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

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1. INTRODUCTION

Forecast Systems Laboratory (FSL) has operated a network of 404-MHz full tropospheric profilers – the NOAA Profiler Network (NPN) – since 1992. The Profiler Program began in 1986 with a congressional initiative for a Wind Profiler Demonstration Network. The NPN Mission Statement was "to develop, deploy, and operate a network of 30 wind profilers in the central United States and, in cooperation with NWS and other agencies, conduct an assessment of that network." Most of these profilers operate today over the central United States, with the exception of a few in Alaska and elsewhere (Fig. 1). Measurements are produced at 36 range gates along each of 3 orthogonal beams (zenith and 16.3 degrees off-zenith in the east and north directions) in both a low mode pulse width with 320 m resolution below 9.25 km and in a high mode from 7.5 to 16.25 km with 1000 m resolution. These data are then combined to produce wind profiles every 6 min with a reporting increment of 250 m. Upon application of additional quality control measures and averaging, hourly wind profiles are obtained, which are the data assimilated into the Rapid Update Cycle (RUC), the Eta and Global Forecast System (GFS) models at the National Centers for Environmental Prediction (NCEP).

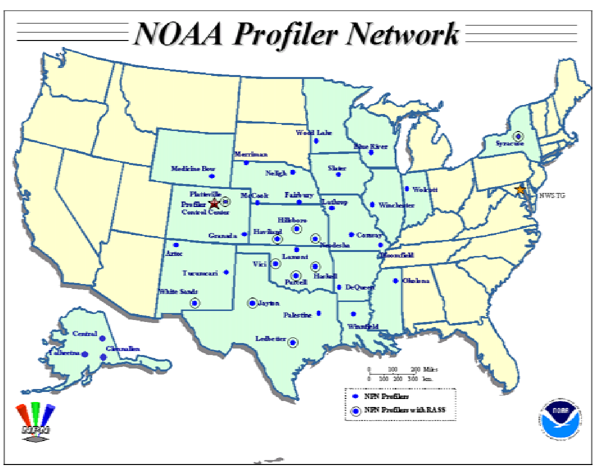

Fig. 1. NOAA Profiler Network as of August 2003. All sites are 404 MHz systems, with the exception of Platteville, CO, Syracuse, NY, and the three Alaska sites (449 MHz), and circled sites also have a Radio Acoustic Sounding System (RASS).

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The delivery rate of wind profiler data from FSL to the National Weather Service (NWS) has steadily increased since 1992, with rates currently approaching 97% (Fig. 2). Such high reliability is a requirement for operational numerical weather prediction (NWP). The keys to this high data availability are redundant hardware and communications links to the profilers, the installation of remote breaker resets to power cycle the site, and monitoring of profiler status after hours.

This paper presents a comprehensive assessment of the value of profiler data in both NWP and subjective weather forecasting [a companion paper by Schwartz and Benjamin (2004) presents an assessment of the value of other observational systems in RUC forecasts]. A series of experiments using the RUC model was conducted for a 14-day period. Data from profilers and from ACARS (Aircraft Communication and Reporting System) were separately denied in the RUC in order to assess the relative importance of the profiler data for short-range wind forecasts. A more drastic data denial experiment in which all observational data were withheld was also performed as a "worst case" calibration. The value of the data on the forecasts was determined by comparing the forecasts to radiosonde observations.

Second, two case studies are presented that illustrate the value of the profiler observations for improving weather forecasts. The first case study assesses the importance of profiler data in the RUC

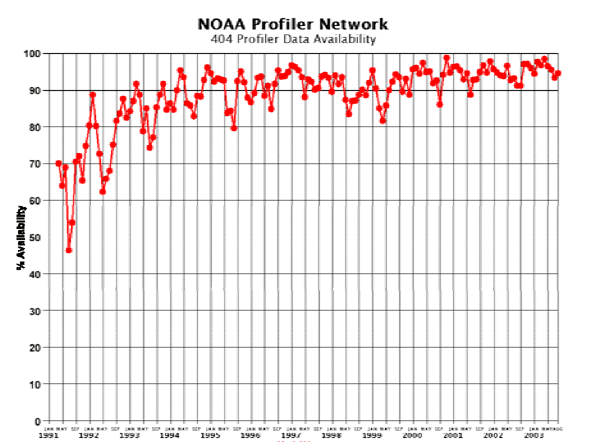

Fig. 2. Hourly rate of availability of profiler data provided by the NPN hub at FSL to the NWS plotted on a monthly basis from 1991 – 2003.

model runs for the 3 May 1999 Oklahoma tornado outbreak. In the second case study, the impact of profiler data in RUC forecasts associated with a severe snow and ice storm that occurred over the Central Plains on 8-9 February 2001 is examined. Third, summaries of NWS forecaster use of profiler data are presented to see whether operational use of these data support the results from the two case studies and the statistical model impact study.

2. RUC NWP IMPACT STUDY

The 20-km operational RUC model with 50 hybrid isentropic-sigma vertical levels (Benjamin et al. 2003a) was used in the model impact experiment. An hourly intermittent assimilation cycle is used in the RUC, allowing full use of hourly profiler (and other high-frequency) observational data in the RUC 3DVAR system (Benjamin et al. 2003b). The 14-day experiment 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 3-h output frequency. The high-frequency observations used in the RUC experiments described in this paper include those from wind profilers, commercial aircraft, Doppler radar velocity azimuth display (VAD) wind profiles, and surface stations.

Verification was performed using conventional 12-hourly radiosonde data over the three domains depicted in Fig. 3: the RUC model domain, a “profiler domain”, and a “downstream domain.” The black box outlining the profiler domain includes most of the Midwest profilers depicted in Fig. 1 and contains 22 radiosonde sites. The area defined by the red box in Fig. 3 referred to as the downstream domain was chosen to depict an area that might be affected by forecasts initialized in the profiler domain due to downstream advection of information originating from the profiler data. For each experiment, RMS vector differences between forecasts and observations were computed at all radiosonde sites located within each of the three domains. These scores were then averaged over the 14-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 or no aircraft, henceforth referred to as EXP-P and EXP-A). In addition, the Student’s-t test was performed on the differences between the CNTL and EXP runs to determine statistical significance of the results.

The average 3-h, 6-h, and 12-h wind forecast impacts (EXP-P – CNTL) for the profiler domain show positive values from 850 to 150 hPa (Fig. 4). Similar analyses for the other two domains (not shown) also exhibited positive impact of profiler data at all levels at 3 h, but the greatest impact occurred over the profiler domain. In general, for all 3 domains, the impact decreased with increased forecast projection and fell to negligible levels by the 12-h forecast.

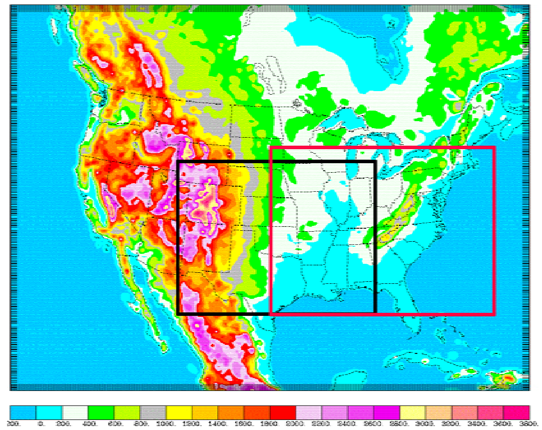

Fig. 3. The full RUC20 domain with model terrain elevation (m), profiler verification domain (black box), and downstream verification domain (red box).

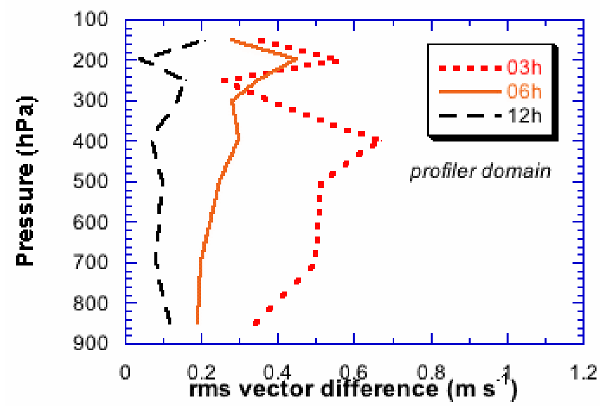

Fig. 4. Effects of profiler data denial on RMSE vector errors (m s^{-1}) over the profiler domain from RUC 3 – 12h forecasts for the 4-16 February 2001 period. Errors resulting from denying profiler data are largest for the 3h model forecasts and diminish with time.

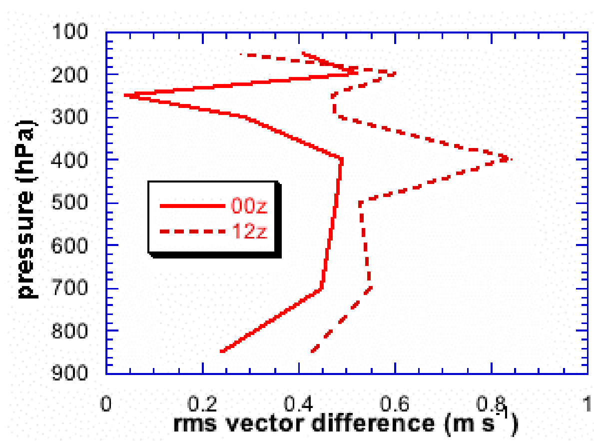

Fig. 5. Diurnal variability of profiler impact (EXP-P – CNTL) on RMSE 3-h wind forecast vector error in profiler domain for 0000 UTC and 1200 UTC.

A breakdown of profiler impact results by time of day over the profiler domain (Fig. 5) shows that the impact is stronger at 1200 UTC than at 0000 UTC, especially above 500 hPa. This is likely the result of a lower volume of aircraft data in the 0600-0900 UTC nighttime period than the 1800-2100 UTC daytime period. This breakdown also shows that the profiler data can contribute strongly to improving wind forecasts even at jet levels and that the accuracy of 3h jet-level wind forecasts valid at 1200 UTC over the United States is strengthened by wind profiler data.

Time series of profiler impact at selected mandatory pressure surfaces at each 12-h verification time are displayed in Fig. 6. Clearly, the impact from profiler data is more often than not positive from one time to the next, especially below 250 hPa. However, it also is apparent that significant day-to-day variations occur in the amount of impact. On several days, the impact is quite a bit larger than on most other days. This behavior suggests that the influence of profiler data on weather prediction depends upon the situation and underscores the importance of performing case studies to understand the manner in which these data actually influence NWP models. Case studies are discussed below.

Automated observations from commercial aircraft over the U.S. (mostly reported through ACARS) are another important source of asynoptic wind observations. In order to calibrate the relative impact of profiler and ACARS data on RUC short-range forecasts, the impact of data denial can be expressed in terms of percentage of forecast error. We first calculated percentage impact as

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

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 used. With this normalization, profiler data were found to reduce 3-h wind forecast error by 12-20% in the 400-700 hPa layer (Fig. 7).

A second normalization to determine data impact – the percentage of the total observational data impact provided by a single observation type – was computed as

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

where NODATA is the error from a model run in which no observations were made available to RUC over the 14-day period. This experiment was 'driven' only by the lateral boundary conditions and the previous RUC

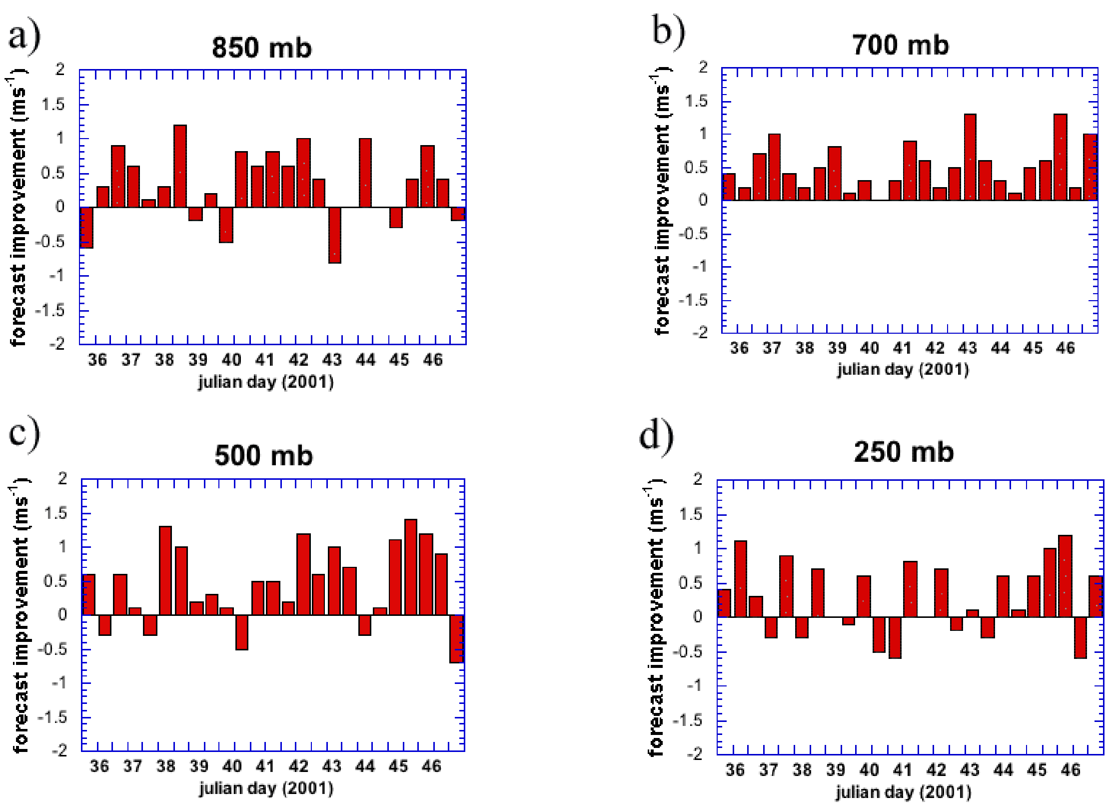

Fig. 6. Difference in 3-h wind forecast rms vector error score between EXP-P (no profiler) and CNTL (all data) from every 12-h verification time during 4-16 February 2001 test period at indicated mandatory isobaric levels.

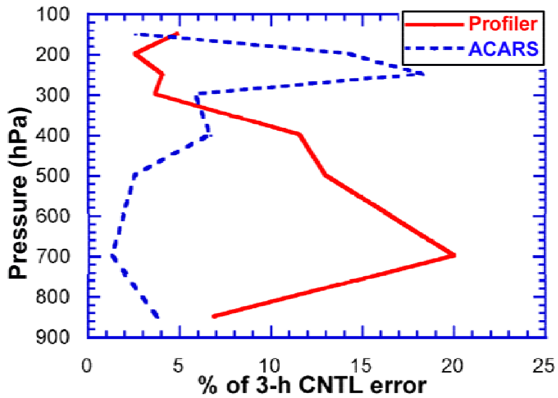

Fig. 7. Normalized impact from profiler and ACARS data denial experiments for RUC 3-h forecasts averaged for the 4-17 February 2001 test period over the profiler domain using the equation for x_1.

hourly analysis. Normalizing the errors as such revealed that the profiler data accounts for up to 30% (at 700 hPa) of the total reduction of wind forecast error from assimilating all observations. ACARS and profiler data offer trade-offs and are complementary to each other. The inclusion of aircraft data accounts for significant upper level forecast improvements in a shallower layer as much as 20% of the total 3-h forecast improvement at 250 hPa. Aircraft data provide high resolution data at flight levels, generally between 300-200 hPa, and a lesser but still significant number of ascent/descent profiles (Moninger et al. 2003). Profilers provide hourly (and even 6-min) wind profiles, and, of course, they are not dependent on flight schedules and route structures.

Regardless of how the impact is normalized, *these results show that a large proportion of the short-range wind forecast skill over the central U.S. in the RUC model is due to its use of wind profiler data and strongly suggest that similar benefits could be realized over much of the CONUS if a national network of profilers existed*. Short-range forecasts of other variables (geopotential height, relative humidity, and temperature) also benefit from the assimilation of wind profiler data (error reduction of 10–18%). The improvement in such forecasts (not shown) is an outcome of the multivariate effects of the RUC 3DVAR and subsequent interaction in the model.

3. CASE STUDIES

In this section, we present highlights from two case studies performed with the RUC20 model. These cases are treated in greater detail, and a third case is also discussed, in Benjamin et al. (2004).

3a.) The 3 May 1999 tornado outbreak

Forecasters at the Storm Prediction Center (SPC) in Norman, Oklahoma typically use profiler data to monitor evolving vertical wind shear, and for issuing both Convective Outlooks as well as watches; in fact, profiler data are often critical for determining the level of thunderstorm severity expected. The case of the Oklahoma-Kansas tornado outbreak of 3 May 1999 offers a prime example (Thompson and Edwards 2000; Edwards et al. 2002). In this event, forecasters observed considerably stronger winds at the Tucumcari, New Mexico, profiler site in the late morning of 3 May than were forecasted by any of the models. Extrapolation of these winds to the afternoon tornado threat area gave the forecasters confidence that the risk of tornadic storms with organized supercell storms would be the main mode of severe weather. Based on the likelihood of stronger vertical wind shear, the risk would be greater than the earlier forecasts based on numerical model forecast winds. With the knowledge gained from the profiler observations, SPC first increased the threat in the Day One Convective Outlook from “Slight Risk” to “Moderate Risk” by late morning, and then to “High Risk” by early afternoon. Response groups such as Emergency Managers regard such changes seriously, and the elevated risk levels result in a more dramatic level of response to a potential tornado threat. Having these higher risk levels forecast in advance by the SPC likely resulted in increased preparedness that made it easier to handle the severe outbreak of tornadoes that followed. In fact, the NOAA Service Assessment Report for the 3 May 1999 tornadoes noted the critical role that the profiler data had in improving the forecasts (Convective Outlooks) from the SPC, and recommended that the existing profiler network be supported as a reliable operational data source (National Weather Service 1999).

The 20-km RUC with a 1-h assimilation cycle (excluding VAD winds from WSR-88D radars) was rerun for the 24-h period 0000 UTC 3 May – 0000 UTC 4 May with (CNTL) and without (EXP) the profiler data to assess their impact on forecasts of pre-convective environment parameters and precipitation over Oklahoma. The 300-hPa winds in the RUC 6-h forecasts initialized at 1800 UTC were stronger in the CNTL experiment than the no-profiler run over a broad area including western Oklahoma and north-central Texas. In addition, the CNTL run produced ~ 50 $m^2 s^{-2}$ greater helicity values compared to the EXP run in central Oklahoma (values in the verifying analysis at 0000 UTC 4 May exceeded 250 $m^2 s^{-2}$). The tornadic storms formed in southwestern Oklahoma and propagated into the central part of the state as they matured, into an environment more favorable for supercell development according to the CNTL run.

CAPE forecasts derived from the CNTL run experiment were also more conducive to tornadic storm activity than in the EXP no-profiler run. Forecast CAPE differences between the CNTL and EXP runs valid at 2100 UTC are displayed in Figs. 8a and 8b, respectively, and the control analysis appears in Fig. 8c. Observed CAPE values are quite large (> 4000 J kg^{-1}) in the area where the first storms formed in southwestern Oklahoma. However, the forecast error for the EXP run indicates an area of strongly underforecast CAPE from west central Texas into southwestern Oklahoma. The CNTL run did not differ nearly as much from the analysis as the EXP run; the large improvement (by ~1000 J kg^{-1}) is primarily the result of a northwestward shift in the location of the axis of maximum CAPE (i.e., reduced phase error). Benjamin et al. (2004) show that dewpoint temperatures in the area of the underforecast CAPE in the EXP run were as much as 3ºC lower than in the CNTL run as the result of weaker southeasterly flow in central Texas. The resulting phase shift of the maximum CAPE in the control run with profiler data brought it closer in agreement with the region where the storms initiated, which resulted in a better forecast of convective precipitation over southwestern Oklahoma.

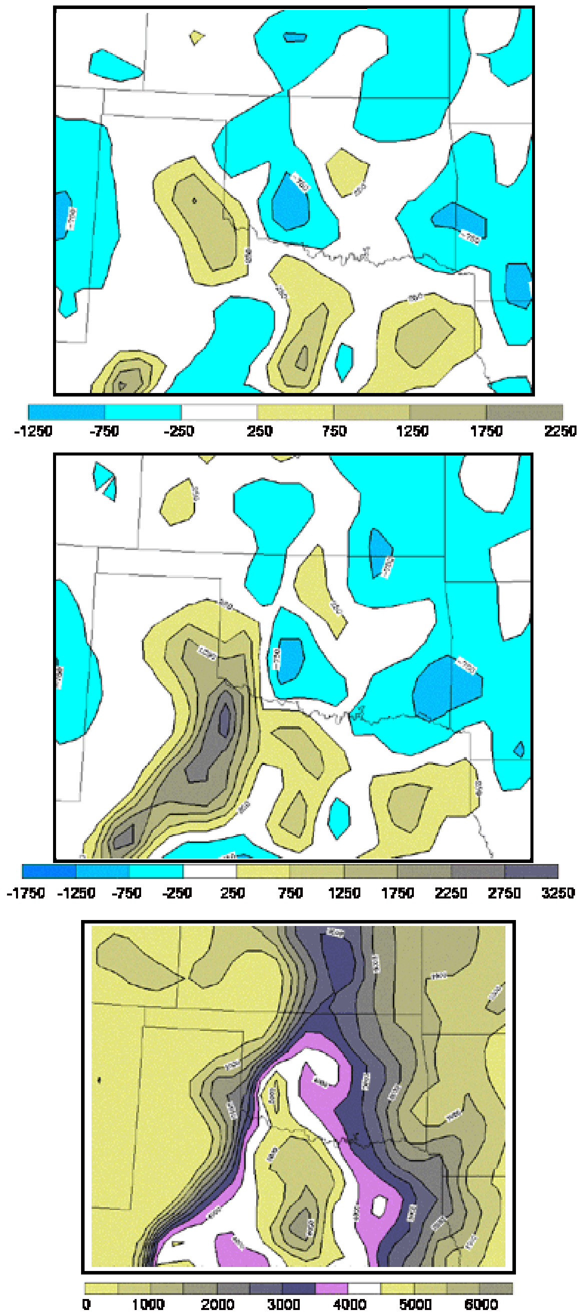

Fig. 8. 3-h CAPE forecast – analysis fields for CNTL (top) and EXP-P (middle). Analysis valid at 2100 UTC 3 May 1999 is displayed in the bottom panel.

3b.) The 8-9 February 2001 winter storm

The 20-km RUC was also used to examine the impact of profiler data for forecasts of a winter storm that brought sleet and freezing rain to south central and eastern Kansas, and heavy snow in central and northern Kansas over the two-day period of 8-9 February 2001. This event fell within the retrospective test period used for the data denial experiments described in section 2. Although this storm system was typical of winter storms in this area, some locations experienced 25 – 40 cm (10 – 16 in) total snowfall. Snow is a prognostic quantity explicitly predicted in the RUC via mixed-phase cloud microphysics (Benjamin et al. 2003a).

The synoptic situation at 0000 UTC 9 February consisted of a region of substantial upper-level forcing ahead of an approaching trough moving out of the Rockies and strong southerly flow at the surface south of a sharp, slow-moving cold front located from Kansas City to just west of Oklahoma City, stretching back to a surface low in western Texas. At this time, a band of heavy snow was moving east across west central Kansas, while sleet and freezing rain were intensifying over south-central Kansas. RUC precipitation forecasts for the period 0000 – 0300 UTC from the CNTL experiment were more intense over the region in south-central Kansas than in the no-profiler EXP-P experiment (not shown). A comparison of the 3-h forecasts from the two experiments showed that the location and curvature of the front was slightly different, with a northward bulge near the Kansas-Oklahoma border in CNTL, and a fairly uniform front about 100 km southward of this location in EXP. Although these differences are not exceptional, they were important enough to result in heavier forecast frozen precipitation to the north of the front in southern Kansas than in the CNTL experiment, resulting in better overall agreement with the observations. Vertical cross sections oriented north-south across the front displayed strong southerly cross-frontal flow of 25-30 m s^{-1} ascending upward over the front in Kansas in both experiments. However, the slantwise ascent was both sharper and deeper in the CNTL experiment, resulting in heavier precipitation about 200 km north of the surface front over southern Kansas. These differences within the frontal zone appeared to be responsible for the improved precipitation forecast in the CNTL experiment. These comparisons will be presented at the symposium.

4. USE OF PROFILER DATA IN NWS OPERATIONAL FORECASTING

The frequent use of profiler data by NWS forecasters is indisputable; mention of features seen using profiler displays on AWIPS (Advanced Weather Interactive Processing System) is common in the Area Forecast Discussions (AFDs) issued by NWS Weather Forecast Offices (WFOs). Forecasters typically use a time series display of hourly profiler winds on AWIPS, 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.

Profilers are located near to many WFOs in the Central and Southern Regions of the NWS. Recently, in a study conducted for a presentation at the National Weather Association's Annual Conference in October 2002, the NWS Southern Region Scientific Services Division sent a survey to WFOs within the Profiler Network to inquire how the profiler data are used in operations. The examples given of profiler use are typical of those seen over the years. An additional part of the survey asked each WFO to characterize the integration of profiler data into operations on a scale of 1 to 10, where "10" means all forecasters know when and how to use the data and do so when appropriate, while "1" means, "What's a profiler?" The average response was 9, indicating very high understanding of the potential for and use of profiler data in forecaster operations.

Even though the NOAA Profiler Network does not extend to the NWS Eastern Region, forecasters there have recently begun using data from a number of boundary layer profilers that have been deployed by other agencies. Although the data from these profilers are not available on AWIPS, forecasters have access to this data through the Internet and have found the data to be quite useful.

While the 3 May 1999 case discussed earlier may be the most dramatic example of profiler impact cited by the SPC, it by no means represents an isolated example of profiler use. Profiler data are not only frequently used at the SPC, but they are considered to be critical to their operations. Profilers are needed to reliably diagnose changes in vertical wind shear at lower levels as well as through a deep layer (through 6 km AGL), both critical to determining potential tornado severity. Profiler data are also used to better determine storm motion, critical in distinguishing stationary thunderstorms that produce flooding from fast moving severe thunderstorms that produce severe weather. Profilers help forecasters to better determine storm relative flows, and consequently the character of supercells. Profiler winds are critical for monitoring the low-level jet life cycle, an important factor in Mesoscale Convective System development and therefore the threat for flooding and/or severe weather. It is worth mentioning that profilers are unique in their ability to provide high-frequency full-tropospheric winds compared to radiosonde and VAD data. While Doppler radar-derived VAD winds also provide such resolution, they cannot monitor deeper level vertical wind shear, information that SPC deems critical to performing its forecast tasks. The SPC has added use of the 6-min profiler data since 2000 to better monitor conditions with rapidly evolving severe weather.

5. CONCLUSIONS

Average verification statistics from a 14-day test period indicate that the profiler data have a positive impact on short-range (3-6 h) forecasts over a central U.S. domain that includes most of the profiler sites as well as immediately downwind of the profiler observations. Averaged over time of day, the profiler data most strongly reduce the overall vector error in the troposphere below 300 hPa where there are relatively few automated aircraft observations. At night when fewer commercial aircraft are flying, profiler data also contribute strongly to more accurate 3-h forecasts at jet levels. For the test period, the profiler data contributed up to 30% (at 700 hPa) of the overall reduction of 3-h wind forecast error by all data sources combined.

Comparisons made between experiments in which profiler data were withheld and a second experiment in which all aircraft data were withheld show the complementary nature of the two types of observations. The picture that emerges from this study is a composite high-frequency observing system, with profiler observations contributing more to improvement through the middle and lower troposphere, and aircraft observations contributing more strongly at jet levels. Profiler observations fill gaps in the ACARS/aircraft observing system, with automated, continuous profiles 24 h per day with no variations over time of day or day of week (package 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 national security (as in the 11-13 September 2001 terrorist event) or as occurred in such severe weather events 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 do 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 conglomerate statistics that generally mask the stronger impact that occurs when there is active weather and a more accurate forecast is most important, and suggest the need to conduct case studies of profiler impact.

Two case studies were presented that illustrate the value of the profiler observations for improving weather forecasts. The first case study indicates that inclusion of profiler data in the RUC model runs for the 3 May 1999 Oklahoma tornado outbreak improved model guidance of convective available potential energy (CAPE), 850-300 hPa wind shear, 0-3 km helicity, and precipitation in southwestern Oklahoma prior to the outbreak of the severe weather. In the second case study, inclusion of profiler data on 8 – 9 February 2001 improved RUC precipitation forecasts associated with a severe snow and ice storm that occurred over the central plains of the United States. Assimilation of profiler data resulted in a better forecast of the strength of the lower level southerly flow overrunning a strong cold front, resulting in a narrow band of strong post-frontal upward motion. The outcome of this improved depiction of the transverse circulation in the frontal zone was a more accurate forecast of sleet and snow in Kansas 200 km north of the surface front. More case studies of this kind would likely provide more understanding of the ways in which wind profiler data affect atmospheric predictability.

Summaries of NWS forecaster use of profiler data in daily operations support the results from these two case studies and the statistical forecast model impact study. Profiler data are widely used and have become an important part of the forecast preparation process. Profilers produce the only full-tropospheric wind data available on a continuous basis over the U.S., and as discussed above, could possibly be the only data that would be available during extreme weather events or a national security event that would ground commercial aircraft. The critical improvements provided to short-range model forecasts and subjective forecast preparation from wind profiler data have been available only over the central U.S. and, to a lesser extent, downstream over the eastern part of the country. These benefits for forecast accuracy and reliability could be extended nationwide by implementation of a national profiler network, strengthening this recommendation made by the NWS Service Assessment Report for the 3 May 1999 tornado case. 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.

6. ACKNOWLEDGEMENTS

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