NOTES AND CORRESPONDENCE

Operational Systems for Observing the Lower Atmosphere: Importance of Data Sampling and Archival Procedures

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23 June 1989 and 1 June 1990

ABSTRACT

A brief field project was conducted during July 1988 to assess the potential for Next Generation Weather Radar (NEXRAD), 404-MHz radar wind profilers, and digital sounding systems to monitor the low-level wind field during clear-air conditions. The low-level jet was chosen as the phenomenon of interest because it is neither well sampled nor resolved by the current upper-air network, yet it is a common feature of mesoscale convective system and severe thunderstorm environments. Data were collected under quiescent synoptic conditions during several low-level jet events using a 10-cm NEXRAD-like Doppler radar and a digital sounding system colocated in Norman, Oklahoma. These data suggest that the areal-averaged horizontal winds calculated from the Doppler radar data using the Velocity Azimuth Display (VAD) technique are comparable with the winds observed using a digital sounding system, except under weak wind conditions. However, the vertical spacing of 304 m (1000 ft) between levels of horizontal VAD calculated winds, as currently proposed for NEXRAD, may not be of sufficient resolution to document the detailed wind structure of these events. The height of the maximum wind speed of the low-level jet on all days studied was below the planned lowest observation range gate of the 404-MHz radar wind profiler, indicating that a combination of NEXRAD and profiler data might be needed to sample the important wind field structure of the lower atmosphere. Lastly, the National Weather Service rawinsonde data processing software affects the vertical resolution of the low-level wind field in operational, and therefore archived, upper-air soundings. The procedure used to calculate NWS 1000 ft winds actually damps the wind speed profile and artificially increases the height of the level of maximum wind speed associated with the low-level jet. The appropriateness of these highly smoothed 1000 ft winds for input into sophisticated mesoscale weather prediction models should be considered.

1. Introduction

The Next Generation Weather Radar (NEXRAD), 404-MHz radar wind profilers, and digital sounding systems are three new operational observing systems that will be installed across the United States by the mid-1990s. NEXRAD and radar wind profilers can be used to monitor the wind field almost continuously, while digital sounding systems can be used to provide a more detailed sampling of atmospheric structure. Rabin (1989) showed that the low-level wind field determined from Doppler radar data can be used with a simple model to deduce changes in boundary layer thermodynamic structure. This suggests that data from NEXRAD and radar wind profilers may help determine boundary layer thermodynamic structure and vertical motions between synoptic rawinsonde launches. Accurate knowledge of boundary layer evolution could lead to improvements in forecasts of severe convection, since changes in low-level wind shear, temperature, and moisture are directly related to severe storm development (Davies-Jones 1984; Doswell 1985; Lilly 1986a,b; Weisman et al. 1988).

Numerical guidance for severe weather events may improve greatly during the next decade as sophisticated mesoscale weather prediction models are run routinely in real-time. The National Meteorological Center (NMC) plans to develop a mesoscale model with 30 or more vertical levels and horizontal resolution of 30–40 km (Bonner 1989). Indeed, the NMC eta-coordinate regional model has produced more accurate predictions at mesoscale horizontal resolutions of 40–50 km than with the larger-scale resolution of 80 km for some weather events (Black and Mesinger 1989). The Pennsylvania State University (PSU) and the National Center for Atmospheric Research (NCAR) have developed a mesoscale numerical weather prediction model that has shown great potential in the simulation of severe convective weather events over the United States (Zhang and Fritsch 1986, 1988; Zhang et al. 1989). A high-resolution boundary layer was used in these simulations to model more realistically environments where strong vertical gradients of temperature, humidity, and momentum often exist or develop (Anthes et al. 1987). Since early 1989, a version of the PSU/NCAR model has been operating in a real-time

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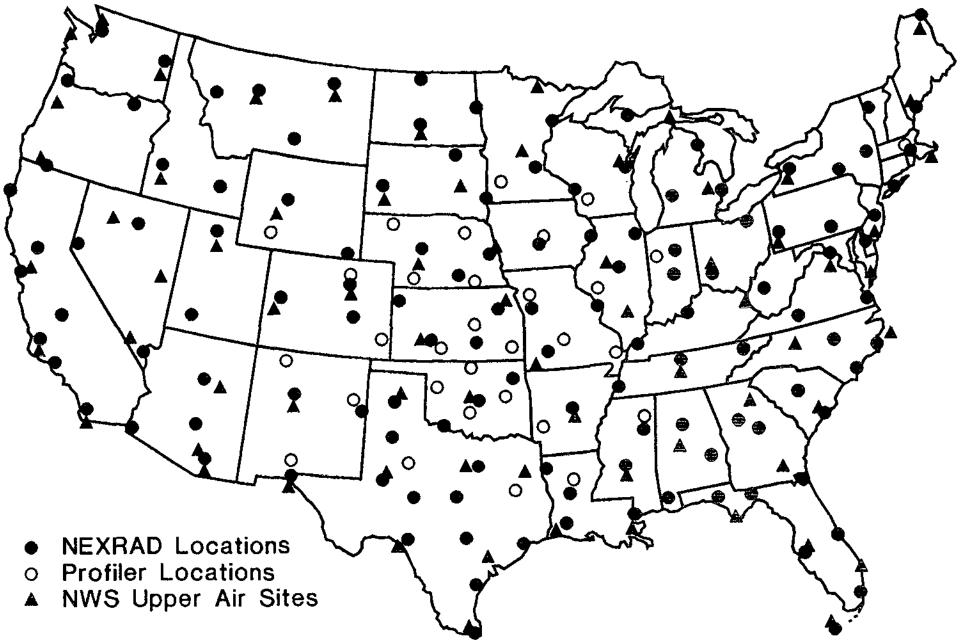

FIG. 1. Locations of the current upper-air sounding network sites (triangles), the proposed NEXRAD network sites (solid circles), and the 404-MHz radar wind profiler demonstration network sites (open circles).

mode at The Pennsylvania State University to support research, teaching, and public service activities (Warner and Seaman 1990). The real-time use of mesoscale models emphasizes the importance of accurate boundary-layer wind and thermodynamic information for model initialization that could be provided by NEXRAD, radar wind profilers, and digital sounding systems.

The 10-cm NEXRAD is scheduled to be deployed by the National Weather Service (NWS) across the United States during the early 1990s (Fig. 1). The radar will be used to sample the winds in the planetary boundary-layer and lower troposphere during clear-air conditions (Rabin and Zrnić 1980), in addition to monitoring precipitation and precipitation motion (see Doviak and Zrnić 1984). It is not possible at present to sample mesoscale variations in boundary layer wind and thermodynamic structure with the current, widely spaced, upper-air network (Fig. 1), but the more dense NEXRAD data network will be able to detect low-level, mesoscale wind features that may have a significant influence on the initiation and subsequent evolution of convection.

The second new observing system expected to become operational during the next few years is the 404-MHz radar wind profiler, with a 30-unit demonstration network being installed in the central United States (Chadwick 1988; see Fig. 1). Initially, these profilers are planned to sample the horizontal winds from 0.5 to 16.25 km above ground level (AGL) at 0.25 km vertical increments; instruments to monitor surface conditions are planned for a limited number of profiler sites. Winds from the profiler network will be available routinely to the operational and research communities, averaged at hourly intervals. Profiler wind observations from a regularly spaced network are expected to have a positive impact on short-range numerical forecasts, as demonstrated by Kuo et al. (1987) in a series of observing system simulation experiments.

Digital upper-air sounding systems have been available to the meteorological community since the late 1980s. These systems provide data every 10 seconds or less, producing high-resolution, vertical profiles of temperature, humidity, wind speed, and wind direction. One such system is the Cross-chain Loran Atmospheric Sounding System (CLASS) developed at NCAR (Lauritsen et al. 1987). Another is the Automatic Radio Theodolite System (ARTS) installed by the National Weather Service in 1986[1] at all upper-air observing sites (Fig. 1). The significant and mandatory temperature and humidity data, and the 1000 ft (304 m) winds that are distributed operationally, are extracted from the raw, high-resolution ARTS data by a data processing routine. These processed data are apparently the only data available retrospectively to re-

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[1] A new version of ARTS, called MicroART, became operational in April 1990. The transmitted coded message of MicroART data is produced under the same guidelines as ARTS data. Thus, the real-time significant and mandatory temperature and humidity data, and the 1000 ft wind data transmitted from the MicroART data should be equivalent to those reported in this paper.

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searchers [see Schwartz (1989) for a complete discussion].

A small field project was conducted during July 1988 to assess the potential for these observing systems to monitor the low-level wind field routinely during clear air conditions. The low-level jet, a nocturnal maximum of wind speed in the planetary boundary layer, is a common feature of the Great Plain's severe weather environment (Bonner 1966; Miller 1972; Uccellini and Johnson 1979; Maddox 1983). Since the low-level jet is not well sampled by the current upper-air network, it provides a good evaluation framework test for comparing data from a NEXRAD-like Doppler radar and a digital sounding system. The likelihood that the 404-MHz radar wind profilers will be able to sample fully the detailed structure of these summertime low-level jet events also is examined.

In sections 2 and 3 we describe the data collection and processing procedures used during the field program, and show examples from two low-level jet events. We discuss in section 4 the current and proposed operational data collection and processing techniques of the National Weather Service for upper-air and NEXRAD VAD wind data. A summary and discussion of the findings are given in section 5.

2. Data collection and processing

Data were collected using a 10-cm NEXRAD-like Doppler radar and the CLASS colocated in Norman, Oklahoma. Operations were initiated in the late afternoon on days when a low-level jet was expected to develop under relatively quiescent synoptic conditions; operations continued through the night and were concluded late the following morning. Doppler radar data were collected every 30 minutes in a volume scan at 0.5° increments from 0° to approximately 8° elevation. The highest elevation angle used was that which would sample adequately the entire depth of coherent Doppler-velocity returns received from the clear air (Zrnić et al. 1986). In addition, CLASS soundings were launched at approximately 90 minute intervals during each low-level jet event to capture changes in the wind, temperature, and moisture structure of the lower troposphere.

Horizontal winds were determined every 50 m in the vertical from the Doppler radar data using the Velocity Azimuth Display (VAD) technique. This technique calculates the discrete Fourier transform of the radial velocities measured by the Doppler radar at a selected distance from the radar, or slant range, and at a fixed elevation angle (Browning and Wexler 1968; Rabin and Zrnić 1980). The calculated harmonics are then used to obtain the areal-averaged horizontal wind speed, and wind direction. The radial velocities used in the VAD calculations were averaged from three adjacent range bins. This averaging reduces the scatter of Doppler velocity measurements caused by the weak return in clear air. When there were two or more VAD calculated winds for the same height, the one with the lowest calculated root-mean-square error (Rabin and Zrnić 1980) was accepted. Calculated winds with root-mean-square errors greater than 5.0 m s^{-1} were rejected.

3. Two low-level jet events

The temporal evolution of the wind speed profile during the low-level jet on 6–7 July 1988 is shown in Fig. 2. The wind speed increased to a maximum value of 15.0 m s^{-1}, 327 m AGL by 0535 UTC 7 July; wind speeds increased at all levels below 1700 m. However, after 0535 UTC 7 July a dramatic decrease in wind speed was observed between 1000 and 1700 m (e.g., the wind profiles at 0830 and 1127 UTC 7 July), coincident with the development of a strong inversion below 1700 m sampled by the 1127 UTC 7 July sounding (Fig. 3). The temperature increased as much as 1.3°C between 1100 and 1960 m AGL (870 and 790 mb) during the 6-hour interval from 0535 to 1127. Large-scale sinking motion, coupled with cooling near the surface, may have caused the development of this pronounced inversion. The slowly descending inversion appeared to restrict the vertical extent of the low-level jet.

On 29 July 1988 the wind speed increased to a maximum value of 21.4 m s^{-1}, 471 m AGL by 0801 UTC 29 July (Fig. 4). Thunderstorms developed in central Oklahoma late on 28 July, and a surface outflow from one thunderstorm passed through Norman shortly before the first sounding launch at 0044 UTC 29 July

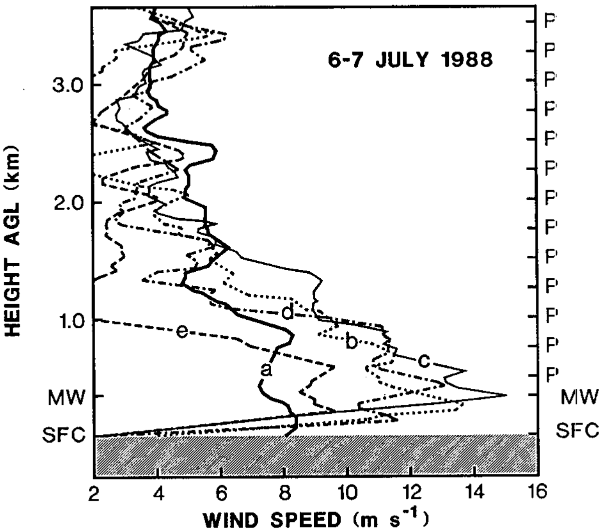

FIG. 2. Profiles of CLASS observed wind speed vs height above ground level from (a) 2331 UTC 6 July, (b) 0229 UTC 7 July, (c) 0535 UTC 7 July, (d) 0830 UTC 7 July, and (e) 1127 UTC 7 July. MW denotes the level of maximum wind speed. P's indicate the 404-MHz radar wind profiler range gates.

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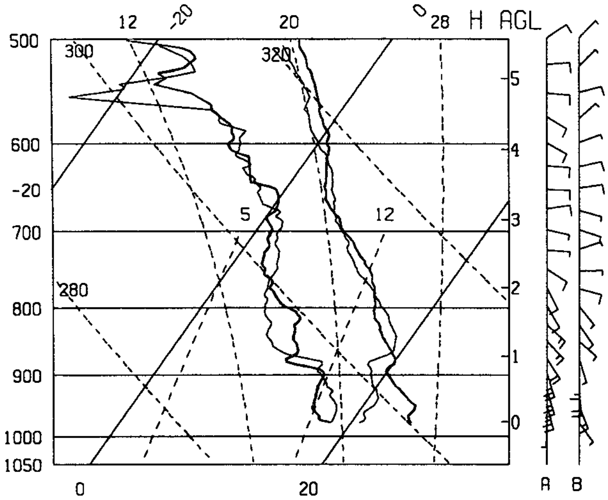

FIG. 3. Skew *T*-log *p* plot for Norman, Oklahoma, CLASS upper-air sounding from 0535 UTC 7 July 1988 (thick solid, wind profile denoted by A) and 1127 UTC 7 July 1988 (thin solid, wind profile denoted by B). Long-dashed lines are constant θ_w (°C), and short-dashed lines are constant mixing ratio (g kg^{-1}).

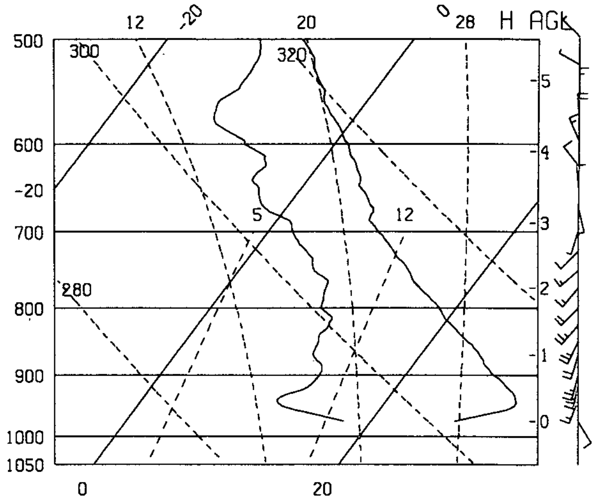

FIG. 5. Skew *T*-log *p* plot for Norman, Oklahoma as in Fig. 3, but for 0044 UTC 29 July 1988.

(Fig. 5). The subsequent development of a strong low-level jet, after the environment was disturbed by a thunderstorm outflow, was not expected. This illustrates one advantage of monitoring the low-level winds routinely.

A comparison of the VAD winds with the CLASS winds is shown in Fig. 6 for the two cases. The height of the VAD calculated maximum wind speed was slightly higher than determined by CLASS, while the maximum wind speed was slightly less than determined by CLASS on 6–7 July 1988 (Fig. 6a). However, the wind speeds captured by both these observing systems agree to within 1 m s^{-1} at most levels below 1700 m. The wind directions calculated using the two systems were within 5° of each other below 1000 m (Fig. 6c). Above 1000 m the differences in wind direction between the two systems average about 20°. A comparison of Fig. 6a with 6c shows that the larger differences in wind direction between the two observing systems occurred at and above the level where the wind speeds rapidly decreased with height, and above the region where the winds were unidirectional. Both the wind speeds and directions calculated from the systems deviate from each other when the wind speeds are less than 5 m s^{-1}.

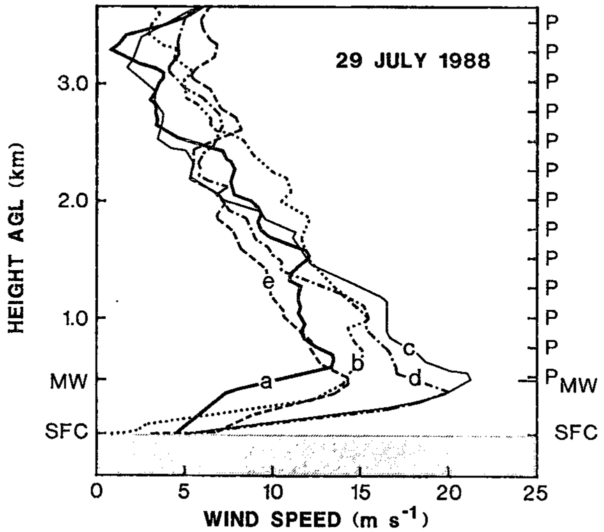

FIG. 4. Profiles of CLASS observed wind speed vs height above ground level from (a) 0044 UTC 29 July, (b) 0335 UTC 29 July, (c) 0801 UTC 29 July, (d) 1057 UTC 29 July, and (e) 1358 UTC 29 July. MW denotes the level of maximum wind speed. P's indicate the 404-MHz radar wind profiler range gates.

Agreement between the VAD and the CLASS wind speeds on 29 July 1988 was very good (Fig. 6b). With this stronger low-level jet, the height of the VAD-calculated wind maximum compared well with the value determined by CLASS. The wind speeds calculated by the two systems were generally within 1 m s^{-1} of each other, although the VAD wind directions deviated as much as 15° from those obtained from CLASS (Fig. 6d).

An examination of other simultaneous measurements collected during this experiment indicate similar behavior. Generally, the magnitude of the winds from the two systems compare well, while the phase discrepancy typically varies from 5° to 15°. The trend is for the VAD-calculated winds to be shifted in the same direction as the winds are turning with height (see Figs. 6c,d). Situations where a substantial depth of the atmosphere is characterized by unidirectional winds, such as below 1000 m AGL at 0830 UTC 7 July (Fig. 6c), often produce good agreement between the VAD and CLASS winds.

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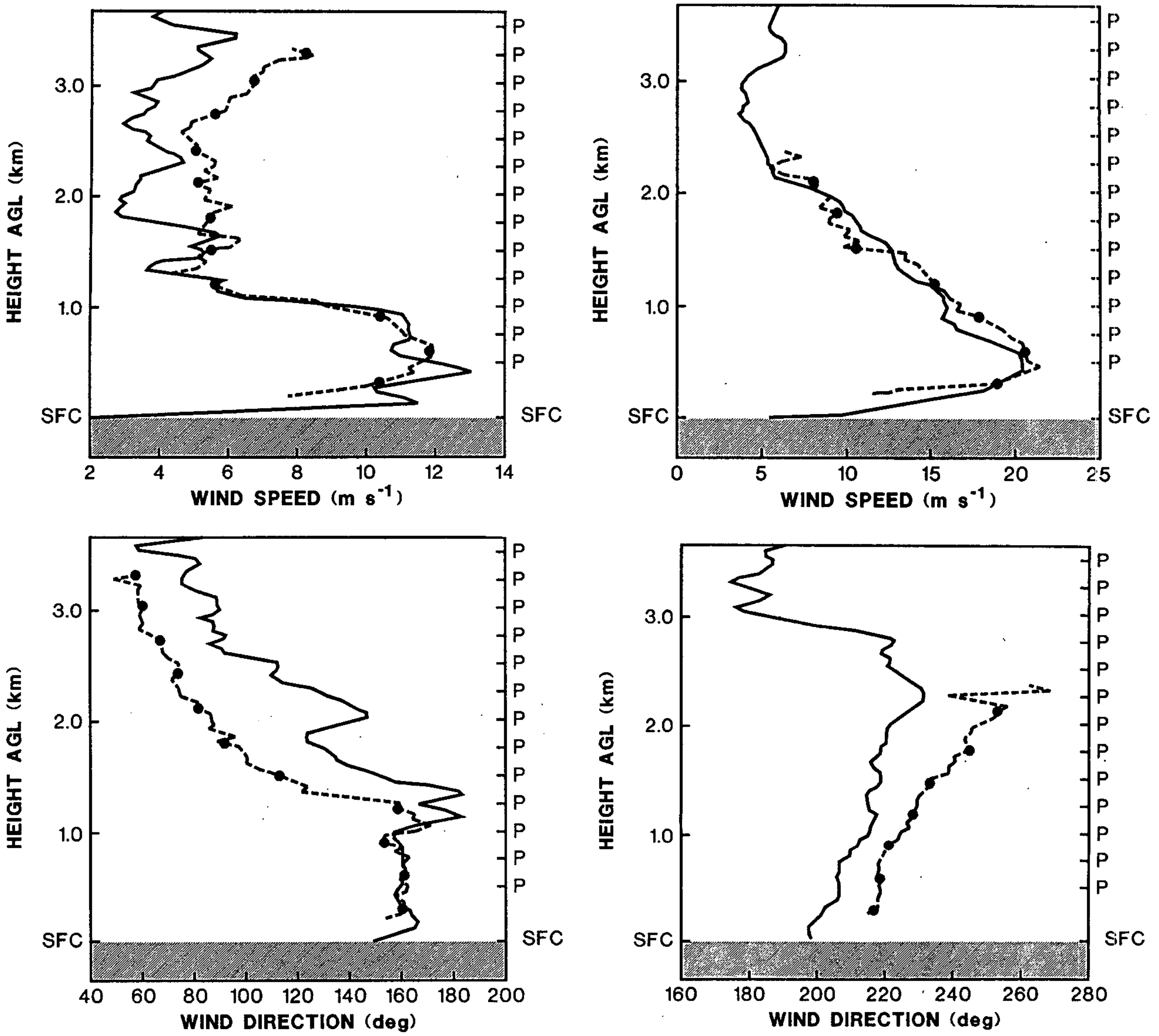

FIG. 6. Profiles of CLASS (solid) and VAD (dashed) calculated wind speed vs height above ground level for (a) 0830 UTC 7 July 1988 and (b) 0930 UTC 29 July 1988. Profiles of CLASS (solid) and VAD (dashed) calculated wind direction vs height AGL for (c) 0830 UTC 7 July 1988 and (d) for 0930 UTC 29 July 1988. Circles along the dashed line indicate the proposed sampling levels of the NEXRAD VAD wind algorithm. P's indicate the 404-MHz radar wind profiler range gates.

The precise explanation for these observations remains illusive. The CLASS quality control procedures and an examination of the time of arrival data indicate no obvious errors in the rawinsonde wind data. However, Oklahoma is in an area of weak Loran signal reception, which may account for some of the observed differences. Radar siting or orientation errors can be ruled out, as one would expect a consistent azimuthal shift under all environmental conditions. However, the two systems are sampling different scales of motion. The balloon may be affected by small scale features on the order of a few tens of meters in size, whereas the VAD technique requires the Doppler radial velocities from around a range circle with 25 to 40 km radius, thus smoothing any small scale variations. These sampling differences are expected to produce variations in the wind estimates; unfortunately, they are not the explanation for the consistent phase discrepancies observed. Radar beam averaging also contributes to the phase discrepancies, since the depth of the radar beam varies from 700 to 1100 m through the slant ranges of 25–40 km. This averaging may explain the "lag" of features observed in the VAD calculated winds versus the CLASS winds. Although considerable variation in wind direction is seen throughout the depth of the low-level jet on these days, the variations are not large

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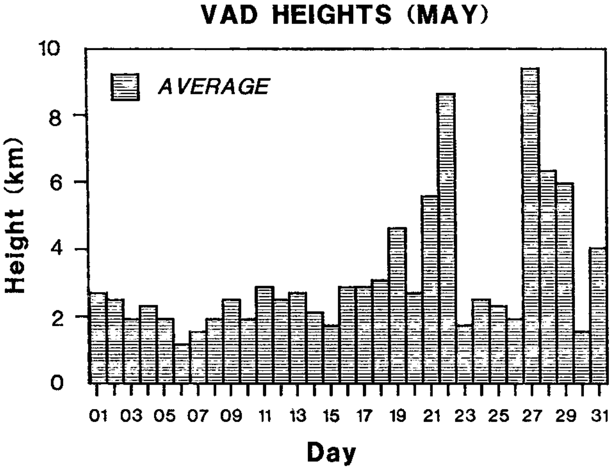

FIG. 7. Average daily highest levels of coherent Doppler return for the month of May 1987 (from Forsyth et al. 1990).

enough to account for all of the observed phase shifts. An investigation into these discrepancies is being conducted.

4. NWS operational data collection and processing strategies

The NEXRAD VAD algorithm to be implemented during the pre-production phase will calculate winds every 304 m in the vertical using data from the 0.5°, 1.5°, 2.5°, 3.5°, and 4.5° elevation angles (T. O'Bannon 1989, personal communication). This choice of levels appears to be sufficient to reproduce the general structure of the summertime low-level jets sampled during this field project (see Fig. 6). However, on 29 July the NEXRAD VAD winds would indicate that the maximum wind speed was at a height of 608 m, when it was actually measured at 471 m (Fig. 6b). An examination of the time evolution of the two low-level jet events (Figs. 2 and 4) shows that a jet can have strong vertical wind shears that may be difficult to sample with vertical sampling resolution of only 304 m. Although one can argue that any sampling resolution is not sufficient for a given event, the ability to correctly sample the low-level jet, a common feature in severe weather events, should be an important consideration in the design of the NEXRAD VAD sampling scheme.

Another important consideration is the depth of the atmosphere that can be sampled during clear air conditions. This depth varies from month to month and day to day, and during individual days (Fig. 7; see Forsyth et al. 1990). The maximum height of coherent Doppler velocity return is well above 2 km AGL during the summer months, but can decrease to below 200 m AGL during the winter months. This indicates that calculation of the lowest proposed NEXRAD VAD wind at 304 m AGL may be impossible during a portion of the calendar year.

The data produced by ARTS, the NWS sounding system, is one of the most important inputs into numerical weather prediction model initialization over the United States (Dey 1989; Hoke et al. 1989). The effects of the NWS data processing software on the observed wind profiles can be examined using the CLASS data obtained during this field program. The wind profiles from the 1100 UTC 29 July 1988 CLASS sounding were compared with profiles from a nearly coincident sounding from the Oklahoma City National Weather Service Office, located approximately 30 km north-northwest of Norman (Fig. 8). Differences in the apparent structure of the low-level jet are large. The data processing software used by the NWS to calculate the winds every 1000 ft (304 m) damps the wind speed profile and artificially increases the height of the wind maximum associated with the low-level jet. This effect also is seen in the CLASS wind profile after it has been altered using an approximation of the NWS averaging routine. [The 10 second average winds were used to calculate the Horizontal Distance Out (HDO) and direction of the balloon from the launch site at each 1000 ft interval in height. These values of HDO and azimuth were then used to compute the winds at the fixed levels, using a two minute interval with a one minute overlap for the levels between 1000 and 9000 ft, and then a two minute interval with no overlap for the 12 000 ft winds.] These highly smoothed winds are apparently the only upper-air wind data transmitted in real-time and available retrospectively to researchers. The quality of operational and archived rawinsonde data is discussed by Schwartz (1989; 1990).

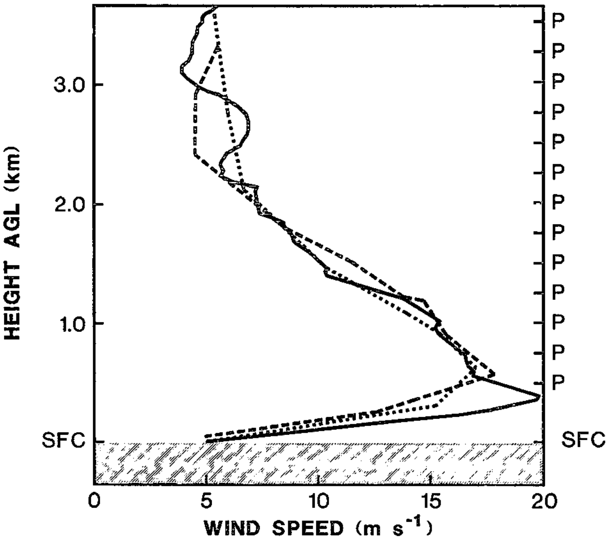

FIG. 8. Profiles of CLASS (solid), the Oklahoma City NWS sounding (dashed) and CLASS altered using an approximation to the averaging routine used by the NWS (dotted). P's indicate the 404-MHz radar wind profiler range gates.

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5. Discussion

The winds during two summertime low-level jet events calculated from data obtained simultaneously with both a 10-cm NEXRAD-like Doppler radar and a digital sounding system (CLASS) have been examined. While the high-resolution wind data from these two systems are comparable, the current and proposed operational data acquisition and processing strategies of the National Weather Service for upper-air and NEXRAD VAD wind data degrade the data substantially. The degradation causes the level of maximum wind (i.e., low-level jet) to be displaced vertically and to be damped, producing a weaker and less distinct jet in the NWS data. The appropriateness of these data for input into sophisticated mesoscale weather prediction models must be questioned.

While detailed consideration of the effects of wind data resolution on numerical model simulations is beyond the scope of this paper, the importance of accurate, high-resolution low-level wind data can be illustrated by examining several case studies that used three-dimensional, mesoscale weather prediction models. Heights of the lowest several model levels are determined for each study by using the 0044 UTC 29 July CLASS sounding in the model level calculations. One study that simulated a low-level jet during an Appalachian cold-air damming event (Stauffer and Warner 1987) would have model levels at approximately 10, 140, 390, and 630 m AGL. Similarly, the numerical simulation of an intense squall line during June 1985 (Zhang et al. 1989) would have model levels specified at approximately 20, 200, 610 and 1100 m AGL. Lastly, the real-time version of the PSU/NCAR model (Warner and Seaman 1990) would have the lowest six model levels specified at 40, 130, 250, 460, 750 and 1150 m AGL. The winds input into these models would not be representative of the atmosphere if the smoothed NWS "1000 ft" (304 m) winds were used from the low-level jet events sampled during July 1988.

The heights of maximum wind speeds from all four low-level jet events sampled during this short field program were between 268 and 471 m AGL. A third observing system, the 404-MHz radar wind profiler, currently is being deployed in a network across the central United States. Since the lowest level of wind observation from the 404-MHz radar wind profilers is planned for 500 m AGL (see Figs. 2, 4), the demonstration network wind profilers could not detect the maximum wind speed level of these summertime low-level jets (the minimum wind observation height of 500 m is not intrinsic to wind profilers and could be lowered to near 250 m by including a high-resolution sampling mode). One possible solution may be to calculate additional wind levels below 500 m AGL from the NEXRAD data and assimilate both NEXRAD and profiler wind data to produce a high-resolution profile of the winds throughout most of the troposphere. However, the utility of hourly-averaged radar profiler winds during rapidly changing mesoscale weather events (i.e., frontal zones, mesoscale convective systems, jet streaks) has yet to be fully explored.

The National Weather Service has digital sounding systems at all upper-air sites; the demonstration network 404-MHz radar wind profilers are being installed; the first Next Generation Weather Radar is undergoing testing, so the technology to sample the vertical wind structure of the atmosphere at very high-resolution is rapidly becoming a reality. However, *the current and proposed NWS operational procedures do not make full use of these high-resolution datasets.* Regardless of our capabilities to transmit high-resolution data operationally, the high-resolution data produced by ARTS, radar wind profilers, and NEXRAD should be saved for research efforts and eventually (when communication capabilities permit) entered into the operational data stream. In only 1 to 2 years, wind data of the types illustrated here will be routinely available over a substantial portion of the central United States. Hopefully, we will be able to begin exploring the value of the full resolution wind data in state-of-the-art mesoscale forecast models.

Acknowledgments. The authors thank Doug Forsyth, Kevin Kelleher, Charlie Crisp, Dave Keller, Ed Brandes, Bob Rabin, Steve Vasiloff, John Augustine and Mark Antolik for their participation in this experiment. Glen Anderson, James McGowen, Mike Schmidt, Lance Scudder, Dennis Nealson, Allen Zahrai and Brian Curran provided technical and software support. The assistance of Tom Matejka and Scott Williams is gratefully acknowledged. Reviews of the manuscript by Tim O'Bannon, Ed Brandes, Chuck Doswell, Peter May and an anonymous reviewer led to numerous improvements. We are thankful for the support of the entire staff of the Norman National Weather Service Forecast Office during the operational period. Tom Davis of the Oklahoma City National Weather Service Office helped clarify the method used by the NWS to calculate the 1000 ft winds. Joan Kimpel skillfully drafted the figures, while Sandy McPherson and Joy Walton assisted in manuscript preparation.

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