NOTES AND CORRESPONDENCE

Accuracy of 404-MHz Radar Profilers for Detection of Low-Level Jets over the Central United States

CHAD J. DANIEL, RAYMOND W. ARRITT, AND CHRISTOPHER J. ANDERSON

Department of Agronomy, Iowa State University, Ames, Iowa

23 June 1998 and 5 December 1998

ABSTRACT

The authors have evaluated the performance of operational hourly data from a NOAA Wind Profiler Network 404-MHz radar profiler for detecting low-level jet (LLJ) events in the central United States. Independent, collocated rawinsonde and radar profiler data were time matched, producing 2614 paired observations over a 2-yr period. These observations were used to determine the impacts of the height of the first profiler range gate (500 m) and contamination of the hourly data by migrating birds on the ability of the profiler to accurately diagnose LLJ events. The profilers tend to underrepresent both the strength and frequency of occurrence of the LLJ. It was found that about 50% of LLJ events with wind speed maxima below 500 m were detected, increasing to 70%–80% for events having their wind speed maxima above 500 m. To reduce contamination by migrating birds when using profilers to detect the LLJ, a second-moment filtering technique with a threshold of approximately 2–2.5 $m^2 s^{-2}$ is suggested as an effective compromise between maximizing threat score and probability of detection while maintaining a low false alarm rate.

1. Introduction

Evaluations of radar profiler wind measurements have focused mostly on quantifying discrepancies between profiler-measured u and v wind components and rawinsonde-observed wind components (e.g., Strauch et al. 1987; Weber and Wuertz 1990; Weber et al. 1990). While these studies have been essential in providing the framework necessary for implementation of radar profiler data into mainstream research activities and operational forecasting, more complete evaluations of profiler performance require knowledge of the ability of the profilers to observe specific atmospheric phenomena. An example is the low-level jet (LLJ) over the central United States. Previous studies have shown that the LLJ is important to the hydrologic cycle over this region and, in particular, that warm-season heavy precipitation episodes are closely related to the incidence of strong LLJs (Stensrud 1996; Higgins et al. 1997; Arritt et al. 1997). Since the LLJ has a pronounced diurnal cycle with peak incidence between the nominal 0000 and 1200 UTC launch times of the conventional rawinsonde network (Mitchell et al. 1995), the continuous hourly observations available from the NOAA Profiler Network (NPN) have the potential to provide valuable insights into the structure and dynamics of the LLJ.

In this note we evaluate the operational ability of NPN hourly 404-MHz radar profiler observations to detect LLJ events. We focus on two specific sources of error that previous studies have suggested may impose limitations in the ability of the profilers to observe LLJs. These are the limitations imposed by the 500-m height of the lowest range gate (Stensrud et al. 1990; Whiteman et al. 1997), and the possibility of contamination by signal returns from migrating birds (Wilczak et al. 1995). Our intent is to provide information on these characteristics of the profiler observations so that forecasters and researchers can make informed choices in using hourly profiler data.

2. Data and techniques

We have compared hourly measurements from the Lamont, Oklahoma, 404-MHz profiler with research rawinsonde data obtained over the period 7 April 1994–30 March 1996. The profiler is 10 km north of the Clouds and Radiation Testbed (CART) rawinsonde launch site and thus provides approximately simultaneous, independent observations of LLJ events. In addition to the spatial proximity of the measurements, the rawinsonde dataset includes up to 3-hourly observations, allowing more frequent time matches for direct profiler comparisons than is possible from standard

Corresponding author address: Dr. Chad J. Daniel, 3010 Agronomy Hall, Iowa State University, Ames, Iowa 50011.
E-mail: cdaniel@iastate.edu

TABLE 1. Low-level jet wind speed and vertical wind difference category classifications, wind speed maximum found in the first 1500 m, and wind decrease up to 3000 m.

LLJ Category	Wind speed	Wind speed decrease
1	$\geq$12 m s^{-1}	$\geq$6 m s^{-1}
2	$\geq$16 m s^{-1}	$\geq$8 m s^{-1}
3	$\geq$20 m s^{-1}	$\geq$10 m s^{-1}

NWS rawinsonde launches. In particular, the CART observations provide data around 0600 UTC when LLJs occur most frequently. The rawinsonde soundings used standard Vaisala RS-80 sondes with Loran C windfinding. The nominal accuracy is about 0.5 m s^{-1} and is primarily a function of the density of the Loran C coverage, which is quite good over the southern Great Plains (B. Lesht 1998, personal communication). For additional details of the rawinsonde dataset, see Whiteman et al. (1997), and for characteristics of the 404-MHz profilers, see, for example, Wilczak et al. (1995), Mitchell et al. (1995), Arritt et al. (1997) and references cited therein.

As in Arritt et al. (1997), we defined usable profiles from the 404-MHz profiler as those that contained any three or more valid data points within the first 1500-m layer above the surface and any four or more within the next 1500 m. Data points were considered valid if they were not flagged as bad or missing and contained wind speed values less than 85 m s^{-1}. Usable hourly profiler wind measurements were aligned with rawinsonde observations yielding 2614 time-matched profiles over the 2-yr period. During the hours of 0000, 0300, 0600, and 0900 UTC 810 observations were available, 446 were available at 1200 UTC, and the remaining 1358 observations were at 1500, 1800, and 2100 UTC. In the analysis of possible data contamination by migrating birds, additional restrictions for determining whether a profile was usable were applied based on the second-moment values in the hourly data files. This method of ''filtering'' data contaminated by returns from migrating birds is similar to that outlined in van de Kamp et al. (1997) and is further explained in section 3b. Criteria used to define the LLJ follow those of Bonner (1968), where values of the requisite wind speed maximum and decrease in wind speed above the maximum are specified (Table 1). High wind events that do not have a local maximum in the wind speed profile exhibit very different behavior from LLJs (see Mitchell et al. 1995) and were not included in this analysis.

Comparison with rawinsonde observations, through the standard method of evaluation for profiler data, carries two sources of uncertainty in the measurements—one for the profiler and another for the rawinsonde. Differences also arise because of differing principles of operation of the instruments. In particular, the profiler samples over a volume, while the rawinsonde is more similar to a point measurement. Thus, while we follow previous studies in using the rawinsonde data as a reference for the comparison, the rawinsonde is not an absolute standard.

Previous studies give some guidance as to the magnitude and nature of expected measurement differences between the rawinsonde and profiler. Weber and Wuertz (1990) found a standard deviation of 2.5 m s^{-1} between profiler and rawinsonde measurements, attributable to the combined effect of instrument error and ''meteorological noise.'' The latter includes microscale perturbations in the wind field that would be smoothed by the volume sampling inherent in the radar wind profilers (see also Stensrud et al. 1990). Smalley and Morrisey (1993) found a similar value of 2.76 m s^{-1} for the vector standard deviation when comparing 404-MHz profiler data to Loran-based radiosonde measurements. These and other comparisons of profiler and rawinsonde data (e.g., Strauch et al. 1987; Martner et al. 1993) suggest that low-level wind speed differences between the two instruments are typically about 2–3 m s^{-1} with little systematic bias. The reader may consult the references given above for additional details of comparisons between profilers and rawinsondes.

3. Results

a. Effect of height limitations

It has long been recognized that LLJs can occur below the 500-m height of the lowest profiler range gate (e.g., Stensrud et al. 1990), but the consequences of this limitation have not been quantified for an extended period of record in a direct comparison of profiler and rawinsonde observations. Using the same rawinsonde data as in the present study, Whiteman et al. (1997) found that more than 50% of the observed LLJs had wind speed maxima below 500 m AGL and that the maximum wind speed occurred most often between 300 and 600 m. Their results imply that the lowest profiler range gate is too high to capture many LLJ wind speed maxima. Note, however, that the profiler data are not point measurements but instead are weighted averages over a vertical interval centered about each 250-m range gate, with a range resolution of 320 m (Barth et al. 1994). Thus, some information from below 500 m is included in the value for the 500-m range gate (for details of profiler operation, see Strauch et al. 1987; Weber et al. 1990; Barth et al. 1994). Additionally, when the peak speed is below 500 m, the LLJ profile may extend far enough aloft so that the LLJ is partially observable.

We evaluated this limitation by stratifying the paired observations into two groups based on whether the height of the rawinsonde reported wind speed maximum was above or below 500 m AGL. (Note that about 97% of our usable profiles include data at the 500-m level.) The rawinsonde profiles contain 828 LLJ events of which 475 have their wind speed maxima below 500 m and 353 have their maxima above 500 m. As expected,

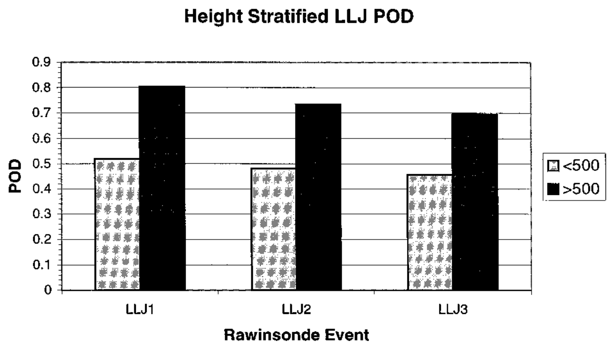

FIG. 1. POD for LLJs stratified by height of the rawinsonde-observed wind speed maximum.

LLJs are more reliably observed by the profiler when the height of the wind speed maximum is above 500 m (Fig. 1); however, even when the maximum is above 500 m there remains a tendency for the profiler to underrepresent the frequency of LLJs. For criterion 1, the LLJ's probability of detection (POD) (see the appendix) was 52.0% when the wind speed maximum was below 500 m, increasing to 80.5% when the wind speed maximum was above 500 m. This trend also applies to criteria 2 and 3 LLJs, with PODs of 48.1% (LLJ2) and 45.6% (LLJ3) below 500 m, as compared to 73.5% (LLJ2) and 69.5% (LLJ3) when the height is above 500 m. Additionally, when the height of the wind speed maximum is below 500 m, the profiler reported LLJ is underclassified as a weaker LLJ than reported by the rawinsonde almost twice as often (54.5% for LLJ3) as when the height of the wind speed maximum was above 500 m (30.4% for LLJ3).

b. Contamination by returns from migrating birds

Several studies have investigated contamination of profiler hourly data by signal returns from migrating birds (e.g., Wilczak et al. 1995; Miller et al. 1997). Arritt et al. (1997) inferred that this contamination could substantially affect observations of LLJs in the springtime. Their results were based on indirect inference from the profiler velocity variance and did not employ independent observations of the LLJ by the profiler and another data source. To evaluate the effect of contamination by migrating birds on profiler-diagnosed LLJs, we implemented a variation of the second-moment (velocity variance) thresholding method outlined by van de Kamp et al. (1997), which outlines six criteria that must be met in order for the hourly data to be flagged as contaminated. These criteria include time of year (spring or fall), time of day (night), height less than 4500 m MSL, wind direction (southerly in the spring, northerly in the fall), adequate velocity variance of the average of the north and east beams, and vertical velocity variance less than 1.5 $m^2\ s^{-2}$ in order to avoid the effects of precipitation on the velocity variance. To evaluate the effect of various second-moment thresholds on a seasonal basis, time of day, season, and wind direction restrictions were not implemented in the present study. We used averaged hourly north and east component second-moment values of 1 $m^2\ s^{-2}$ and greater as threshold values, above which data were considered contaminated.

Verification statistics similar to those given in Miller et al. (1997) were used to quantify the influence of the second-moment threshold on LLJ observations. We calculated the POD, false alarm rate (FAR), threat score (TS), and bias (see the appendix for definitions). We also computed the data availability (DA) as the ratio of the number of usable profiles to the maximum possible number of usable profiles in a given period. Since the current study evaluates paired observations from two datasets, we base the data availability on the number of rawinsonde profiles. The data availability thus ranges from 0 (no profiler observations are available) to 1 (a profiler observation is available at the time of each rawinsonde observation).

The results (Fig. 2) show that POD varies over a fairly narrow range (about 0.58–0.64) with the most substantial increase for thresholds of 1–3.5 $m^2\ s^{-2}$. The TS also varies over a narrow range (0.53–0.55) and peaks around a threshold of 2.5 $m^2\ s^{-2}$. This result implies that for thresholds above 2.5 $m^2\ s^{-2}$ the TS decreases because spurious LLJ events are reported, while below 2.5 $m^2\ s^{-2}$ the TS decreases because valid LLJ observations are disproportionately rejected. FAR increases most rapidly for thresholds above about 2 $m^2\ s^{-2}$ and the bias increases approximately linearly from 0.69 to 0.83 over the 1–5 $m^2\ s^{-2}$ threshold range. These values suggest that when using hourly profiler data to diagnose LLJ events a second moment threshold of approximately 2–2.5 $m^2\ s^{-2}$ produces close to the maximum POD and TS without substantially increasing the FAR.

Evaluation statistics were calculated independently for each LLJ criterion in order to evaluate differences in the ability of the profiler to correctly classify the intensity of the LLJ (Fig. 3). FAR was systematically greater for stronger LLJs than for weaker ones. This result supports previous inferences that the contamination is correlated with LLJ intensity (Arritt et al. 1997). POD values indicate that the strongest LLJs show the greatest sensitivity to the choice of threshold. The TS values follow the same trend with lower accuracy for stronger LLJs, while the bias again shows that the stronger LLJs are more sensitive to the choice of threshold. It was found that about one-third of the contaminated LLJ3s were, in fact, correctly classified by the profiler. In these cases the contamination probably results from the tendency for birds to fly in favorable winds.

Seasonal variations in contamination due to migrating birds are expected, with maximum contamination during spring and fall (Miller et al. 1997; Arritt et al. 1997). For summer (June, July, and August) and winter (December, January, and February) the FAR is relatively insensitive to the threshold, which is consistent with the

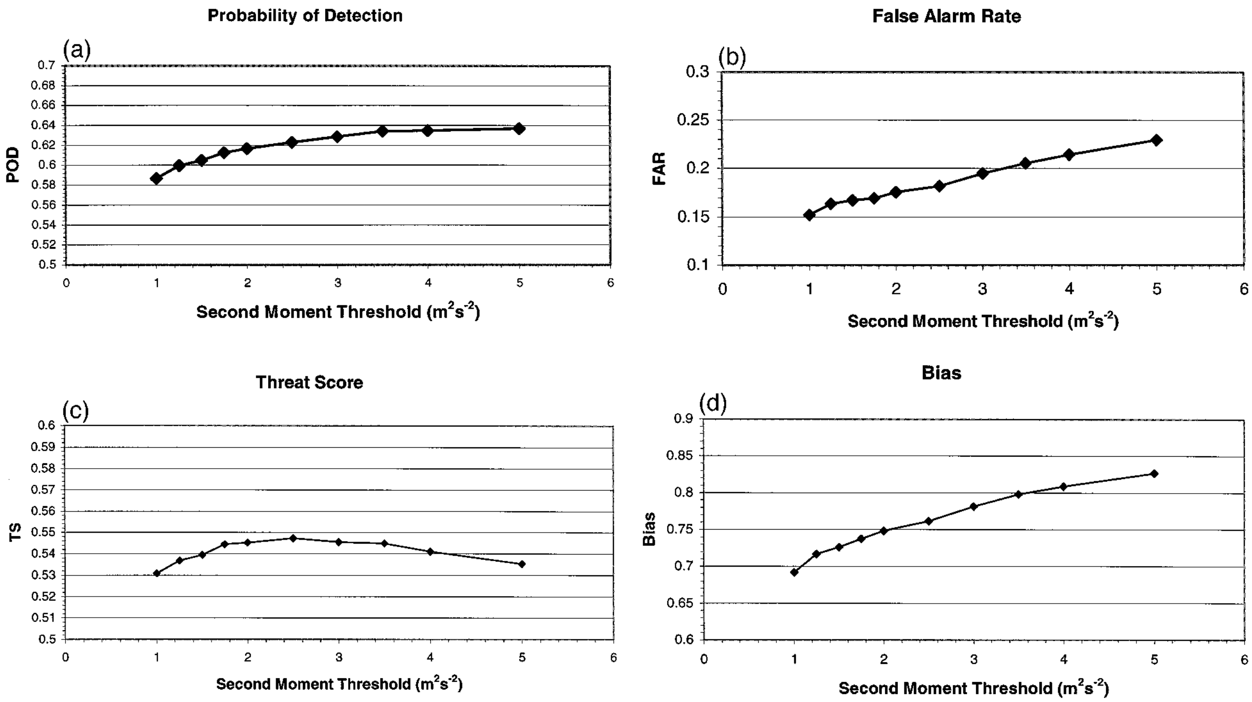

FIG. 2. (a) POD, (b) FAR, (c) TS, and (d) bias values at various second-moment (velocity variance) threshold values.

notion that contamination by migrating birds is infrequent during these seasons (Fig. 4). During springtime (March, April, and May), the FAR decreases as the threshold is made more stringent (i.e., smaller) until a threshold around 2.5 $m^2 s^{-2}$ is reached. An unexpected result is that when the threshold is decreased below 1.75 $m^2 s^{-2}$, the FAR actually increases. Given the definition of FAR, this result indicates that for a threshold below 1.75 $m^2 s^{-2}$ a substantial number of accurate profiler observations of LLJs are rejected. During fall (Septem-

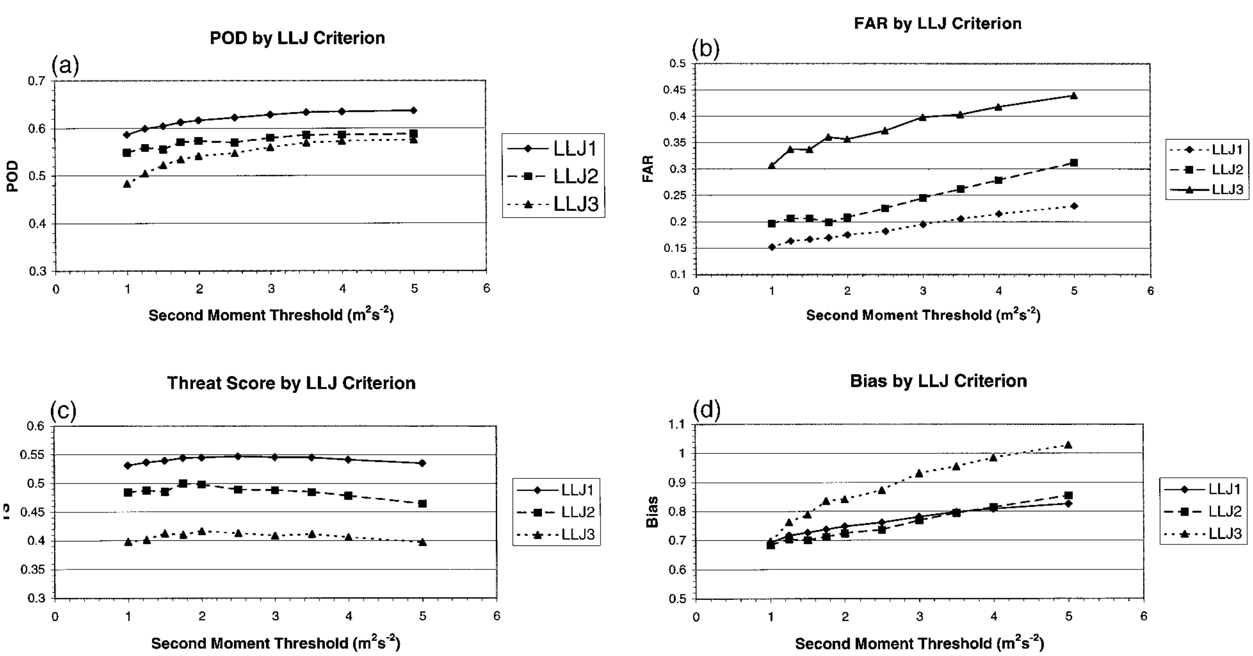

FIG. 3. (a) POD, (b) FAR, (c) TS, and (d) bias for profiler observation of inclusive category LLJ events observed by rawinsonde (i.e., an LLJ3 also qualifies as an LLJ2 and an LLJ1).

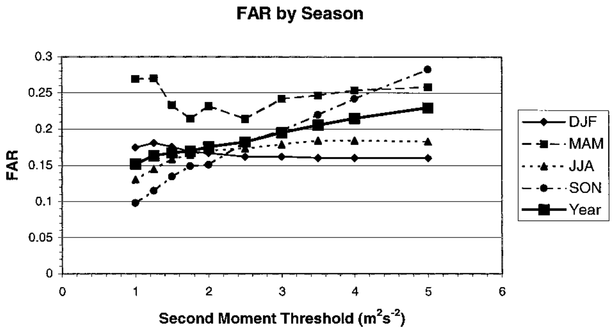

FIG. 4. Seasonal dependence of FAR on second-moment (velocity variance) thresholding levels.

ber, October, and November), the minimum in FAR is reached at the most stringent threshold (1 m^2 s^{-2}). During spring and fall, the DA is notably lower than during winter and summer, especially at low threshold values (Fig. 5). The DA for winter and summer is insensitive to the threshold above 2 m^2 s^{-2}, and again the trend is consistent with previous inferences that profiler data in these seasons are seldom contaminated by returns from migrating birds.

4. Conclusions

As with all observing systems, instrument and environmental constraints must be taken into account to ensure the quality of profiler-based LLJ observations. Our results indicate that even though the height of the first range gate is 500 m, LLJs having wind speed maxima below this height are partially detectable (see Fig. 1 and related discussion), albeit often weaker than indicated by the rawinsonde. Although LLJ events having wind speed maxima below 500 m are less accurately represented than those above 500 m, about 50% of the events having wind speed maxima below 500 m are detected. There is a general tendency for the profilers to underrepresent the frequency of occurrence of LLJs, even when the wind speed maximum is above 500 m (about 70%–80% POD), and to underreport the strength of the LLJ.

Velocity variance thresholding provides an objective means for evaluating contamination of profiler data by migrating birds. Nevertheless, the method in the end remains subjective because one must choose the threshold value according to the purposes for which the data will be used. We suggest that a threshold around 2–2.5 m^2 s^{-2} is generally appropriate when using the profiler data to evaluate LLJs. Such a value maximizes TS and provides nearly the maximum POD while still including a large percentage of the observations (DA = 81% at 2 m^2 s^{-2}). Above this threshold FAR begins to increase substantially, while more stringent thresholds reject numerous valid LLJ reports. The threshold recommended here is somewhat less restrictive than the value of 1.75 m^2 s^{-2} recommended by van de Kamp et al. (1997) and the value 1.8 m^2 s^{-2} proposed by Wilczak et al. (1995). Our results confirm previous inferences that contamination by returns from migrating birds often occurs in spring and to a lesser extent in fall, but it is not a significant source of error during summer and winter.

Finally, note that our results are based on intercomparisons at a single site. It is possible that other sites could exhibit different behavior than found here, owing to differences in the characteristics of the instruments or local climatological differences.

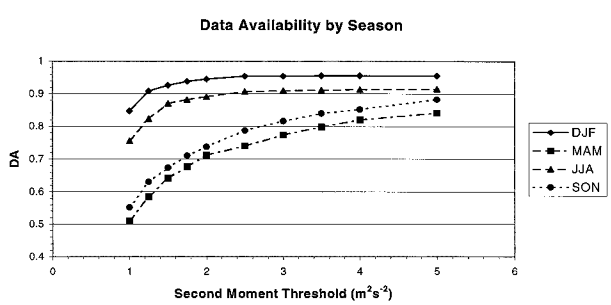

FIG. 5. Data availability stratified by season for second-moment (velocity variance) thresholding levels.

Acknowledgments. We gratefully acknowledge the provision of the rawinsonde dataset by Dave Whiteman and Xindi Bian of Pacific Northwest National Laboratories, which made this study possible. The hourly profiler data were obtained from archives at the National Center for Atmospheric Research, which is sponsored by the National Science Foundation. We also are grateful for correspondence with Patricia Miller of NOAA/ERL and Barry Lesht of Argonne National Laboratories. This study was supported by National Science Foundation Grant ATM-9616728. This is Journal Paper J-18307 of the Iowa Agricultural and Home Economics Experiment Station Project 3245, supported by Hatch Act and State of Iowa funds.

APPENDIX

Verification Statistics

The measures used to define accuracy of the profiler observations can be illustrated concisely if the profiler and rawinsonde observations are placed into a matrix as follows, where the variables j and n refer to an observation that contains an LLJ or no LLJ, respectively, and the subscripts r and p refer to the rawinsonde and profiler (see Table A1). Verbal and quantitative defini-

TABLE A1. Matrix of possible measurement result combinations.

	Profiler	
Rawinsonde	LLJ	No LLJ
LLJ	$j_r j_p$	$j_r n_p$
No LLJ	$n_r j_p$	$n_r n_p$

tions of the POD, FAR, TS, and bias are given as follows.

Probability of detection

$$= \frac{\text{Number of correct profiler observations of LLJ}}{\text{Total number of rawinsonde observations of LLJs}}$$

$$= \frac{j_r j_p}{j_r j_p + j_r n_p}.$$

The POD ranges from 0 to 1 with an ideal value of 1. Note that events in which the LLJ does not occur in the rawinsonde data (i.e., observations of type $n_r n_p$ and $n_r j_p$) or spurious profiler observations of LLJs (i.e., $n_r j_p$) have no effect on the POD.

False alarm rate

$$= \frac{\text{Number of spurious profiler observations of LLJ}}{\text{Total number of profiler observations of LLJs}}$$

$$= \frac{n_r j_p}{j_r j_p + n_r j_p}.$$

The FAR ranges from 0 to 1 with an ideal value of 0. Note that the FAR is unaffected by observations in which no LLJ appears in the profiler (i.e., $j_r n_p$ and $n_r n_p$).

Threat score

$$= \frac{\text{Number of correct profiler observations of LLJ}}{\text{Total number of profiler observations of LLJs} + \text{Number of rawinsonde observations of LLJs missed by the profiler}}$$

$$= \frac{j_r j_p}{j_r j_p + n_r j_p + j_r n_p}.$$

TS ranges from 0 to 1 and is the only measure used here that is affected by all types of observations in the matrix.

Bias

$$= \frac{\text{Total number of profiler observations of LLJ}}{\text{Total number of rawinsonde observations of LLJs}}$$

$$= \frac{j_r j_p + n_r j_p}{j_r j_p + j_r n_p}.$$

The bias ranges from 0 to infinity. While the ideal value of the bias is 1, the bias alone does not necessarily indicate whether the profiler observations are correct: a bias of 1 could be obtained if all of the profiler observed LLJs are incorrect, so that $n_r j_p = j_r n_p$ and $j_r j_p = 0$.

REFERENCES

Arritt, R. W., T. D. Rink, M. Segal, D. P. Todey, C. A. Clark, M. J. Mitchell, and K. M. Labas, 1997: The Great Plains low-level jet during the warm season of 1993. *Mon. Wea. Rev.,* **125,** 2176–2192.

Barth, M. F., R. B. Chadwick, and D. W. van de Kamp, 1994: Data processing algorithms used by NOAA's wind profiler demonstration network. *Ann. Geophysicae,* **12,** 518–528.

Bonner, W. D., 1968: Climatology of the low-level jet. *Mon. Wea. Rev.,* **96,** 833–850.

Higgins, R. W., Y. Yao, E. S. Yarosh, J. E. Janowiak, and K. C. Mo, 1997: Influence of the Great Plains low-level jet on summertime precipitation and moisture transport over the central United States. *J. Climate,* **10,** 481–507.

Martner, B. E., and Coauthors, 1993: An evaluation of wind profiler, RASS, and microwave radiometer performance. *Bull. Amer. Meteor. Soc.,* **74,** 599–613.

Miller, P. A., M. F. Barth, J. R. Smart, and L. A. Benjamin, 1997: The extent of bird contamination in the hourly winds measured by the NOAA profiler network: Results before and after implementation of the new bird contamination quality control check. *First Symposium on Integrated Observing Systems,* Long Beach, CA, Amer. Meteor. Soc., 138–144.

Mitchell, M. J., R. W. Arritt, and K. Labas, 1995: A climatology of the warm season Great Plains low-level jet using wind profiler observations. *Wea. Forecasting,* **10,** 576–591.

Smalley, D. J., and J. F. Morrisey, 1993: Observed differences of winds measured by a wind profiler and loransondes. *26th Int. Conf. on Radar Meteorology,* Norman, OK, Amer. Meteor. Soc., 617–619.

Stensrud, D. J., 1996: Importance of low-level jets to climate: A review. *J. Climate,* **9,** 1698–1711.

——, M. H. Jain, K. W. Howard, and R. A. Maddox, 1990: Operational systems for observing the lower atmosphere: Importance of data sampling and archival procedures. *J. Atmos. Oceanic Technol.,* **7,** 930–937.

Strauch, R. G., B. L. Weber, A. S. Frisch, C. G. Little, D. A. Merritt, K. P. Moran, and D. C. Welsh, 1987: The precision and relative accuracy of profiler wind measurements. *J. Atmos. Oceanic Technol.,* **4,** 563–571.

van de Kamp, D. W., F. M. Ralph, M. F. Barth, P. A. Miller, J. R. Smart, and L. A. Benjamin, 1997: The new bird contamination quality control check applied to hourly winds from NOAA's profiler network. *28th Conf. on Radar Meteorology,* Austin, TX, Amer. Meteor. Soc., 131–132.

Weber, B. L., and D. B. Wuertz, 1990: Comparison of rawinsonde and wind profiler radar measurements. *J. Atmos. Oceanic Technol.,* **7,** 157–174.

——, and Coauthors, 1990: Preliminary evaluation of the first NOAA demonstration network wind profiler. *J. Atmos. Oceanic Technol.,* **7,** 910–918.

Whiteman, C. D., X. Bian, and S. Zhong, 1997: Low-level jet climatology from enhanced rawinsonde observations at a site in the southern Great Plains. *J. Appl. Meteor.,* **36,** 1363–1376.

Wilczak, J. M., and Coauthors, 1995: Contamination of wind profiler data by migrating birds: Characteristics of corrupted data and potential solutions. *J. Atmos. Oceanic Technol.,* **12,** 449–467.