

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

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Severe-weather cases and a winter test period show that the NOAA wind profiler network in the central United States can improve short-range (3-12 h) forecasts.

The National Oceanic and Atmospheric Administration (NOAA) Forecast Systems Laboratory (FSL) has operated a network of 404-MHz tropospheric wind profilers since 1992 (online at www.profiler.noaa.gov/jsp/aboutNpnProfilers.jsp; van de Kamp 1993; Weber et al. 1990). Most of these platforms operate over the central United States, with the exception of a few profilers in Alaska and elsewhere (Fig. 1). The role of wind profiler data in forecaster decision making is typified in the following two accounts regarding significant weather events:

The NOAA Storm Prediction Center (SPC) in Norman, Oklahoma, located in the middle of the

NOAA Profiler Network (NPN), has a high interest in monitoring evolving low-level and deep vertical wind shear that is conducive to severe thunderstorms. SPC forecasters frequently use the profiler data for issuing both convective outlooks as well as watches, with the data often critical for determining the level of severity expected. A prime example occurred with the 3 May 1999 Oklahoma–Kansas

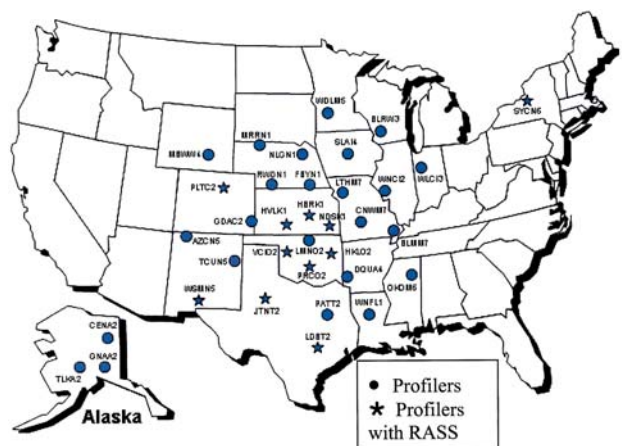


FIG. 1. NPN site locations as of Aug 2002. The LDBT2 site in southeastern Texas was not operational for the cases in May 1999 and February 2001 discussed in this paper. RASS (Martner et al. 1993) observations, including lower-tropospheric profiles of virtual temperature, were not used in this study.

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tornado outbreak (Edwards et al. 2002). The forecasters on 3 May observed considerably stronger winds at the Tucumcari, New Mexico, profiler site than were forecasted by the models. Extrapolation of these winds to the afternoon threat area gave the forecasters confidence that tornadic storms with organized supercells would be the main mode of severe weather risk. Based on the likelihood of stronger vertical wind shear, the risk would be greater than that previously suggested by numerical models. Armed with the profiler observations, SPC forecasters first increased the threat in the current-day convective outlook from slight to moderate risk, and then to high risk by early afternoon. Such changes are regarded seriously by response groups such as emergency managers, and the elevated risk levels from SPC resulted in a more intense level of civic and government response (Morris et al. 2002) to this potential tornado threat. In fact, NOAA's Service Assessment Report for the 3 May 1999 tornadoes (NWS 1999) noted the critical role that the profiler data had in improving the forecasts (convective outlooks and watches) from the SPC, and recommended that the existing profiler network be supported as a reliable operational data source (S. Weiss, 2002, personal communication).

The National Weather Service Forecast Office in Sioux Falls, South Dakota, described a wintertime application of profiler data: "Tonight the profiler network was useful for determining the end time of snowfall which coincided with the mid-level trough passage. We had a main trough passage produce up to 6 inches (of snow) and a secondary trough produce areas of IFR (Instrument Flight Rules) conditions but no accumulating snow. The profilers are used almost daily by the forecasters in this office" (P. Browning, 2002, personal communication).

The two previous paragraphs describe examples of wind profiler data use by operational forecasters. In this article, we discuss the use of profiler data in both numerical weather prediction (NWP) and subjective weather forecasting in three aspects. First, a series of experiments was performed using the Rapid Update Cycle (RUC) model and hourly assimilation system (Benjamin et al. 2004a,b) for a 13-day period in February 2001 comprised of a control experiment with all data and a series of denial experiments in which different sets of observations were withheld. Data denial experiments were conducted denying profiler and aircraft data. For the control and denial experiments withholding profiler, aircraft, and all data, average verification statistics for RUC wind forecasts

against radiosonde observations were compiled for the test period. The day-to-day differences in these errors and in profiler impact were also calculated. In addition to the average root-mean-square (rms) wind vector errors, statistics were compiled for the 5% largest errors at individual radiosonde locations to focus on the impact of data denial for *peak* error events. Significance tests were performed for the difference between experiments with and without profiler data.

Second, three case studies illustrating the positive impact of profiler data on RUC forecasts are discussed briefly in section 3 and in more detail in Benjamin et al. (2004c). For each case study, reruns of the RUC with and without profiler data are contrasted. The first case is derived from RUC forecasts of the 3 May 1999 Oklahoma tornado outbreak. The second case study is taken from the 13-day test period for a significant snow and ice storm that affected parts of Oklahoma, Kansas, Nebraska, and Missouri on 9 February 2001. The third case is for a tornadic event in central Oklahoma on 8 May 2003 that closely followed the track of the most destructive tornado on 3 May 1999.

DATA-DENIAL EXPERIMENTS USING THE RUC MODEL. Observation system experiments (OSEs) have been found to be very useful in determining the impact of particular observation types on operational NWP systems (e.g., Graham et al. 2000; Bouttier 2001; Zapotocny et al. 2002). Four multiday RUC experiments (or OSEs) with an assimilation of different observational mixes were performed for the 4–17 February 2001 period. This 13-day period was characterized by strong weather changes across the United States and has been used for retrospective testing at the National Centers for Environmental Prediction (NCEP) for modifications to the Eta and RUC model systems. During this period, at least three active weather disturbances traversed the profiler network, including the severe ice and snow that affected parts of the U.S. central plains on 8–9 February 2001. This case is discussed in more detail in section titled "Case studies."

Experimental design. The version of the RUC used in these experiments is the 20-km version run operationally at NCEP as of June 2003, including 50 hybrid isentropic-sigma vertical levels and advanced versions of modeled physical parameterizations. An hourly intermittent assimilation cycle allows full use of hourly profiler (and other high frequency) observational datasets. The analysis method is the three-dimensional variational data assimilation (3DVAR) technique (Devenyi and Benjamin 2003; Benjamin

et al. 2003) implemented in the operational RUC in May 2003. Additional information about the 20-km RUC is provided by Benjamin et al. (2002, 2004a,b). The experiment period began at 0000 UTC 4 February 2001 with the background provided from a 1-h RUC forecast initialized at 2300 UTC 3 February. Lateral boundary conditions were specified from the NCEP Eta Model initialized every 6 h and available with a 3-h-output frequency. The high-frequency observations used include those from wind profilers, commercial aircraft, Doppler radar velocity azimuth display (VAD) wind profiles, and surface stations. No Radio Acoustic Sounding System (RASS; e.g., Martner et al. 1993) temperature profiles, also available at many NPN sites (Fig. 1), were used in any of these experiments because they are not yet available in the operational data stream at NCEP.

Verification was performed using conventional 12-hourly radiosonde data over the three domains depicted in Fig. 2. The entire RUC domain contains ~90 radiosonde sites. The solid box outlining the profiler subdomain includes most of the Midwest profilers depicted in Fig. 1 and contains 22 radiosonde sites.

The dashed box area in Fig. 2, referred to as the “downstream” subdomain, contains 26 radiosonde sites. It was chosen to depict an area that might be affected due to downstream propagation of information originating from the profiler data. For each RUC experiment, residuals (forecast minus observed) were computed at all radiosonde locations located within each respective verification domain. Next, the rms vector difference between forecasts and observations was computed for each 12-h verification time. This difference is sometimes referred to below as “forecast error,” but in fact also contains a contribution from the observation error (including representativeness “error” from the inability of a grid to resolve subgrid variations sometimes evident in observations). These scores were then averaged linearly over the 13-day test period. In many of the figures that follow, the statistic displayed is a *difference* between these average scores: the control (RUC run with all data, henceforth referred to as CNTL) minus the experiment (no profiler, no aircraft, or no observations at all; henceforth referred to as EXP). In addition, the Student’s *t* test was performed on the differences between the

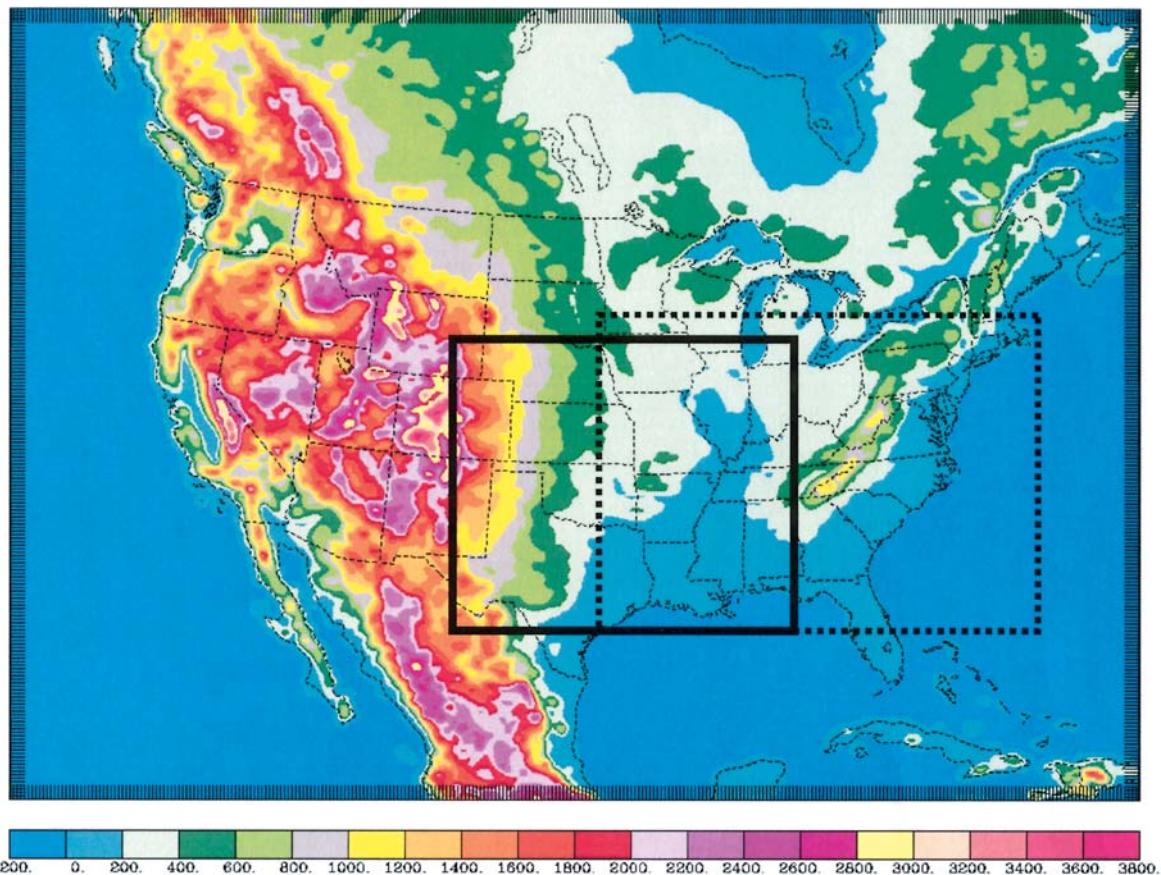


FIG. 2. The full 20-km RUC domain with terrain elevation (m), with outlines of profiler (solid line) and downstream (dotted line) verification subdomains.

CNTL and EXP standard deviations of the residuals to determine statistical significance of the results. Finally, the mean differences were normalized by three different methods to clarify their contribution to forecast error, as described in the “Normalized results for profiler and aircraft data denial experiments” section. Quality-control flags from RUC analyses in the CNTL cycle were applied to verifying radiosonde data.

Control experiment. We first consider rms wind differences from radiosonde observations for RUC forecasts from the control experiment with all observational data included. Figure 3 shows the rms wind vector difference between 3- and 6-h RUC forecasts and radiosonde observations by mandatory level averaged over the 13-day period. Results for both the CNTL and EXP (discussed in next section) experiments are shown. These statistics are only for the 22 radiosondes within the profiler subdomain (Fig. 2). Three-hour forecasts show an improvement of about $0.2\text{--}0.7\text{ m s}^{-1}$ over 6-h forecasts valid at the same time, corresponding to the benefit of assimilating more recent observations (Benjamin et al. 2004a). The typical peak of rms wind vector error is evident at near-tropopause jet levels, where wind speeds are highest. The fit of the RUC analysis to rawinsondes is also shown in Fig. 3, corresponding approximately to expected observation error and, therefore, equivalent to a “perfect” forecast. This statistic will be used in one of the score normalizations described in the “Normalized results for profiler and aircraft data denial experiments” section.

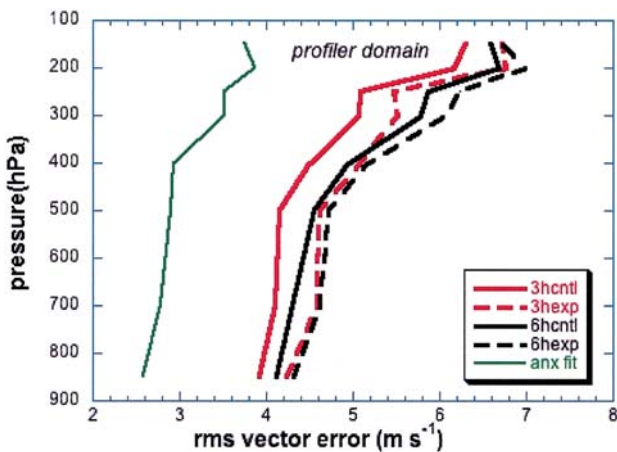


FIG. 3. Rms vector difference between RUC 3- and 6-h wind forecasts and radiosonde observations over profiler subdomain for 4–17 Feb 2001 period for CNTL and EXP experiments. Also shown is rms vector difference between *analysis* from CNTL experiment and radiosonde observations (leftmost solid line).

Profiler data-denial results. In this section, we discuss results from the difference between the control experiment and an experiment in which all wind profiler data were withheld. Figure 4 shows the aver-

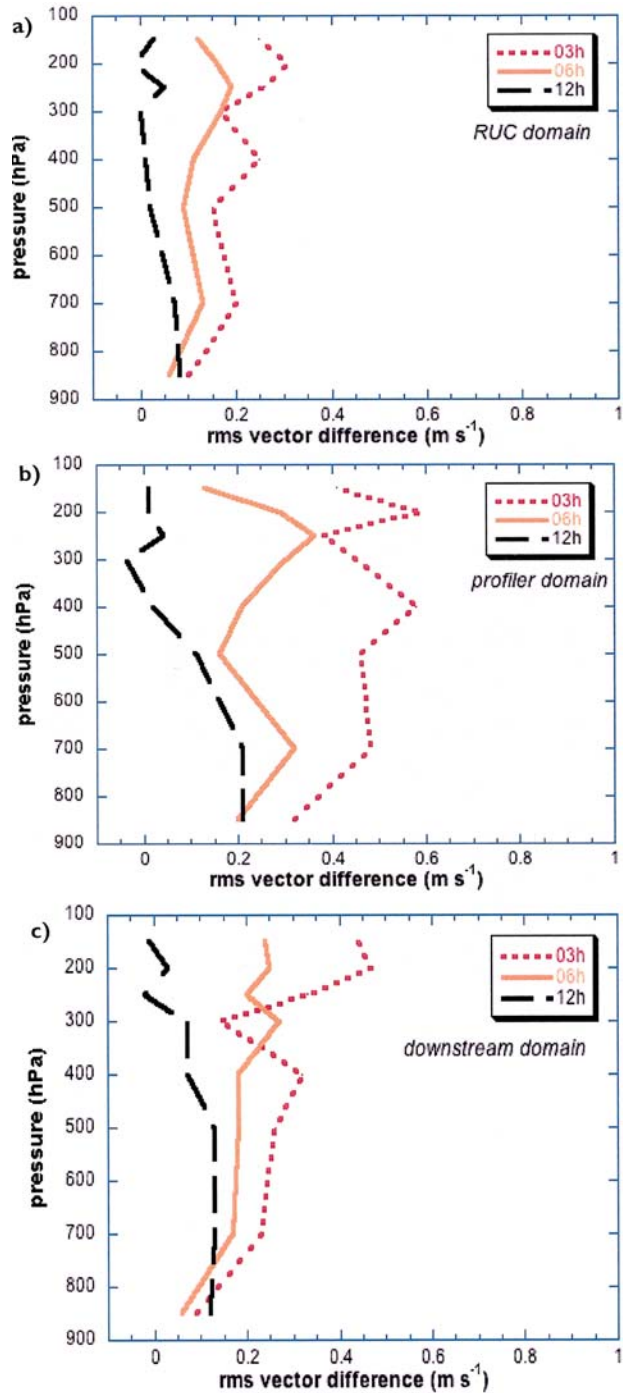


FIG. 4. Effects of profiler data denial (CNTL) on average rms vector errors for 4–17 Feb 2001 over (a) the full RUC domain, (b) the profiler subdomain, and (c) the downstream subdomain. Positive difference indicates that CNTL experiment with profiler data had lower rms vector error than the EXP experiment.

age 3-, 6-, and 12-h wind forecast impact (EXP – CNTL) results for the 4–17 February test period (rms vector score from each radiosonde verification time averaged over each period) for the three different verification domains. This score, reflecting the impact of wind profiler data, is positive for all levels and all domains. As expected, the greatest impact at 3 h is evident over the profiler subdomain (Fig. 4b), from 0.3 to 0.6 m s⁻¹ at all mandatory levels (850–150 hPa), with an average value of 0.46 m s⁻¹ (Table 1). By contrast, the 3-h vertically averaged impact is 0.28 m s⁻¹ over the downstream domain and 0.21 m s⁻¹ over the full RUC domain. In general, the impact decreases with increased forecast projection. The 12-h-forecast impact is quite small over the three verification domains (< 0.1 m s⁻¹). [Plots of wind forecast error from different RUC forecasts for a particular case are shown in Benjamin et al. (2004b, Fig. 11), illustrating that differences in rms vector error of 0.5 m s⁻¹ are easily apparent in visual inspection.]

A stratification of profiler impact results by the time of day over the profiler subdomain (Fig. 5) revealed that the profiler impact is stronger at 1200 than at 0000 UTC at most vertical levels. This is likely a result of a lower volume of aircraft data in the 0600–0900 UTC nighttime period than the 1800–2100 UTC daytime period (3-h periods preceding the initial time for 3-h forecasts valid at 1200 or 0000 UTC). It also shows that the profiler data can contribute strongly to improving wind forecast at near-tropopause jet levels and that the accuracy of 3-h jet-level wind forecasts valid at 1200 UTC over the United States is strengthened by wind profiler data.

The statistical significance of mean absolute (not rms) CNTL – EXP differences for 3–12-h forecasts by mandatory levels is examined with the Student’s *t* test in Table 2. The difference between 3-h forecasts with and without profiler data is statistically significant at the 99% confidence level for the 700–400-hPa levels. The difference for 6-h forecasts was significant at the 80% level or higher at three levels in the profiler and

downstream domains and for five of eight mandatory levels over the full RUC domain.

In considering multiday experiments to test forecast impact from some change, a problem with any long-period average statistic is that it may mask the potentially more significant impact associated with larger errors in active weather events. In Fig. 6, a time series is shown of the 3-h RUC and persistence forecast 500-hPa wind vector errors from the control experiment at each 12-h verification time. The 3-h persistence forecast is determined simply as the RUC CNTL analysis from 3 h before the verification time.

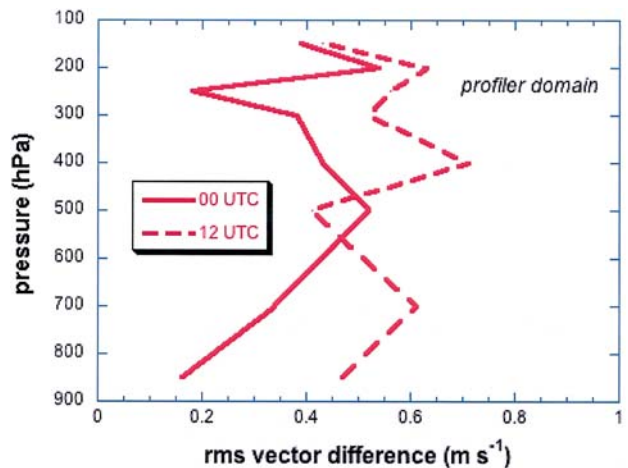


FIG. 5. Diurnal variability of profiler impact (CNTL) on rms 3-h wind forecast vector error in profiler subdomain. Same as Fig. 4b, but with separate results for 0000 and 1200 UTC.

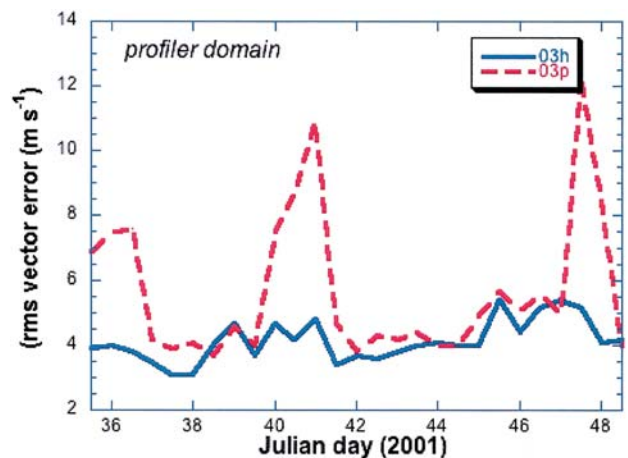


FIG. 6. Time series of 500-hPa wind rms vector differences between forecasts and radiosonde observations over profiler subdomain for 5–17 Feb (Julian date 36–48) 2001 period. Values are shown for 3-h RUC forecasts from control experiment (03h) and 3-h persistence forecasts (03p, using RUC analyses valid at 0900 and 2100 UTC), also from the control experiment.

TABLE 1. Mean reduction in rms wind vector error (m s⁻¹) from EXP to CNTL experiments over Feb 2001 test period, averaged over eight mandatory pressure levels.

Domain	3 h	6 h	12 h
	Mean diff	Mean diff	Mean diff
Profiler	0.46	0.25	0.07
Downstream	0.28	0.19	0.06
Full RUC	0.21	0.13	0.03

TABLE 2. Significance scores for the difference between CNTL and EXP mean wind vector errors over three domains for the Feb 2001 test period, calculated over all radiosonde observations (averaging different than shown in Fig. 5, leading to slightly different results). PRS is pressure level, DIFF is (CNTL – EXP) average difference, SIGLV is the significance level exceeded by the Student’s *t*-test score (only values of at least 80% are shown), and NUM is sample size.

National domain							
PRS	3 h		6 h		12 h		NUM
	DIFF	SIGLV	DIFF	SIGLV	DIFF	SIGLV	
850	0.08	—	0.06	—	0.06	—	2047
700	0.17	95	0.11	85	0.05	—	2226
500	0.15	90	0.09	80	0.04	—	2226
400	0.20	95	0.10	—	0.06	—	2192
300	0.14	80	0.15	80	0.01	—	2115
250	0.24	90	0.18	85	0.04	—	2011
200	0.23	90	0.15	80	0.02	—	1927
150	0.21	85	0.12	—	0.01	—	1862
Profiler domain							
PRS	3 h		6 h		12 h		NUM
	DIFF	SIGLV	DIFF	SIGLV	DIFF	SIGLV	
850	0.31	95	0.18	80	0.13	—	515
700	0.38	99	0.23	85	0.14	—	578
500	0.42	99	0.16	—	0.08	—	580
400	0.49	99	0.15	—	0.05	—	575
300	0.35	90	0.23	—	–0.05	—	547
250	0.29	85	0.33	80	0.03	—	513
200	0.45	90	0.24	—	0.04	—	489
150	0.31	80	0.09	—	–0.04	—	450
Downstream domain							
PRS	3 h		6 h		12 h		NUM
	DIFF	SIGLV	DIFF	SIGLV	DIFF	SIGLV	
850	0.09	—	0.07	—	0.10	—	826
700	0.18	90	0.12	80	0.09	—	823
500	0.24	90	0.15	80	0.10	—	822
400	0.26	90	0.12	—	0.10	—	809
300	0.13	—	0.20	80	0.08	—	777
250	0.27	85	0.18	—	0.01	—	733
200	0.30	85	0.19	—	0.05	—	677
150	0.39	90	0.21	—	–0.07	—	639

There are three higher error events (over the profiler subdomain) evident in this figure for 5, 10, and 16 February (Julian dates 36, 41, and 47, respectively), which are all associated with the passage of strong upper-level waves. The 3-h persistence errors peak

much more sharply than the 3-h forecast error, indicating that the rapid changes in the 500-hPa wind field are largely, but not completely, captured by the model forecasts.

A time series of the profiler impact at each 12-h verification time (0000 and 1200 UTC) at selected mandatory pressure surfaces (Fig. 7) reveals significant day-to-day variations in the profiler impact. Comparing time series of 500-hPa persistence error (Fig. 6) and profiler impact (Fig. 7) shows some correlation between larger profiler impact (at 850 hPa on 5 and 10 February, and at 500 hPa on 16 February) and more changeable weather situations. Figure 7 also shows that the time-by-time impact from profiler data is usually positive. Intermittent negative impacts evident in Fig. 7 are attributed to aliasing, which can occur from any in situ observing system.

The impact from denying data on active weather days shown in Fig. 7 underscores the importance of performing case studies. However, it is also possible to stratify statistics to isolate the impact for peak error events. The values of the top 5% of the largest CNTL and EXP observation–forecast differences (residuals) were also computed. Residuals at each radiosonde location for every 12-h verification time (0000 and 1200 UTC) were combined for each mandatory level and then ranked from largest to smallest. The effective sample size of this combination of residuals for the en-

tire RUC domain is ~2000 (number of radiosondes per 12 h × two launch times per day × 12 days), and ~528 for the profiler verification domain.

The top 5% of the CNTL and EXP residual values for 3- and 6-h forecasts over the profiler domain are

shown in Fig. 8. The errors at the top 5% level are about twice as large as the errors shown in Fig. 3. The top 5% level differences between CNTL and EXP forecasts are also considerably larger (generally $0.5\text{--}1.0\text{ m s}^{-1}$) than the overall average values (only up to $0.3\text{--}0.6\text{ m s}^{-1}$, see Fig. 4 and Table 1). This indicates that profiler data have a larger impact for large-error cases generally associated with active, more difficult forecast situations. We suggest that this approach is appropriate for other observation NWP impact studies, because significant reduction of error in difficult situations may justify new observations even if the effect on overall statistics may not appear to be impressive.

Aircraft data-denial results. Automated observations from commercial aircraft [mostly reported over the United States through the Aircraft Communication Addressing and Reporting System (ACARS)] are another important source of asynoptic wind observations. There are contrasts and complementarity between aircraft data and profiler data coverage in the central United States. Aircraft data provide high-resolution data at enroute flight levels, generally between 300 and 200 hPa, and at a lesser but still significant amount of ascent/descent profiles (Moninger et al. 2003). Profilers provide hourly (and even 6 min) wind profiles, and, of course, are not dependent on flight schedules and route structures.

In this experiment, all aircraft data at all levels were withheld over the entire RUC domain. The aircraft data denial impact results for wind forecasts over the profiler subdomain (Fig. 9) indicate that these data impact the forecasts most strongly in the upper troposphere (jet levels). The impact is considerably less in the lower troposphere, both because there are fewer ascent and descent reports and because of the influence of the profiler data. The broader coverage of aircraft data than the current profiler network leads to a longer-lasting forecast impact for 6- and 12-h forecasts. A more complete de-

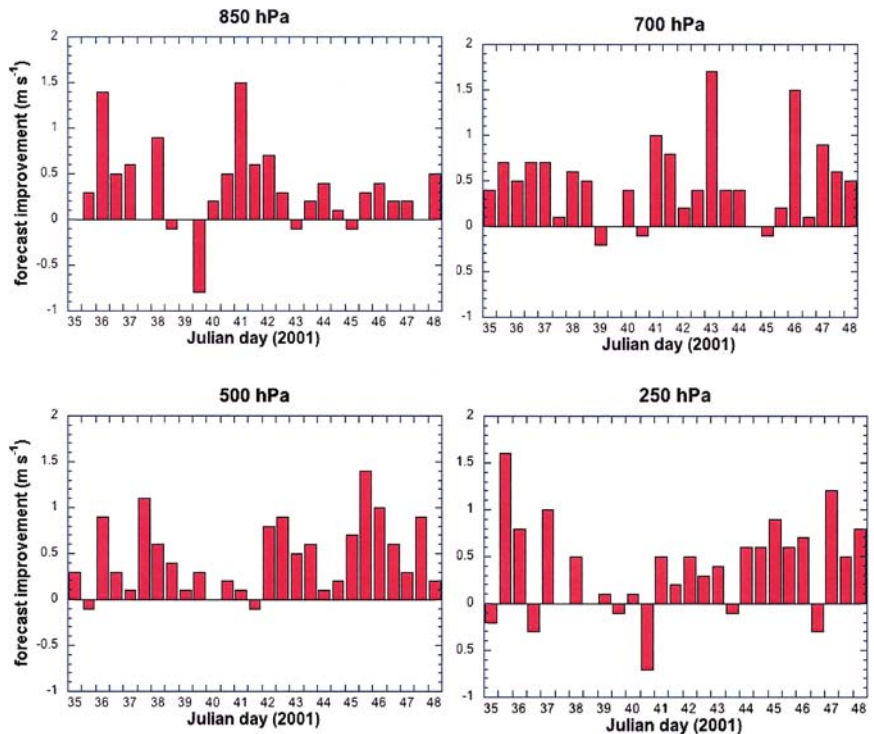


FIG. 7. Difference in 3-h wind forecast rms vector error score over profiler domain between EXP and CNTL from every 12-h verification time during 4–17 Feb 2001 (Julian date 35–48) test period at indicated mandatory isobaric levels.

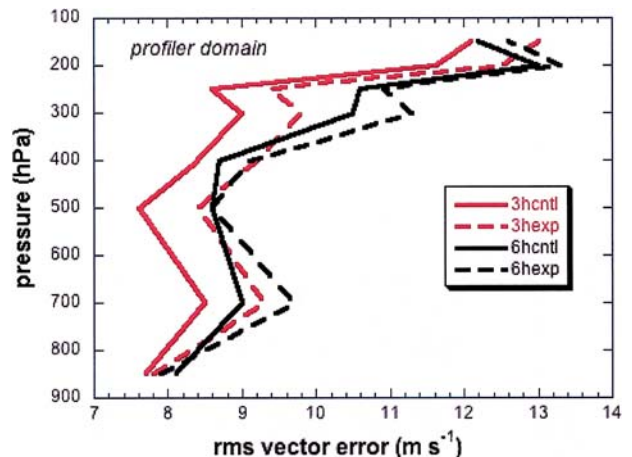


FIG. 8. Top 5% value of observation–forecast events (residuals) over all radiosondes within profiler domain and all verification times. For CNTL and EXP for 3- and 6-h forecast residuals.

scription of aircraft versus profiler impact is presented in the section on “Normalized results for profiler and aircraft data denial experiments.”

All observational data-denial results. In order to calibrate the impact of the profiler data on the accuracy of RUC forecasts, a “NO-DATA” experiment was performed.

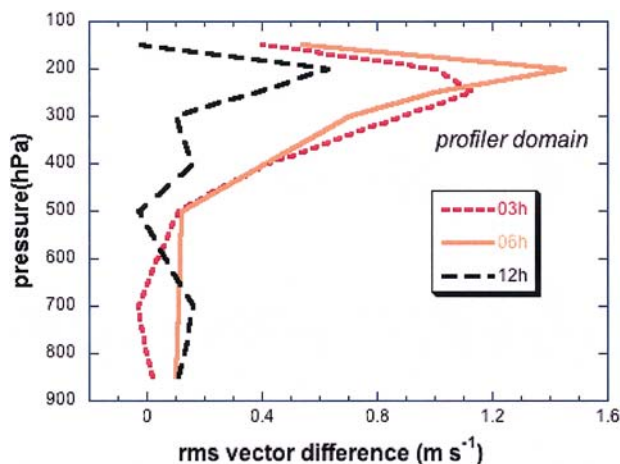


FIG. 9. Difference in rms vector error scores between no-ACARS experiment and CNTL experiment over the profiler subdomain for the 4–17 Feb 2001 period.

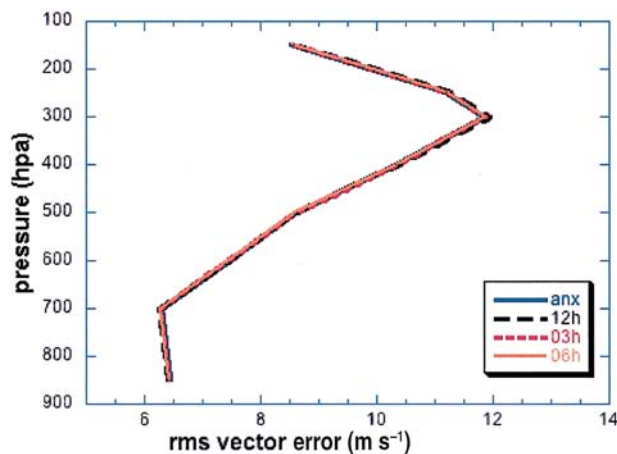


FIG. 10. Rms vector difference between radiosonde observations and RUC analyses (anx) and 3-, 6-, and 12-h wind forecasts over RUC domain for 4–17 Feb 2001 period for the EXP experiment.

In this no-data experiment, the same initial conditions were used as those in CNTL, but no observations were made available after that point to correct model grids over the 13-day period. This experiment was able to more freely drift away from observed conditions and was constrained only by the updated lateral boundary conditions—the same as those used in all other experiments. Because no observations are assimilated in this experiment, it is essentially equal to a 13-day forecast with updated boundary conditions. For this no-data experiment, the rms vector differences (forecast – observed) for 3-, 6-, and 12-h forecasts, and even analyses (Fig. 10), are essentially equal, which is expected because no observations are available to allow shorter-range forecasts to provide improvement over longer-range forecasts. Also, the scores are much higher (peaking at $\sim 12 \text{ m s}^{-1}$ at near-tropopause jet

levels) than those for the CNTL experiment (Fig. 3, peaking at $\sim 7 \text{ m s}^{-1}$).

The difference between the errors from the NO-DATA (Fig. 10) versus the CNTL run (Fig. 3) corresponds to the combined effect of all observational data toward reduction of the overall forecast error with a given set of lateral boundary conditions. In other words, this difference is that between the “worst case” experiment when all of the data are denied from the RUC and the best-case experiment when all of the data are available to the RUC. It is notable that results from NO-DATA are no worse than shown—an indication of the strong constraint (and damping of observation impact) from given lateral boundary conditions. This difference will be used in the next section as one way to calibrate the contribution that denying each individual data source has on the total forecast error. Graham et al. (2000) performed a similar no-data experiment with the same purpose in their global NWP impact experiments.

Normalized results for profiler and aircraft data denial experiments. The impact of data denial can be expressed in terms of percentage of forecast error. In this section, we present results for impact of both profiler and aircraft data within the profiler domain, normalized with two different methods. We first calculate percentage impact as

$$x_1 = \frac{(\text{EXP} - \text{CNTL})}{\text{CNTL}}, \quad (1)$$

where EXP is the average score for profiler or aircraft data denial experiments, and CNTL is the average forecast error score for the control experiment with all data. Using the x_1 normalization, profiler data are shown to reduce 3-h wind forecast error by 11%–20% in the 400–700-hPa layer (Fig. 11a). The inclusion of aircraft data is shown to be highly complementary in the vertical with the profiler data, accounting for up to 22% of the 3-h forecast improvement at 250 hPa.

A second normalization to determine data impact, the percentage of the total observational data impact provided by a single observation type in the presence of all other observation types, can be computed as

$$x_2 = \frac{(\text{EXP} - \text{CNTL})}{(\text{NODATA} - \text{CNTL})}, \quad (2)$$

as discussed in the previous section. This normalization was also used by Graham et al. (2000) for their global OSEs. Normalizing with the no-data versus

control difference (x_2), profiler data accounts for up to 30% (at 700 hPa) of the total reduction of wind forecast error from assimilating all observations (Fig. 11b). Regardless of the normalization, these results show that a significant proportion of the short-range wind forecast skill over the central United States is due to profiler data. The inclusion of aircraft data is shown to be highly complementary in the vertical with the profiler data, accounting for up to 20%–25% of the 3-h-forecast improvement at 250 hPa, but is much less than profiler data in the 500–850-hPa layer.

Because the forecast–observation difference consists of both forecast and observation error (discussed in the “Experimental design” section), we also present profiler impact results (Fig. 11c) for a third normalization, preferred by us because it best accounts for observation error,

$$x_3 = \frac{(\text{EXP} - \text{CNTL})}{(\text{EXP} - \text{ANX}_E)}, \quad (3)$$

where EXP and CNTL are as described above and ANX_E is the analysis fit to observations (shown in Fig. 3) for the EXP run. This score may be interpreted as the percentage reduction of forecast error produced by some change, assuming that a forecast that fit observations as well as the analysis would be a perfect forecast. By this normalization, profiler data produce a 13%–30% reduction of 3-h wind forecast error at all mandatory levels shown from 150 to 850 hPa. Even though profiler observations are for wind only, they also benefit short-range forecasts of other variables (Fig. 11c): height (error reduction of up to 30%), relative humidity, and temperature. Averaged over mandatory levels, the mean reduction of 3-h-forecast error from assimilation of profiler data is 6% for temperature, 5% for relative humidity, 15% for height, and 21% for wind. If RASS temperatures had also been included in the CNTL run (see the section titled “Experimental design”) more impact from the profiler–RASS combined observations would likely have been evident in the lower troposphere. This improvement in forecasts of other variables results from the multivariate effects of the RUC analysis and subsequent interaction in the forecast model.

Profiler data have more impact than aircraft data on 3-h wind forecasts in the lower troposphere over the profiler subdomain because there are fewer, less frequent, and less evenly distributed (in a spatial sense) ascent/descent profiles compared to the ~30 profilers within the profiler domain. Figure 12 shows

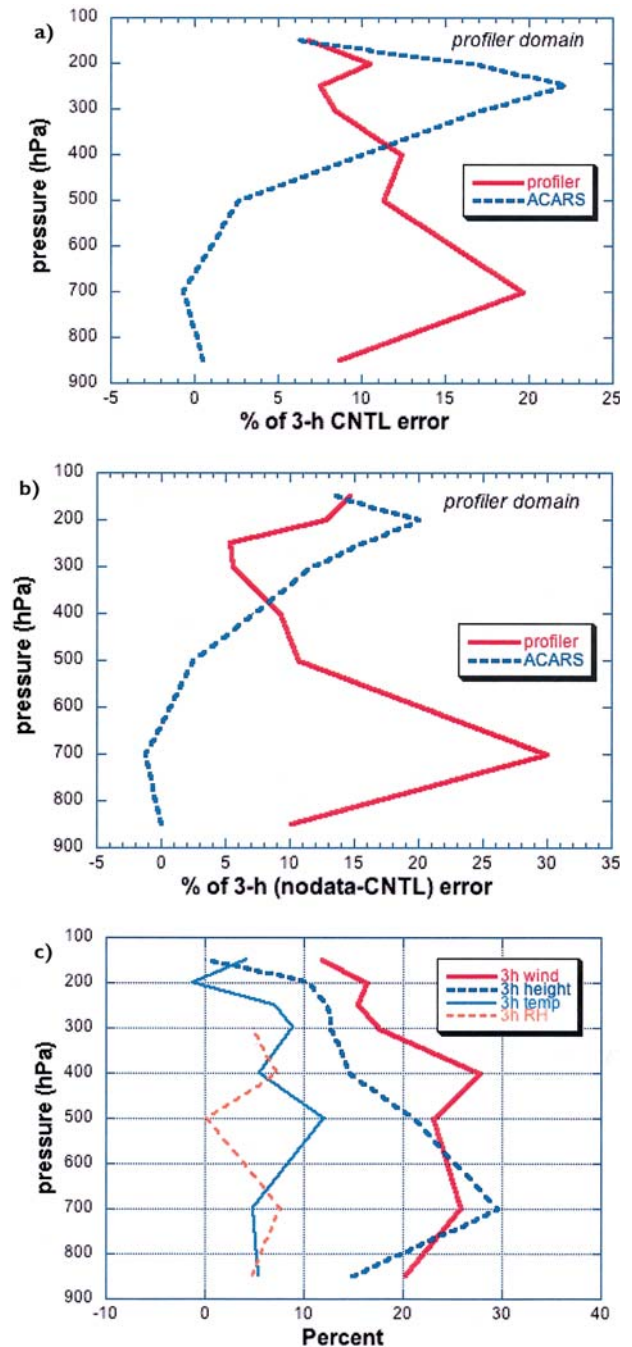


FIG. 11. Normalized impact from observation data denial experiments for RUC 3-h forecasts averaged for profiler domain. Relative impact from profiler and aircraft data normalized at each level by (a) 3-h control forecast error (x_1), and (b) difference between EXP error and CNTL error (x_2) for 3-h forecast. Also, (c) impact of profiler data for wind, height, temperature, and relative humidity, normalized with x_3 as in the “Normalized results for profiler and aircraft data denial experiments” section.

a distribution of ACARS-relayed aircraft observations below 300 hPa for a representative daytime weekday 12-h period from the experiment period. Most of the ascent/descent profiles are found at major airport hubs located primarily on the edges of the profiler subdomain, especially on its eastern edge. The spatial coverage of profiler lower-tropospheric wind observations is more complete (Fig. 1) than that of the ACARS ascent/descent profiles within the profiler domain. However, at jet levels near 200–300 hPa, aircraft observations from enroute flights give better coverage than profiler data.

CASE STUDIES. In this section, we present highlights from results for data assimilation/model forecast experiments run for two specific cases of inter-

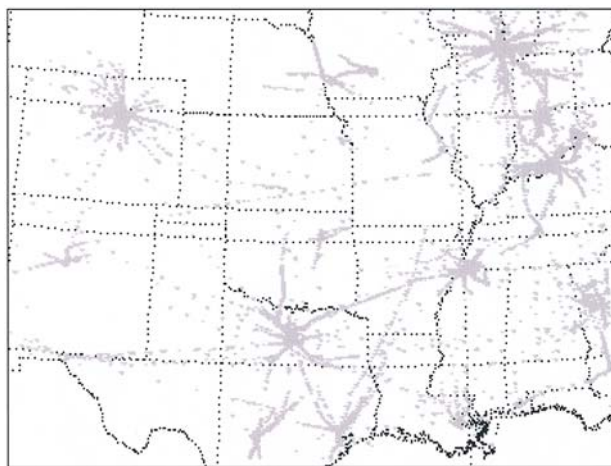


FIG. 12. Location of ACARS-relayed aircraft observations below 300 hPa for the 12-h period from 1200 UTC 8 Feb–0000 UTC 9 Feb 2001 within the profiler subdomain.

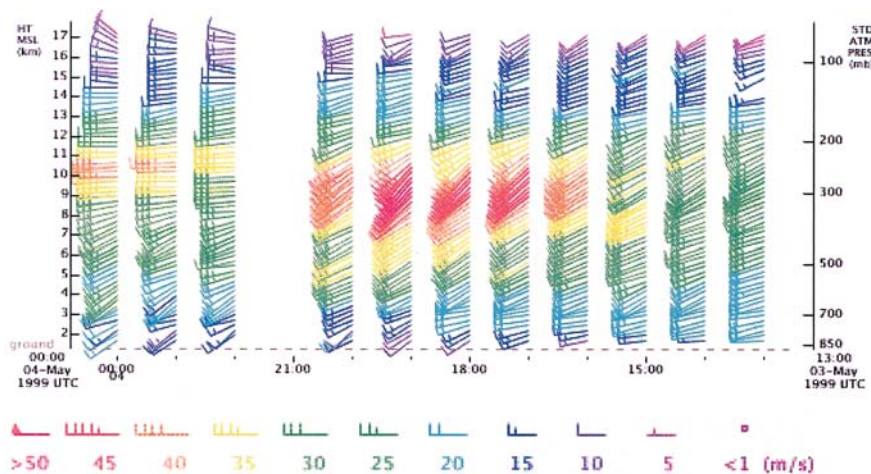


FIG. 13. Tucumcari, NM (TCUM5), profiler time series valid for 1300 UTC 3 May–0000 UTC 4 May 1999. Wind speed (m s^{-1}) is coded by color in legend at bottom.

est. These cases are treated in greater detail in the accompanying online supplement for this article (Benjamin et al. 2004c). A third case study (8 May 2003) is also described in the online supplement.

3 May 1999 Oklahoma tornado outbreak. Numerous papers (including the March 2002 issues of *Weather and Forecasting*) describe the significance of the 3 May 1999 Oklahoma City, Oklahoma, 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, as previously discussed in the beginning of this paper. The 20-km RUC with a 1-h assimilation cycle was rerun for the 24-h period (0000 UTC 3 May to 0000 UTC 4 May 1999) with (CNTL) and without (EXP) wind profiler data to assess their impact on forecasts of preconvective environment parameters and precipitation over Oklahoma.

Prompted by the remarks of Thompson and Edwards (2000), we examined the difference between upper-level wind analyses and forecasts in the CNTL and EXP runs beginning at 1500 UTC. SPC forecasters had noted that a jet streak associated with a deepening trough approaching Oklahoma from the west was underforecast by model runs initialized at 0000 UTC 3 May 1999. They based their assessment on the Tucumcari, New Mexico, profiler time–height time series (Fig. 13), showing increasing winds in the 4–10-km layer, with 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 (Fig. 14),

the winds are stronger at 300 hPa in the CNTL experiment compared to the EXP run by about $4\text{--}6 \text{ m s}^{-1}$ over a broad area, including western Oklahoma and north-central Texas (vector difference of up to 10 m s^{-1} , Fig. 14d). According to the verifying CNTL analysis at 0000 UTC (Fig. 14c), the profiler data improve the accuracy of the short-range RUC upper-level wind forecast by better capturing the jet streak noted in the Tucumcari profiler observations and its subsequent effect on the upper-level

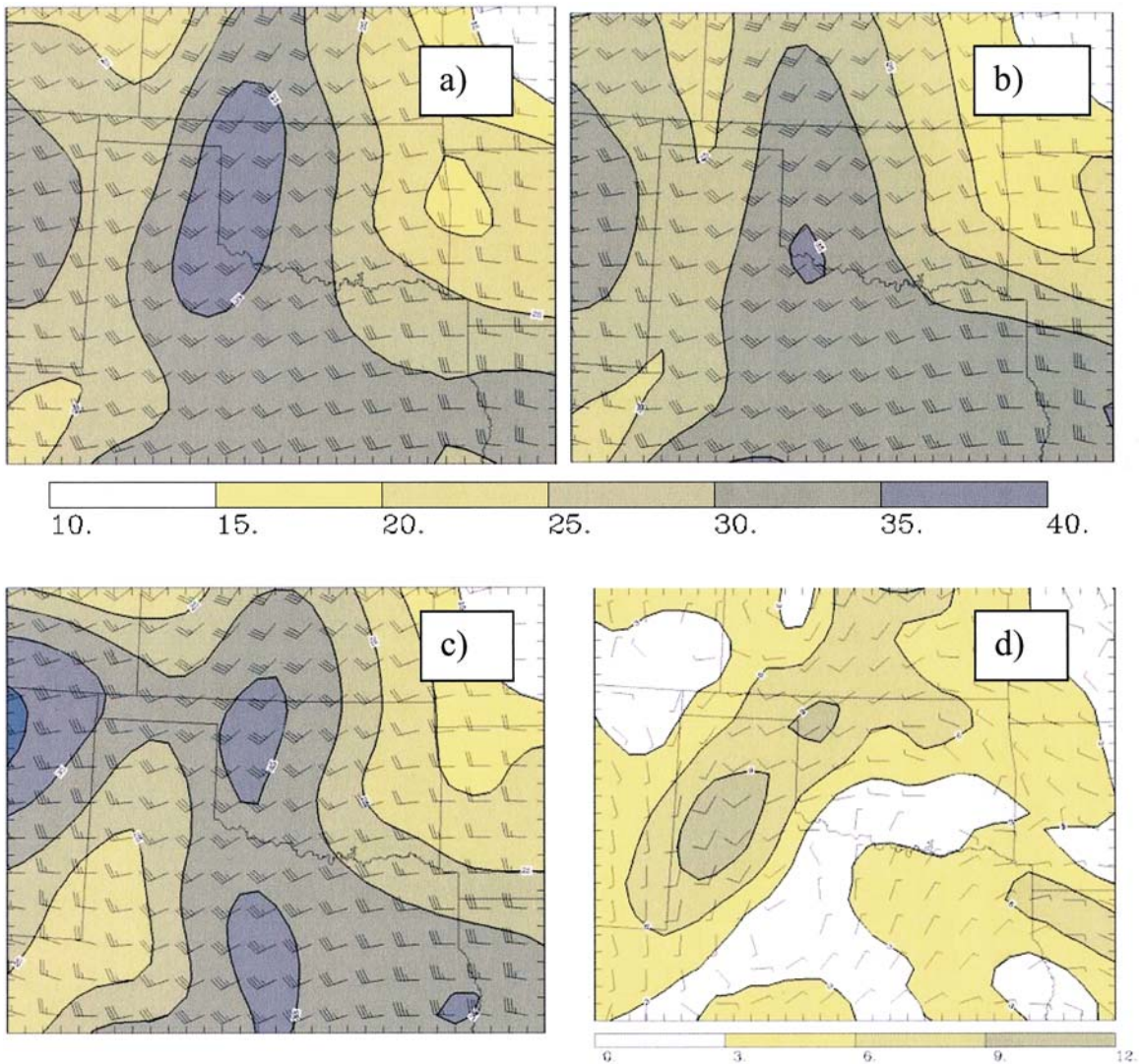


FIG. 14. The 6-h forecasts of 300-hPa wind (m s^{-1}) for (a) CNTL and (b) EXP initialized at 1800 UTC 3 May 1999 and valid at 0000 UTC 4 May 1999. (c) Verifying (CNTL) analysis at 0000 UTC 4 May 1999, and (d) CNTL – EXP vector difference between 6-h forecasts.

winds over the area of convective development in Oklahoma.

In addition to wind fields, forecasts of convective available potential energy (CAPE; an important parameter indicating instability available to fuel convective storm development) derived from the RUC were also examined from the CNTL and EXP experiments. (CAPE is calculated here with averaging of potential temperature and water vapor mixing ratio in the lowest 40 hPa.) Figure 15a shows the difference between CNTL and EXP 6-h CAPE forecasts valid at 2100 UTC 3 May 1999. Observed CAPE values (Fig. 15b, CNTL analysis) are generally large ($> 4000 \text{ J kg}^{-1}$) in the area where the first storms formed (see supercell track summary, Fig. 16, upper-left inset) in southwestern Oklahoma. The increase

in CAPE values (by $\sim 1000 \text{ J kg}^{-1}$) 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 the assimilation of profiler data was largely related to an enhanced southeasterly flow of moisture (see Benjamin et al. 2004c, their Fig. S3) into the area of convective initiation and a westward shift of dryline position. Both changes agree more closely with the observations.

Severe snow and ice storm of 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 U.S. southern plains on 8–9 February 2001, including heavy sleet and freezing rain

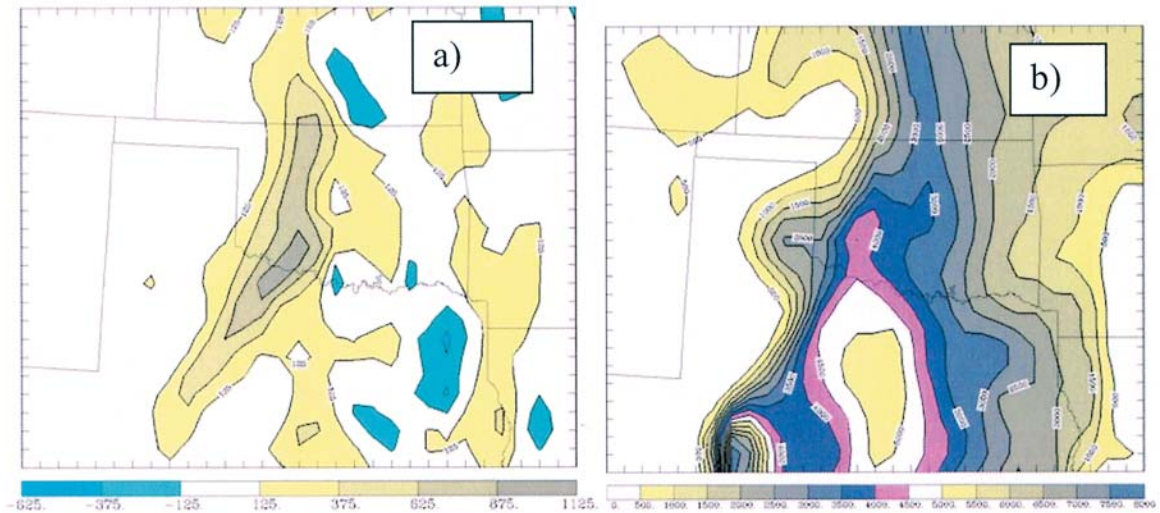


Fig. 15. (a) CNTL – EXP difference for 6-h CAPE forecasts valid at 2100 UTC 3 May 1999, and (b) CAPE field from CNTL analysis valid at the same time.

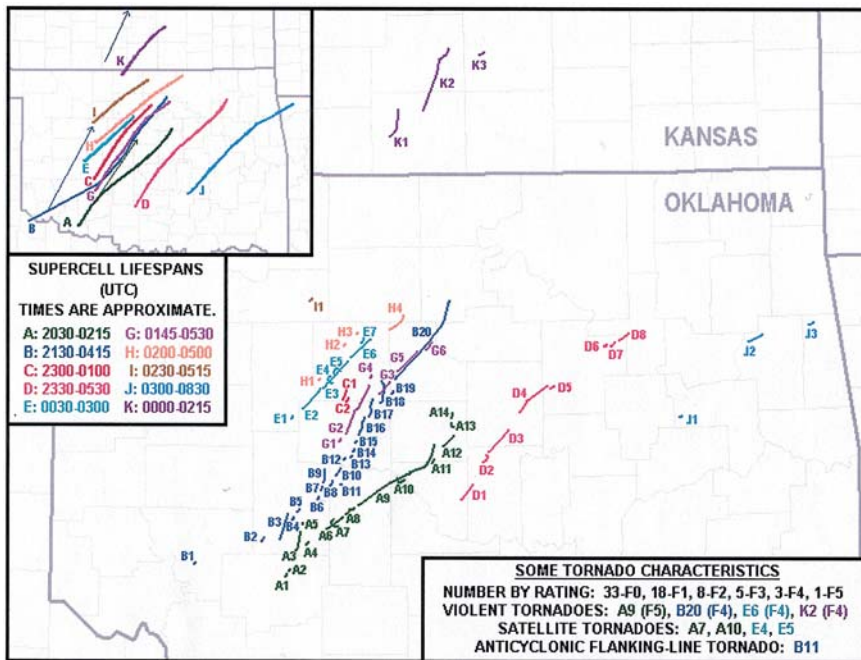


Fig. 16. Tornado and supercell (upper left) track summary for 3 May 1999 storms. Provided by NWS Forecast Office, Norman, OK.

from south-central into eastern Kansas. Short-range (3 h) forecasts from RUC experiments with (CNTL) and without (EXP) profiler data extracted for a 3-h period of intensifying precipitation (0300–0600 UTC 9 February 2001) from the 13-day experiment described in the section titled “Case studies” 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) 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. By 0600 UTC (Fig. 17), radar reflectivity 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.

The RUC precipitation forecasts (Fig. 18) for this 3-h period show that the CNTL experiment was more intense (7–12 mm) throughout this frontal zone than in EXP (4–9 mm). The CNTL forecast more 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 and slope. A three-dimensional analysis of wind flow responsible for these differences in precipitation, including comparisons of vertical cross sections of horizontal and vertical velocity and hydrometeors, is presented in Benjamin et al. (2004c).

DISCUSSION AND CONCLUSIONS. The importance of data from the wind profiler network for forecasting in the United States has been documented through data denial experiments with the RUC for a 13-day period from February 2001, three severe storm case studies [3 May 1999, 9 February 2001, and 8 May 2003 (see online supplement)], and a summary of the use of profiler data within the National Weather Service. Verification statistics from the RUC profiler data denial experiments shown in this paper demonstrate that profiler data contribute significantly to the reduction of

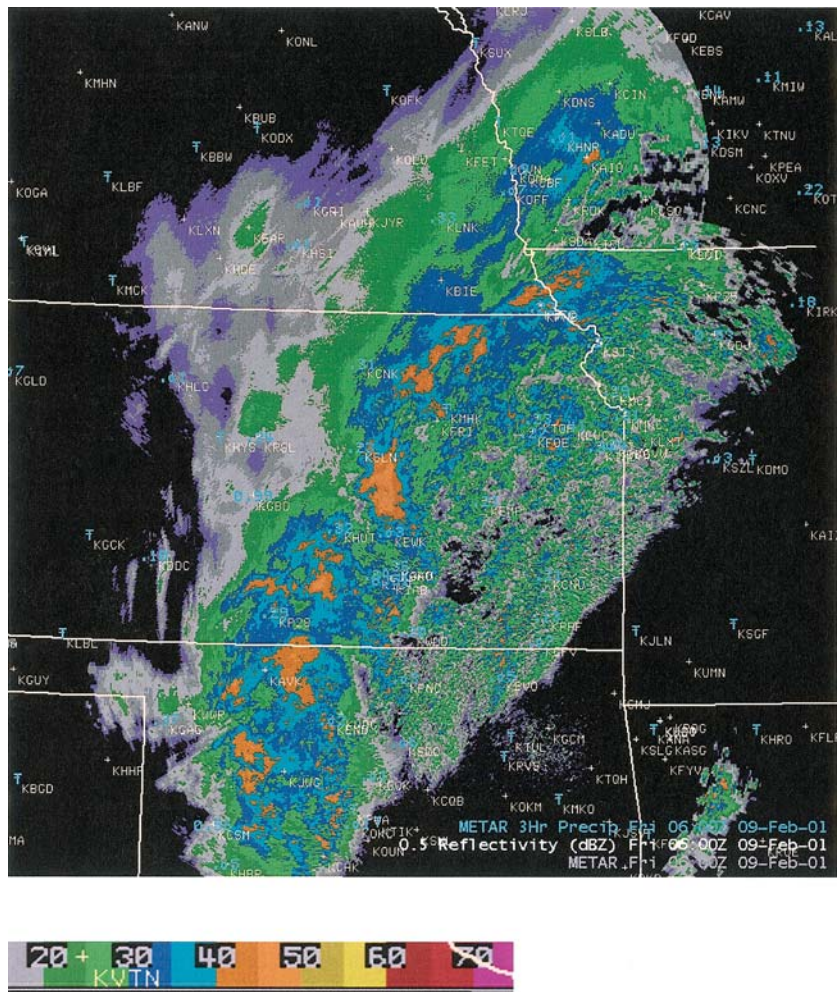


Fig. 17. Radar reflectivity (0.5° elevation scan, dBZ color scale shown at bottom) valid at 0600 UTC 9 Feb 2001 and METAR precipitation (in.) totals for 3-h period ending 0600 UTC. (From AWIPS.)

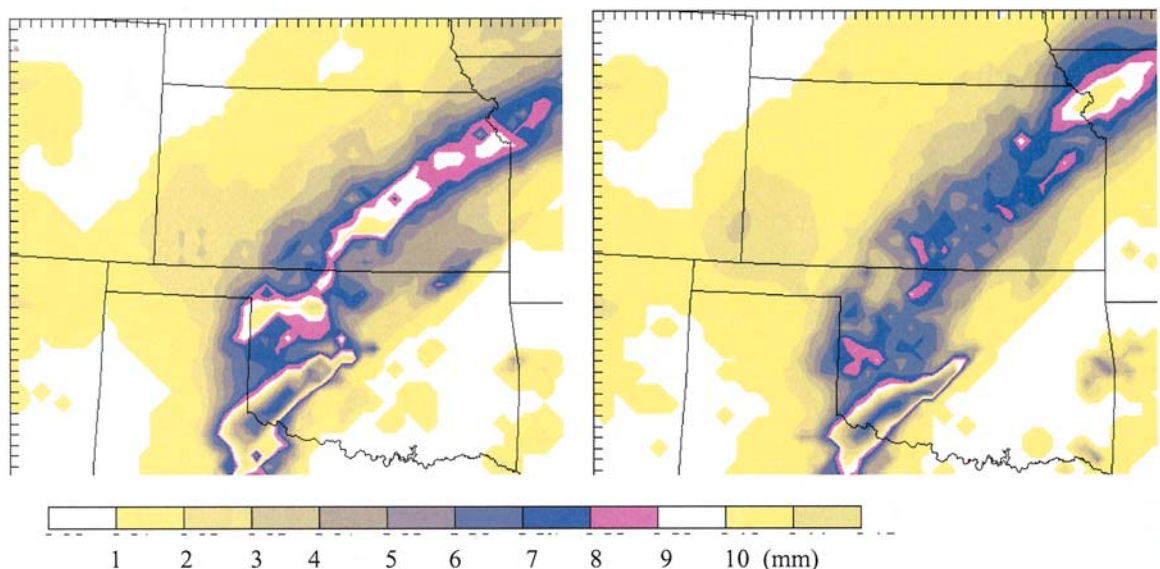


Fig. 18. Forecast 3-h precipitation (mm) for 0300–0600 UTC 9 Feb 2001 from (left) CNTL and (right) EXP forecasts initialized at 0300 UTC.

USE OF PROFILERS BY OPERATIONAL FORECASTERS

Wind profiler data are used regularly by NWS forecasters. Forecasters typically use a time-series display of hourly profiler winds and also display overlays of profiler winds on satellite and/or radar images to better discern mesoscale detail. In addition, profiler data are often used to help verify analyses and short-range forecasts from the models, enabling forecasters to judge the reliability, in *real time*, of the model guidance. NPN profilers are located near many Weather Forecast Offices (WFOs) in the NWS Central and Southern Regions. (Also, boundary layer profilers located near each coast, not used in NWP tests described here, are used by the NWS Western and Eastern Regions). In 2002, the NWS Southern Region Scientific Services Division conducted a survey for WFOs within the NPN area to inquire how the profiler data are used in operations. Forecasters noted that they use profiler data for synoptic analysis, evaluation of model guidance, mesoscale analysis, discerning short-term changes, checking the prestorm environment, monitoring evolving upper-level jet streaks, and for LLJ detection and monitoring moisture advection with the LLJ. Forecasters described more specific instances in which profiler data were used, and some of these are given below:

- **Topeka and Wichita (Kansas) WFOs:** Monitored a rapidly evolving low-level shear profile that resulted in conditions favoring supercells, which enabled the forecasters to be well prepared in anticipating the tornado outbreak on 19 April 2000. (The Neodesha, Kansas, profiler showed a vertical speed–directional shear profile developing rapidly over a 3–6-h time period that was ideal for tornadic storms. Mesoscale data, including profilers, were used to put out an accurate and specific nowcast about exactly where severe convection would develop in the next 1-h period.)
- **Amarillo (Texas) WFO:**
 - Forecast high wind events by monitoring strong above-surface winds in the Texas and Oklahoma Panhandles;
 - Forecast cold air fronts through high-frequency monitoring of depth and strength of cold-air surge, which is possible only with profiler data;
 - Monitor low-level jets and low-level wind shear profiles important for forecasting thunderstorm outbreaks and possible rotating storms and tornadoes.
- **Topeka (Kansas) WFO:** Ended a winter weather warning. (Profiler data confirmed that placement of an upper-level low in the models was incorrect, and the warning was cancelled much sooner than it otherwise would have been.)
- **Albuquerque (New Mexico) WFO:** Specialized weather forecasting for fires near Albuquerque. (Wind observations from the Tucumcari profiler helped forecasters to accurately predict a midnight wind surge that led to a fire blowup. Fire fighters were, therefore, prepared and able to contain the fire during intensification.)

While the 3 May 1999 case was a dramatic example of profiler data use at the NOAA Storm Prediction Center (see the beginning of this article), SPC forecasters often use profiler data on an hourly basis. The impacts/uses of profiler data at the SPC are summarized below:

- Needed to reliably diagnose changes in vertical wind shear at lower levels (< 3 km above ground level) as well as through a deep layer (through 6 km AGL), both critical to determining potential tornado severity;
- Used to better determine storm motion, critical in distinguishing stationary thunderstorms that produce flooding from fast-moving thunderstorms that produce severe weather;
- Used to better determine storm relative flows and, consequently, the character of supercells [heavy precipitation (HP) versus classic];
- Critical for monitoring the low-level jet life cycle, an important factor in mesoscale convective system (MCS) development and, therefore, the threat for flooding and/or severe weather; and
- Unique in providing high-frequency full-tropospheric winds compared with radiosonde and VAD data. (While Doppler radar-derived VAD winds also provide a high frequency, they cannot monitor deeper-layer vertical wind shear, critical information for SPC. The SPC has added use of the 6-min profiler data since 2000 to better monitor conditions with rapidly evolving severe weather.)

[The material presented in the introduction and this sidebar were contributed by P. Browning of the NWS and S. Weiss of the NCEP Storm Prediction Center.]

the overall error in short-range wind forecasts over the central United States for this February 2001 test period. Forecast errors for height, relative humidity, and temperature were also reduced by 5%–15% averaged over vertical levels. This contribution from profiler data is above and beyond the contributions to initial conditions provided by complementary observations from ACARS aircraft, VAD, and surface stations. A significant contribution from profiler data to improved short-range (3 h) forecast accuracy of 12%–28% at all mandatory levels from 850–150 hPa was shown from the RUC experiments for the 13-day test period. Moreover, a substantial reduction of wind forecast error (~25%) was shown to occur even at near-tropopause jet levels for forecasts initiated at night from the assimilation of profiler data.

Comparisons were made between experiments in which profiler data were withheld and a second experiment in which all aircraft data were withheld. The complementary nature of the two types of observations contributing to a composite high-frequency observing system over the United States was evident, with profiler observations contributing more to improvement through the middle and lower troposphere, and aircraft observations contributing more strongly at near-tropopause jet levels. The picture is actually more complex, with aircraft ascent/descent data adding full-tropospheric profiles of winds and temperature and profilers contributing high-frequency jet-level wind observations at night, both adding further accuracy to short-range forecasts. Benjamin et al. (2004a), in a detailed description of the RUC and the performance of its assimilation–forecast system, show the effectiveness of the RUC in using high-frequency observations over the United States to provide improved skill in short-range wind forecasts down to as near term as a 1-h forecast. These accurate short-range forecasts are critical for a variety of users, including aviation, severe weather forecasting, the energy industry, spaceflight operations, and homeland security concerns. Without question, it is the combined effect of the profiler–aircraft composite observing system that is most responsible for this strong performance in RUC short-range wind forecasts over the United States.

Profiler observations fill gaps in the ACARS aircraft observing system, with automated, continuous profiles 24 h day^{-1} , with no variations over the time of day or the day of the week (package air carriers operate on a much-reduced schedule over weekends). Profiler data are available (or could be) when aircraft data may be more drastically curtailed, owing to na-

tional security (e.g., 11–13 September 2001) or severe weather events such as the East Coast snowstorm of 15–17 February 2003. Profiler observations also allow improved quality control of other observations from aircraft, radiosonde, radar, or satellite.

Although the average statistical NWP impact results are compelling evidence that the profiler data add value to short-range (0–6 h) NWP forecasts, the value ranges from negligible, often on days with benign weather, to much higher, usually on days with more difficult forecasts and active weather. This day-to-day difference was evident in breakdowns of profiler impact statistics to individual days and to peak error events. These breakdowns were made to accompany the cumulative statistics that generally mask the stronger impact that occurs when there is active weather and a more accurate forecast is most important.

Detailed case studies were carried out using the RUC assimilation cycle and forecast model with and without profiler data for three severe weather cases. A fairly significant positive impact was demonstrated for the Oklahoma tornado outbreak cases of 3 May 1999 and 8 May 2003. Wind data from the profilers resulted in an improvement in the forecast CAPE, shear, and precipitation forecasts valid at or near the time of the storm development. In the 1999 case, 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. Assimilation of profiler data for the 8–9 February 2001 snow and ice storm case study resulted in a better forecast of the ascent of the lower-level southerly flow overrunning a strong cold front, resulting in stronger and broader upward motion. The outcome of assimilating profiler data in this case was a more accurate RUC precipitation forecast in an area of significant sleet and snow in Oklahoma and Kansas north of the surface front.

As summarized in this paper, profiler data are widely used and have become an important part of the forecast preparation process in the National Weather Service. Clearly, the utility of NPN data to local forecast offices is greatest for short-term forecasts and warnings, reflecting the unique high time resolution from profilers. The NPN is capable of providing data with time resolution as high as 6 min, and forecasters in the NWS Central Region have only recently begun to access the 6-min data routinely. Early indications are that the utility of profiler data in critical short-fuse-warning situations is even further enhanced by the 6-min data.

Profiler data are the only full-tropospheric wind data available on a continuous basis over the United States and, as discussed above, could possibly be the only such data that would be available during extreme weather events or a national security event that would ground commercial aircraft. Profilers also routinely provide full-tropospheric wind observations in conditions of full cloud cover that cannot be made from any current or planned satellite system.

The critical improvements provided to short-range model forecasts and subjective forecast preparation from wind profiler data, as documented in this paper, have been available only over the central United States and, to a lesser extent, downstream over the eastern United States. The NWS Service Assessment Report for the 3 May 1999 tornado case (NWS 1999) recommended full operational support for the existing profiler network. These benefits for forecast accuracy and reliability could be extended nationwide by implementation of a national profiler network, although this needs to be the subject of a cost–benefit analysis. As described earlier, the interests that would obtain a national-scale benefit from such a profiler network include not only severe weather forecasting, but also aviation, energy, space flight, and homeland security.

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