Impact of Network Wind Profiler Data on a 3-h Data Assimilation System

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Abstract

This paper examines the influence of data from the NOAA Wind Profiler Demonstration Network on a mesoscale data assimilation system. The Mesoscale Analysis and Prediction System is a 3-h intermittent data assimilation system configured in an isentropic-sigma framework. To measure the impact from profiler data on 3-h forecasts valid at 0000 and 1200 UTC, parallel runs with and without profiler data were verified against rawinsonde data. A sample case study is also presented to show the magnitude of the modifications at verification sites. In evaluations from case studies and statistics gathered over longer test periods, the profiler data improved the overall short-range forecasts in the study area. This improvement was most evident at 300 hPa where the root-mean-squared wind errors (averaged over the verification area) were reduced by 0.7 m s^{-1}, and corresponding height errors were reduced by 2 m. The 300-hPa improvement in short-range forecasts from the case study at individual rawinsonde stations was as large as 10 m s^{-1} for winds and 40 m for heights.

1. Introduction

The National Oceanic and Atmospheric Administration (NOAA) has installed a demonstration network of 31 wind profilers across the United States, concentrated mainly in the central part of the country (Chadwick and Hassel 1987) (Fig. 1). Data from the network profilers have been incorporated in a 3-h intermittent data assimilation system that uses isentropic coordinates in the free atmosphere and terrain-following (sigma) coordinates near the ground. This system is the Mesoscale Analysis and Prediction System (MAPS) developed at NOAA's Forecast Systems Laboratory (FSL).

Experiments with simulated (Kuo et al. 1987) and real (Cram et al. 1991) profiler data have indicated that a network of profiler data should be able to resolve features not readily discernible in the present rawinsonde (RAOB) network. Data from NOAA's Wind Profiler Demonstration Network should give added detail in time and space. This detail should improve asynoptic analyses and forecasts of wind and, indirectly, height, temperature, and moisture in that area and downstream. Heights and temperatures are influenced by wind data in MAPS through a multivariate optimum interpolation analysis. Any improvement in moisture forecasts will primarily arise from improvements to the vertical and horizontal velocity fields brought about by the inclusion of profiler data.

No previous tests have assessed the potential of wind profilers to improve analyses and forecasts based on currently available data. To what extent are profiler data redundant with data from RAOBs, aircraft, and surface stations? To answer this question, we describe a preliminary assessment using a series of parallel analyses and 3-h forecasts with and without profiler data. We use statistics from the parallel runs as well as an individual case study to illustrate the effects of the wind profiler data on the MAPS data assimilation system.

2. The Mesoscale Analysis and Prediction System

For the past three years, MAPS has been producing updated analyses over the United States every three hours. This cycle has been based primarily on automated aircraft reports {relayed via ACARS, [ARINC (Aeronautical Radio, Inc.) Communications, Addressing and Reporting System]} as well as surface observations (surface aviation observations and buoys) and wind profiler data. A few asynoptic RAOB profiles have also been available as well as the standard 12-h RAOB data. Wind profiler data are in the form of 1-h averages, while all other data are point measurements. Short-range forecasts with asynoptic data show consistent improvement over MAPS forecasts without asynoptic data and even over 12-h upper-tropospheric forecasts from the Nested Grid Model (NGM) run at the National Meteorological Center (NMC) without asynoptic data (Benjamin et al. 1991a,b). This result demonstrated that asynoptic aircraft data reports (now numbering up to 500 per hour over the United States) can produce significant improvements in short-range

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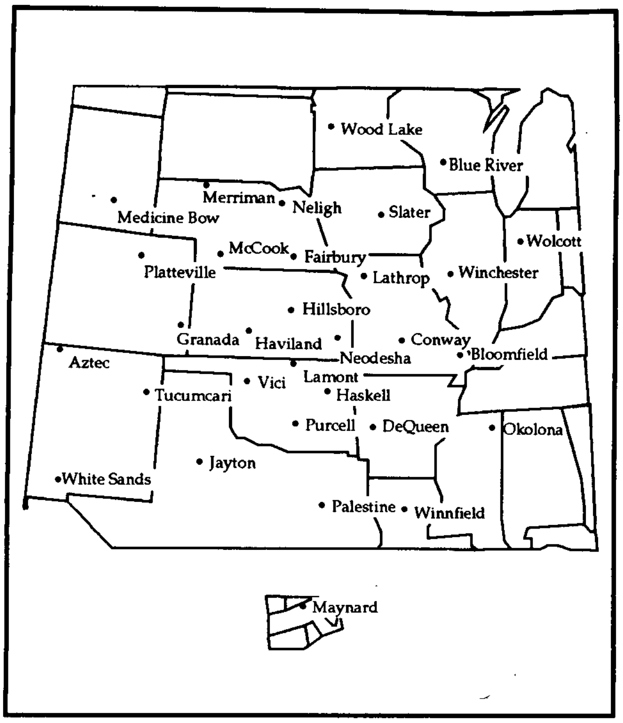

FIG. 1. The NOAA Wind Profiler Demonstration Network.

forecasts. This previous experience with MAPS establishes it as a valid testbed for evaluating information added by wind profiler data.

The components of MAPS are data ingest, data quality control, objective analysis, and a primitive equation forecast model, all designed in hybrid isentropic–sigma coordinates. In this hybrid vertical coordinate, terrain-following sigma coordinates resolve a layer of approximately 150 hPa near the ground, and isentropic coordinates resolve the remainder of the vertical domain. [The hybrid-coordinate assimilation system is described in Benjamin et al. (1991b), and isentropic versions of the assimilation system and analysis scheme are described, respectively, in Benjamin et al. (1991a) and Benjamin (1989).] Four-dimensional data assimilation is achieved by using the 3-h MAPS forecast as a first guess for the next analysis cycle. MAPS has been running a 3-h data assimilation cycle in real time since August 1988. Output from MAPS is available to operational forecasters on a prototype forecaster workstation at the Denver National Weather Service Forecast Office, and therefore the system has been designed to run in a real-time environment. The MAPS domain covers the contiguous 48 states and adjacent areas of Canada and Mexico. It is presently configured using a grid increment of 60 km in the horizontal and with 25 vertical levels (6 sigma, 19 isentropic). MAPS is also being implemented at NMC as a rapid update cycle that will produce high-frequency upper-air analyses and short-range forecasts.

Observations allowed to influence a particular grid point in MAPS analyses are selected from each of eight sectors shaped like pieces of a pie centered on the grid point (Benjamin 1989). Up to one station with a vertical profile of data (RAOB or wind profiler) and two single-level observations (aircraft or surface) per sector are allowed. At asynoptic times, this means that up to 8 profilers and 16 aircraft or surface reports can be used to influence a single grid point. For all variables, the differences between the observations and the first guess are analyzed; this analysis increment is then added to the first guess to produce the analysis. Expected observation errors used in MAPS are listed by Benjamin (1989) and are set such that the analysis draws quite closely to observations, including profiler wind observations.

It is possible to specify the degree of geostrophic coupling between mass and wind analysis increments. In the experiments described here, a geostrophic coupling coefficient of 0.5 was used, consistent with MAPS assimilation experiments showing improved performance with partial rather than full geostrophic coupling. This result was due to better resolution of smaller-scale motions, which, typically, are not always geostrophic.

3. Methodology

The effect of profiler data on short-range forecasts was measured by comparing results of two parallel data assimilation cycles. The first cycle, the control, was run with a complete dataset, including profiler data. In the second cycle, profiler data were withheld. Statistics were generated by verifying 3-h forecasts from each system against RAOBs. Since RAOBs are generally available only at 0000 and 1200 UTC, our comparison is limited to 3-h forecasts initialized at 0900 and 2100 UTC. Note that the error estimates in this paper include both observation error from the RAOBs and true forecast error.

The parallel cycles ran independently, so that cumulative influences of the profiler data are inherent in the control forecast. Our verification area shown in Fig. 2 includes the central United States. All the network profilers except Maynard, Massachusetts, are located within this verification area. Additional profilers were available through 30 March 1992 from Platteville, Colorado (50 MHz), and Stapleton Airport at Denver, Colorado (912 MHz).

In addition, error fields from case studies were used to determine how the profiler data influence horizontal structure in meteorological fields. As a benchmark,

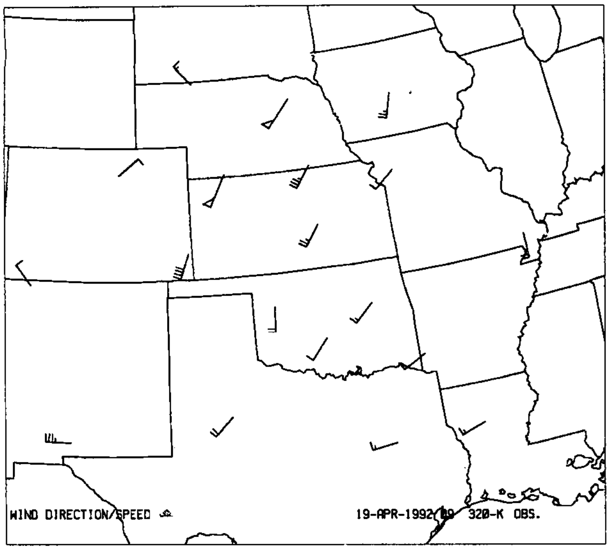

FIG. 2. The verification area, a subarea of the MAPS domain. Wind barbs denote the locations and observations (kts) on the 320 K analysis level of the profilers used in the control MAPS analysis from 0900 UTC 19 April 1992.

both runs were compared with the NGM forecasts valid at the same times. Similar methods were used previously (Benjamin et al. 1991a,b) to determine the effects of aircraft data on the resolution of mesoscale structure and the overall statistical performance of short-range forecasts.

4. Results

Several parallel cycles were run over the course of 1991–1992 as more profilers came on line. The effect on the wind fields in the MAPS system from the profilers was to bring the forecast closer to the verifying RAOBs at all levels, and the magnitude of the effect increased as the number of profilers increased. A similar trend was evident with height forecasts. Earlier results with only 13 profilers (Smith and Benjamin 1991) had shown negligible (0.1–0.2 m) impact, but when most of the network became available there was measurable positive impact at all levels. We focus here on the results from a 10-day period in January and a 14-day period in April 1992.

The impact from an average of 20 profilers over a 10-day period in January 1992 was consistently positive for short-range forecasts of winds and heights, marginally positive for temperatures, and inconsistent for relative humidity. Figure 3 shows a comparison of root-mean-squared (rms) wind differences between verifying RAOBs and the 3-h MAPS forecasts with and without profiler data and the benchmark 12-h NGM forecast. The control runs are better than the no-profiler runs at all levels. Winds from both MAPS runs generally verify better than the 12-h NGM wind forecasts, especially above 500 hPa, indicating that assimilation of asynoptic observations is improving short-range forecasts. The larger margin of improvement aloft in the MAPS runs is mainly due to the ACARS winds, but even with the large numbers of ACARS observations available, the profilers add as much as 0.7 m s^{-1} at 300 hPa to the improvement. This is more easily seen in Fig. 4, which depicts the rms vector error differences between the parallel MAPS runs. A positive value in this diagram indicates positive impact from profiler data at a particular level. The standard deviation of differences for heights (Fig. 5) also shows a consistently positive effect from the profilers where the maximum was over 2 m at 150 hPa, and a secondary maximum was 2 m at 300 hPa. Statistics for temperature forecasts show a very small but positive impact, of about 0.1 K (not shown), whereas those from relative humidity forecasts vary from level to level by about ±2% (not shown). In general, the level that showed the greatest improvement for all fields was

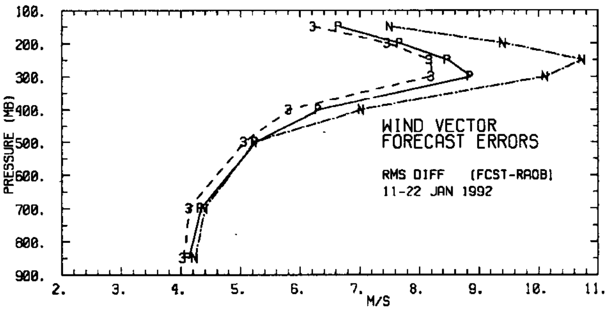

FIG. 3. Wind rms vector difference (m s^{-1}) between RAOBs and NGM 12-h forecast (N), MAPS 3-h forecast (3), and MAPS 3-h forecast without profilers (W) at mandatory pressure levels for 11–22 January 1992.

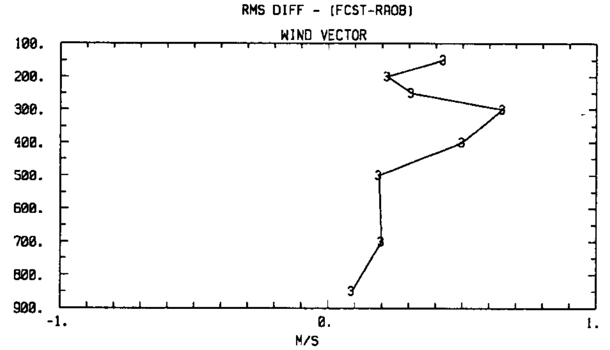

FIG. 4. Difference between the MAPS 3-h control forecast and MAPS 3-h forecast without profilers for the wind rms vector difference (m s^{-1}) between RAOBs and forecasts at mandatory pressure levels for 11–22 January 1992. (Values to the right of the zero line denote a positive impact by the profiler data.)

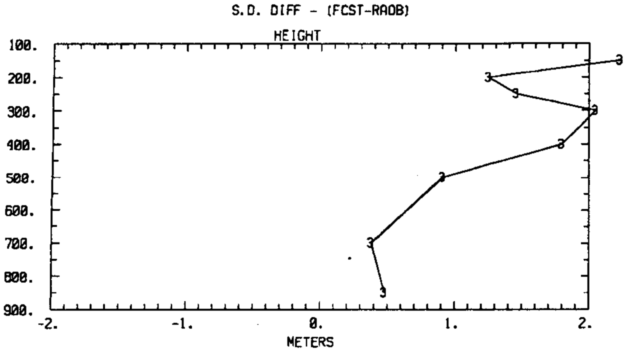

FIG. 5. Difference between the MAPS 3-h control forecast and MAPS 3-h forecast without profilers for the height standard deviation difference (m) between RAOBs and forecasts at mandatory pressure levels for 11–22 January 1992.

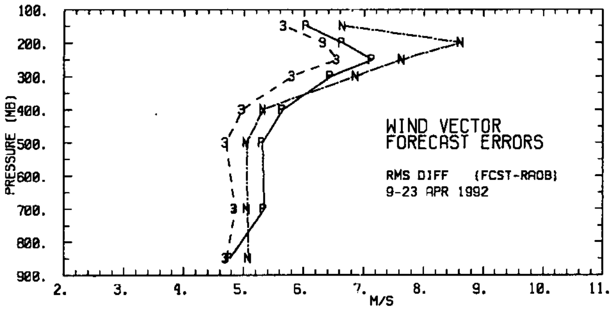

FIG. 6. Same as Fig. 3 but for 9–23 April 1992.

300 hPa. This "peak" level for improvement is found in the layer between levels with large volumes of other kinds of asynoptic observations: aircraft reports in the upper troposphere, most numerous around 250–200 hPa, and surface reports near the ground. Since wind forecast errors generally increase upward toward a peak at jet levels, the greatest potential for improvement due to profiler data is shifted up to the levels just below 250–200 hPa, where the aircraft data have already shown a sharp improvement. Since height forecast errors increase with height, the potential for improvement from profiler data also increases with height, except for the 300–200-hPa layer where aircraft data are plentiful.

For the springtime study, based on two weeks in April 1992, an average of 22 profilers were available. The impact of the profiler data was similar to the wintertime (January) study, where the profiler data improved the wind and height forecasts at every level. A stronger, more consistent effect on wind forecasts (Fig. 6) was apparent for the 300–700-hPa layer, where profiler data allowed the 3-h MAPS control forecast to improve on the 12-h NGM forecast. This effect is more apparent in Fig. 7, which compares the parallel runs. In contrast to the January results, the April plot shows a substantial (>0.5 m s^{-1}) contribution from the profilers through a large depth of the troposphere. This contribution may be calibrated against the difference in 12-h and 24-h 250-hPa wind forecasts from the NGM (DiMego et al. 1992), which is about 1 m s^{-1}. The heights (Fig. 8), while better through the depth of the troposphere, show less effect in the upper troposphere in April than in January, perhaps showing the decreased variability in the springtime weather patterns. Examples of annual variability in forecast errors are given by Kalnay et al. (1990). The level of peak improvement for both variables for this time period was 400–500 hPa. Results for both temperature and relative humidity statistics (not shown) were nearly identical to the January data, again showing little effect from the inclusion of the profiler data.

5. Case study

We examine the impact of the profiler data for 1200 UTC 19 April 1992, a case with a deep upper-level trough over the central United States and a blizzard in the Dakotas. The parallel no-profiler cycle had been running independently for the previous 48 hours. This day was chosen by looking at the daily statistics generated by the verification program. On this particu-

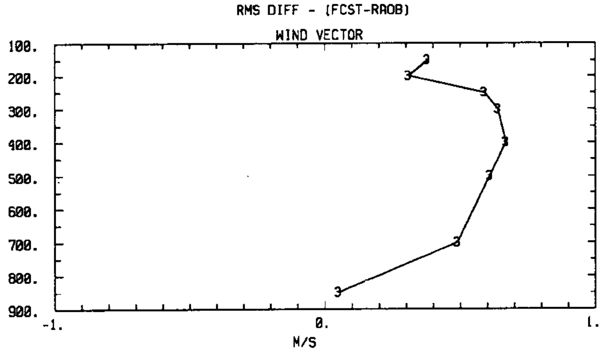

FIG. 7. Same as Fig. 4 but for 9–23 April 1992.

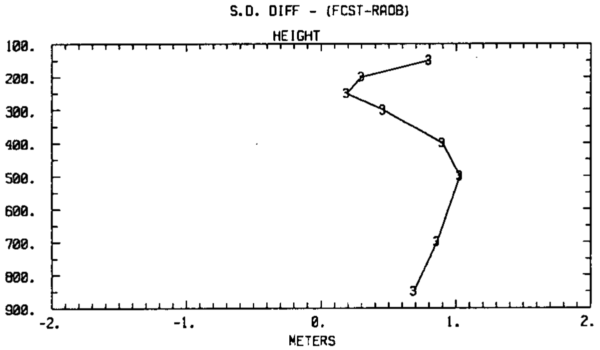

FIG. 8. Same as Fig. 5 but for 9–23 April 1992.

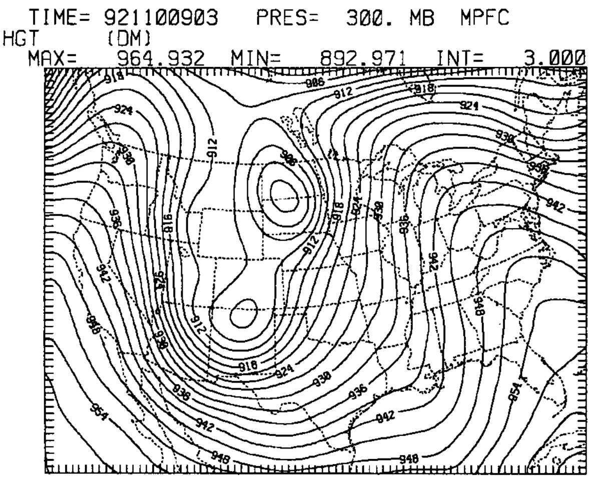

Fig. 9. The 3-h height (dam) forecast for 300 hPa from 0900 UTC 19 April 1992 (Julian date 92110) valid at 1200 UTC from the MAPS control run.

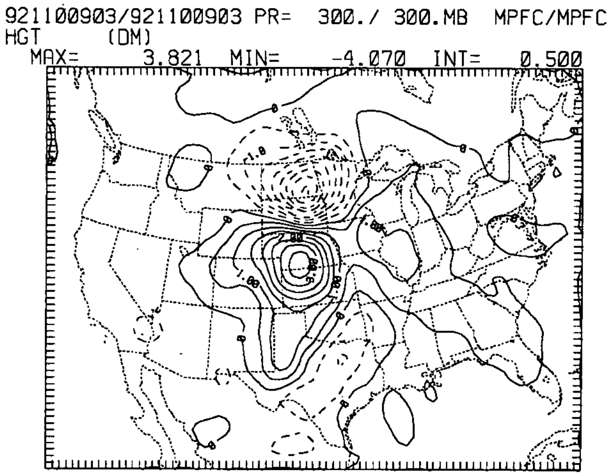

Fig. 11. Differences (dam) between control and no-profiler 3-h forecasts for heights at the 300 hPa level valid at 1200 UTC 19 April 1992.

lar day, the improvement in the wind field (rms vector error) over the verification area due to the profilers peaked at 2.5 m s^{-1} at 300 hPa. Significant improvements (over 1 m s^{-1}) occurred from 500 to 250 hPa. In general, improvements in quiet weather regimes averaged around 0.5 m s^{-1} rms for winds and 1 m for heights. When a feature such as the upper-level wave seen in this case moves into the verification area, the effect of the profiler data becomes more pronounced. This was seen in both the April and January test periods. For the April period, "active" cases were identified by relatively large values of 12-h persistence forecast error for 300-hPa winds. These cases (seven) showed a mean improvement at 300 hPa of 0.9 m s^{-1} compared to 0.7 m s^{-1} for the entire April sample.

The 3-h height forecast for 300 hPa (Fig. 9) valid at 1200 UTC (initialized at 0900 UTC) from the control run shows the wave with two closed centers; one in the western Dakotas and the other on the Colorado–New Mexico border. The forecast from the no-profiler run (Fig. 10) shows a similar pattern, but the northern center is somewhat less intense. The height differences (Fig. 11) between the two 3-h forecasts show that the addition of profiler data not only deepened the low but also adjusted the location slightly eastward. The wind differences (Fig. 12) are comparable to the geostrophic wind difference implicit in Fig. 11 but exhibit more small-scale detail. The magnitude of the wind differences reaches nearly 14 m s^{-1} over northern Nebraska.

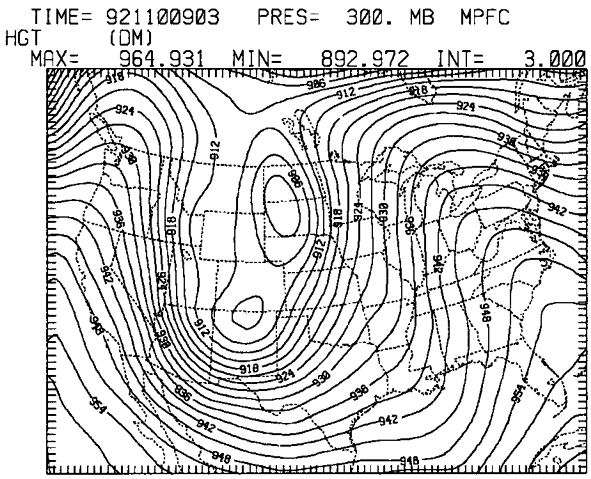

Fig. 10. Same as Fig. 9 except for the MAPS no-profiler run.

In this particular case, as in the overall statistics, the inclusion of profiler data resulted in an improved short-range forecast. Errors of wind, temperature, dewpoint, and height at individual rawinsonde stations at 1200 UTC are shown for 3-h forecasts with and without profiler data, respectively, in Figs. 13 and 14. The control forecast (with profiler data) verified more closely with the height observations. This "first guess" was only 2 dam off from the observed 300-hPa height at North Platte, Nebraska, where the no-profiler run had an error of 6 dam. Similarly, at Dodge City, Kansas, the control run was 3 dam closer to the observed value. Wind forecasts were also improved in the control run, with significantly lower errors present at many stations. Temperature and dewpoint again show little overall effect.

It is noteworthy that the area of improved forecasts was more extensive than the area of the profiler network itself for both heights and winds, especially to the north of the network area. Since the prevailing winds were southerly, this effect appears to be due to advection of features that were better resolved by

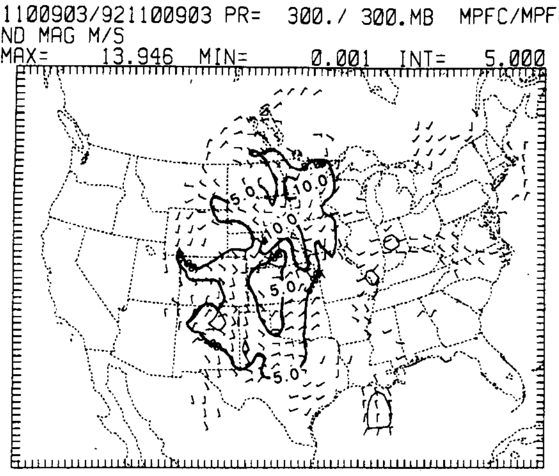

FIG. 12. Wind vector differences (m s⁻¹) between control and no-profiler 3-h forecasts at the 300 hPa level valid at 1200 UTC 19 April 1992. Barbs are plotted for grid points with differences greater than 2.5 m s⁻¹, and isotachs are drawn at 5 m s⁻¹ intervals.

assimilating the profiler data at a 3-h frequency. In this case, the downstream effects appear to be limited to profiler data assimilated within the last 12-h period. Upstream effects of varying magnitude have been observed by the authors in other cases. These upstream and downstream effects do not often extend much beyond the 12-h advection distance in short-range MAPS forecasts because differences are constrained by common lateral boundary conditions and common nonprofiler data. In the no-profiler runs, forecast errors may be larger in and downstream of the network, but these errors tend to be eventually corrected by the nonprofiler data in later assimilation cycles. This may be particularly true for the United States demonstration network, which is surrounded by a data-rich region. Differences between profiler and no-profiler forecasts, however, may be expected to carry much farther downstream in longer duration forecasts with larger domain models; such comparisons have not been performed in this study.

6. Conclusions

Results from parallel data assimilation cycles, with and without profiler data, indicate that the wind profiler demonstration network, though incomplete at the time of the tests, was already providing consistent statistical improvement in short-range (3-h) numerical forecasts of winds and heights over the midwestern United States. These tests, performed using the MAPS assimilation system developed at NOAA/FSL, demonstrate the incremental improvement when profiler data are added to the asynoptic data already present in this area, most notably commercial aircraft data relayed via ACARS and surface observations. Despite competing with these other types of data, profiler data were able to produce additional improvements in short-range forecasts of winds and heights. These tests were performed for 10–14-day periods in January and April 1992, during which times data were received from an average of 20–22 profilers.

The peak improvement in wind forecasts was near

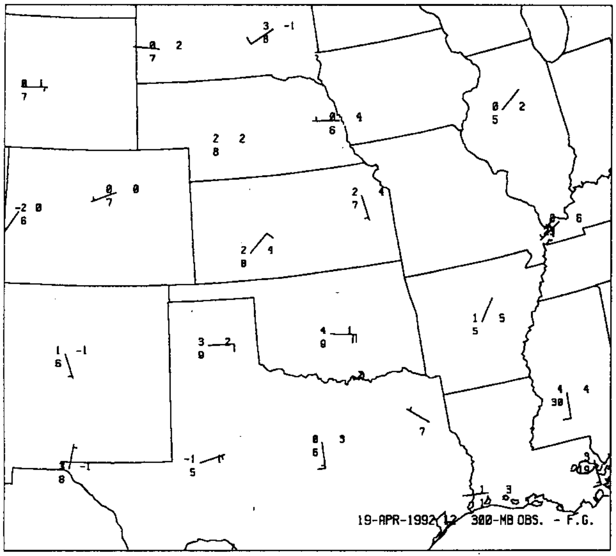

FIG. 13. Station plots of differences of temperature (°C), dewpoint (°C), height (dam), and wind (m s⁻¹) between verifying RAOB sites and the 3-h MAPS control forecast (first guess) at 300 hPa valid at 1200 UTC 19 April 1992.

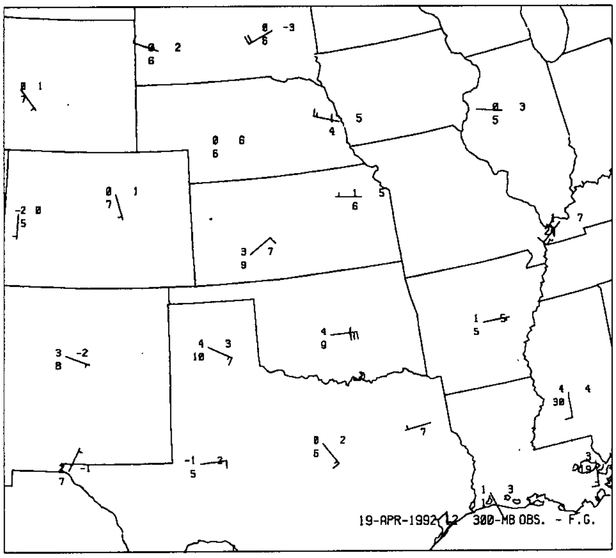

FIG. 14. Same as Fig. 13 except for the 3-h MAPS no-profiler forecast.

300 hPa, just below the layer where aircraft reports are clustered. Positive impact of profiler data was stronger on days with significant weather systems passing through the network, indicating that the extra temporal and spatial resolution provided by the network improves the definition of these systems. This result might have been expected, given that large-scale synoptic systems are already well resolved by the RAOB network, and, for this type of weather pattern, the profiler data will be more redundant than if there is more small-scale variability.

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