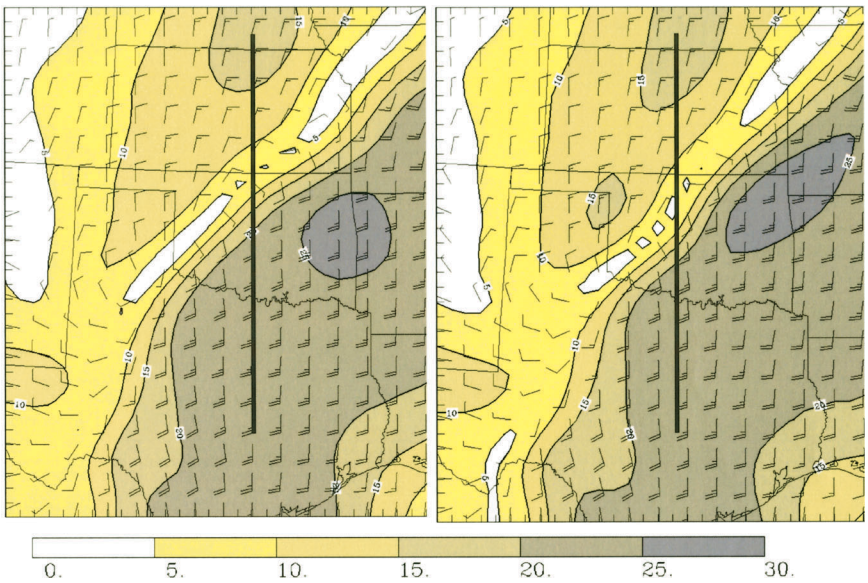

Fig. S11. The 900-hPa wind analysis for 0300 UTC 9 Feb 2001 from (left) CNTL and (right) EXP experiments. Contour interval is 5 m s^{-1} with darker shading for higher wind speed and a full barb is 10 m s^{-1}. Solid line is location of cross-sectional fields displayed in Figs. S12–S14.

8 May 2003 Oklahoma tornado case. Isolated supercell thunderstorms moved through central and north-

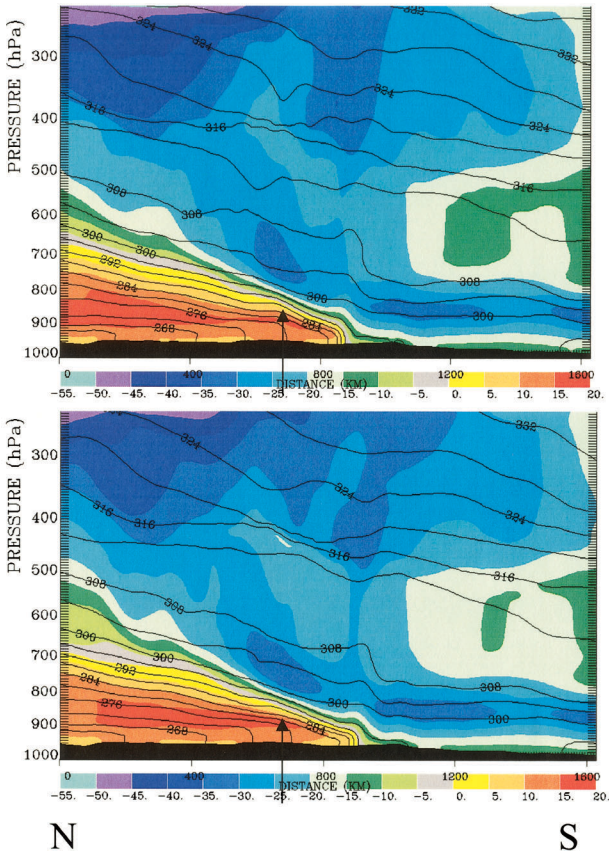

Fig. S12. Vertical cross section of potential temperature (solid, plotted every 4 K) and along-section wind component (color shading, m s^{-1}, positive: northerly flow, negative: southerly flow) for north–south line shown in Fig. S11 (left end over southern Nebraska, right end over southern Texas). The 3-h forecasts are valid at 0600 UTC 9 Feb 2001 from (top) CNTL and (bottom) EXP experiment. Position of heavy observed precipitation in southern Kansas at 0600 UTC is noted by the position of the arrow.

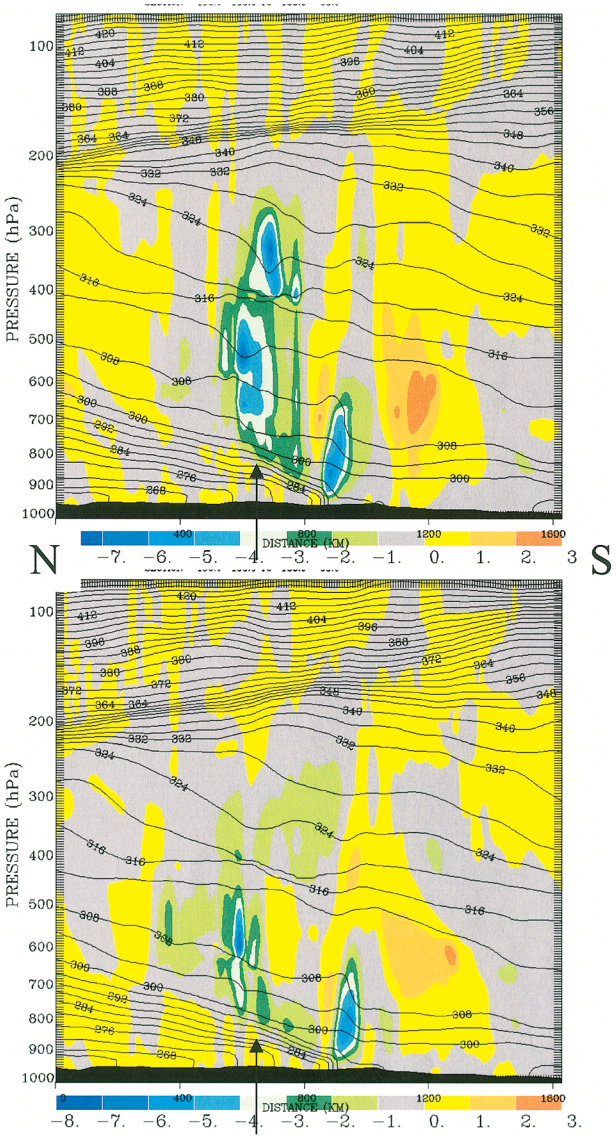

Fig. S13. Same as Fig. S12, but showing vertical velocity, × 10 μb s^{-1}, for example, –5 = –50 μb s^{-1} (upward motion).

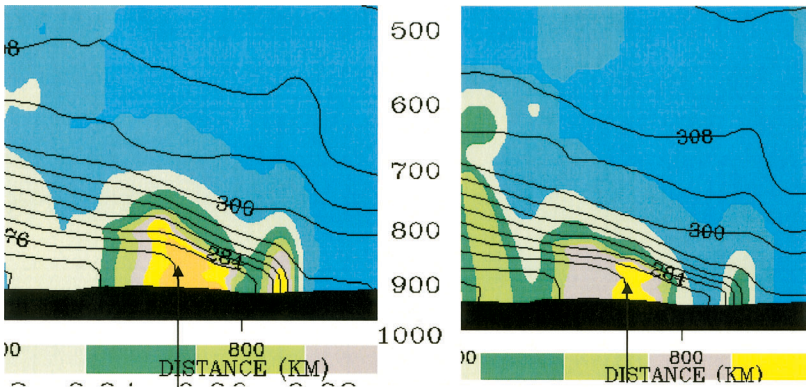

Fig. S14. Vertical cross section of combined precipitation hydrometeor (snow, rain, graupel) mixing ratio (contour interval 0.02 g kg^{-1}) zoomed over center of the vertical cross section shown in Figs. S12 and S13. For (left) CNTL and (right) EXP experiments.

eastern Oklahoma in the late afternoon on 8 May 2003, including a destructive tornado that passed just south of Oklahoma City, resulting in more damage than any Oklahoma tornado since 3 May 1999. Again, RUC parallel cycles were run for a 24-h period with and without wind profiler data, similar to the 3 May case. Full hourly VAD data were assimilated in both experiments for this case. Difference (CNTL – EXP) fields (Fig. S15) showed that assimilation of hourly profiler data resulted in

a band of increased CAPE (by over 1000 J kg^{-1}) and helicity (by over 75 m^{-2} s^{-2}) in the area of storm initiation in central Oklahoma. Thus, the profiler data again enhanced indicators for severe weather in the area where such storms formed. A similar pattern (not shown) was found for another set of RUC profiler impact experiments on 4 May 2003, the date of a major multistate tornado outbreak.

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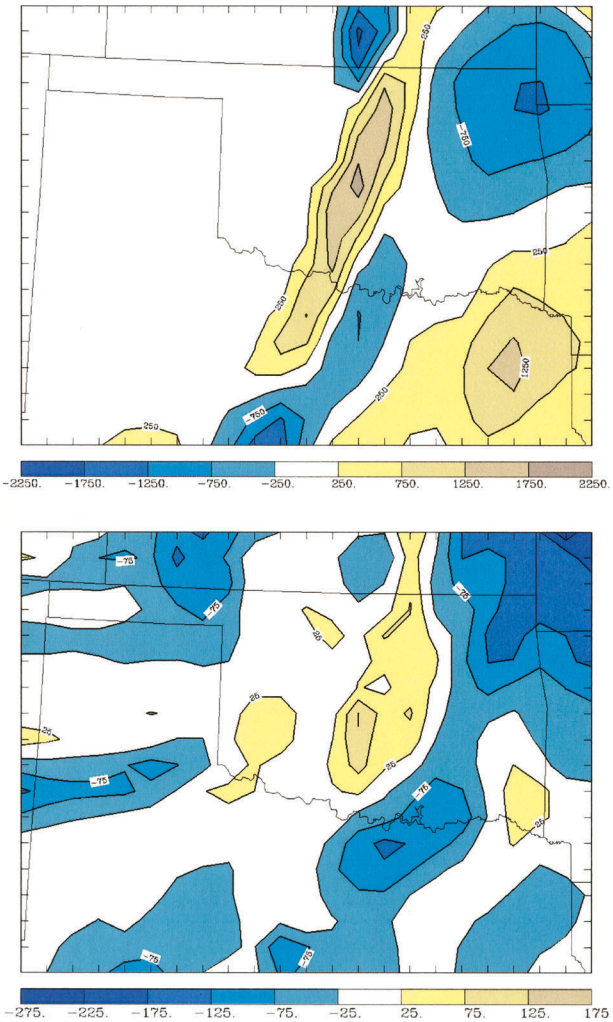

FIG. S15. CAPE and helicity differences from inclusion of wind profiler data for 8 May 2003 case. CNTL – EXP difference for 3-h forecasts initialized at 2100 UTC 8 May 2003: (top) CAPE (J kg^{-1}) and (bottom) helicity (m^{-2} s^{-2}).