Modeling, Error Analysis, and Evaluation of Dual-Polarization Variables Obtained from Simultaneous Horizontal and Vertical Polarization Transmit Radar. Part II: Experimental Data

J. C. HUBBERT, S. M. ELLIS, M. DIXON, AND G. MEYMARIS

National Center for Atmospheric Research,* Boulder, Colorado

(Manuscript received 21 May 2009, in final form 8 April 2010)

ABSTRACT

In this second article in a two-part work, the biases of weather radar polarimetric variables from simultaneous horizontally and vertically transmit (SHV) data are investigated. The biases are caused by cross coupling of the simultaneously transmitted vertical (V) and horizontal (H) electric fields. There are two primary causes of cross coupling: 1) the nonzero mean canting angle of the propagation medium (e.g., canted ice crystals) and 2) antenna polarization errors. Given herein are experimental data illustrating both bias sources. In Part I, a model is developed and used to quantify cross coupling and its impact on polarization measurements. Here, in Part II, experimental data from the National Center for Atmospheric Research’s (NCAR’s) S-band dual-polarimetric Doppler radar (S-Pol) and the National Severe Storms Laboratory’s polarimetric Weather Surveillance Radar-1988 Doppler (WSR-88D), KOUN, are used to illustrate biases in differential reflectivity (Zdr). The S-Pol data are unique: both SHV data and fast alternating H and V transmit (FHV) data are gathered in close time proximity, and thus the FHV data provide “truth” for the SHV data. Specifically, the SHV Zdr bias in rain caused by antenna polarization errors is clearly demonstrated by the data. This has not been shown previously in the literature.

1. Introduction

There is now widespread recognition that dual-polarized radars, as compared to single polarization radars, can significantly increase the amount of meteorological information gathered. The two most common ways to accomplish dual-polarimetric measurements are by 1) using fast alternating horizontal (H) and vertical (V) polarization transmission and 2) using simultaneous H and V polarization transmission (SHV), both of which employ simultaneous reception of H and V polarizations.

As discussed in Hubbert et al. (2010, hereafter Part I), the premise of the SHV technique to achieve unbiased dual-polarimetric measurements is that there is negligible cross coupling of the H and V transmitted fields.

The two primary causes of cross coupling are the nonzero mean canting angle of the propagation medium and antenna polarization errors. In Part I, a radar model is developed that both demonstrates and quantifies 1) the effects of the nonzero mean canting angle of the propagation medium, 2) antenna polarization errors, and 3) the effects of phase differences between the H and V components of the transmitted wave. Herein, experimental data from the National Center for Atmospheric Research’s (NCAR’s) S-band dual-polarization Doppler radar (S-Pol) are used to illustrate the theory developed in Part I. Recently, S-Pol collected data in fast alternating H and V transmit (FHV) modes, followed immediately by data collected in SHV mode. These data clearly illustrate the effects of antenna polarization errors on SHV mode Zdr. This is the first time, to our knowledge, that such data have been collected and intercompared. Data from the National Severe Storm Laboratory’s (NSSL’s) S-band research radar KOUN are also used to demonstrate the effects of antenna polarization errors on SHV Zdr.

The paper is organized as follows. In section 2, S-Pol data are used to illustrate SHV Zdr biases caused by cross coupling. The principle of self-consistency (Gorgucci et al.
2. S-Pol experimental SHV data

During May and June of 2008, S-Pol was deployed in southern Taiwan for the Terrain-Influenced Monsoon Rainfall Experiment (TiMREX). S-Pol was operated in the FHV transmit mode for the majority of the project (normal operation mode). However, limited data were collected in the SHV mode interleaved with the FHV data. Thus, SHV and FHV data that were gathered only minutes apart can be compared. The following two cases are examined: 1) 8.6° elevation data, which demonstrate $Z_{dr}$ (differential reflectivity) bias, likely caused by the non-0 mean canting angle of the propagation medium, and 2) 2.0° elevation data, which demonstrate $Z_{dr}$ bias in rain caused by antenna polarization errors. The S-Pol data presented here were gathered on 2 June 2009.

a. SHV $Z_{dr}$ bias in the ice phase

As shown in Part I, the non-0 mean canting angle of the propagation medium causes cross coupling between the H and V components of the electric field. The data presented here show SHV $Z_{dr}$ bias stripes along the radar radials that appear after the wave has propagated through the several kilometers of the ice phase. Only a few degrees of principal plane $\phi_{dp}$ need to accumulate before significant $Z_{dr}$ bias (i.e., tenths of a decibel) is observed if there is a significant nonzero mean canting angle.

Figures 1a–c show S-Pol FHV mode $Z$, $Z_{dr}$, and $\phi_{dp}$ gathered at 0619:36 UTC at 8.6° elevation. Figures 1d–f show SHV $Z$, $Z_{dr}$, and $\phi_{dp}$ gathered at 0613:59 UTC at 8.6° elevation. A line of convective cells lies to the southeast of the radar, with trailing stratiform rain to the west. Storm cells were moving from west to east. At about 35-km range, high and variable $Z_{dr}$ values mark the bright band. Note the radial stripes of $Z_{dr}$ in the SHV mode data beyond the bright band (Fig. 1e). No $Z_{dr}$ radial stripes are evident in the FHV $Z_{dr}$ data of Fig. 1b. The $Z_{dr}$ striping in Fig. 1e is likely due to the non-0 mean canting angle of the ice particles in the propagation path, in agreement with Ryzhkov and Zrnić (2007). Figures 1c,f show that FHV and SHV $\phi_{dp}$ are similar. This is expected from the model, even though significant differences between SHV and FHV $K_{dp}$ (specific differential phase) can occur for large non-0 mean canting angle of the precipitation medium coupled with significant increase of $\phi_{dp}$. Both plots show a similarly large $\phi_{dp}$ increase versus range with a maximum increase of about 30° along the 178° radial. Such a large increase of $\phi_{dp}$ in the ice phase of storms indicates that there are highly aligned ice crystals, which could be due to electrification (Caylor and Chandrasekar 1996). It is difficult to precisely quantify the mechanisms that cause the radial SHV $Z_{dr}$ biases that are evident in Fig. 1e without having in situ verification of the precipitation particle size and shape. These figures do indicate that there is a significant alignment of the ice particles, and the radar model from Part I shows that such radial SHV $Z_{dr}$ bias stripes can be caused by such particles if they possess a nonzero mean canting angle.

b. SHV $Z_{dr}$ bias in rain

Less well known is the possible SHV $Z_{dr}$ bias in rain resulting from antenna polarization errors. It was demonstrated in Part I that radars that have an LDR system limit of −30 to −35 dB posses antenna polarization errors on the order of 1°–0.5° when these errors are quantified with the polarization descriptors of canting and ellipticity angle of the polarization ellipse. Furthermore, the radar model showed that for these antenna error levels, an SHV $Z_{dr}$ bias of up to about a 0.5-dB maximum can occur when $\phi_{dp}$ increases significantly. In this section we present experimental data that demonstrate the existence of this SHV $Z_{dr}$ bias in rain.

Figures 2a–c show S-Pol FHV mode $Z$, $Z_{dr}$, and $\phi_{dp}$ gathered at 0617:06 UTC at 2.0° elevation. Figures 2d,e show SHV $Z$ and $Z_{dr}$ gathered at 0611:28 UTC at 2.0° elevation. There is no $Z_{dr}$ striping evident in the SHV data of Fig. 2e because the elevation angle is low and most of the data are in rain, which should have a 0 mean canting angle. The SHV and FHV $Z_{dr}$ data appear fairly comparable, but in fact, there is a bias in the SHV data. To show this, we employ the self-consistency $Z$ calibration technique of Vivekanandan et al. (2003). The technique is based on the relationship of $Z$, $Z_{dr}$, and $\phi_{dp}$ in rain. Assuming the typical range of raindrop sizes and shape equilibrium distributions, $\phi_{dp}$ can be estimated from measured $Z$ and $Z_{dr}$. This estimated $\phi_{dp}(\phi_{dp})$ is compared to the measured $\phi_{dp}(\phi_{dp})$. A scatterplot is generated and a straight-line fit is calculated. If the calculated mean line differs from the one-to-one line, this indicates a reflectivity bias. The technique assumes that $Z_{dr}$ is well calibrated (S-Pol $Z_{dr}$ is well calibrated via vertically pointing data in light rain).

Shown in Fig. 3 is a scatterplot of $\phi_{dp}$ versus $\phi_{dp}$ for the 2° elevation angle FHV TiMREX data in Figs. 2a,b. The $Z$ bias is about 0.03 dBZ, that is, negligible. Note the tight scatter about the one-to-one line. The figure indicates that S-Pol is well calibrated, and such self-consistency
FIG. 1. PPI data for 8.6° elevation. (left) FHV and (right) SHV data include (a),(d) reflectivity ($Z$), (b),(e) $Z_{dr}$, and (c),(f) $\phi_{dp}$. The data were gathered by S-Pol at 0619:36 UTC 2 Jun 2008 during TiMREX in southern Taiwan. Range rings are in 15-km increments.
FIG. 2. As in Fig. 1, but for 2.0° elevation and without the SHV $\phi_{dp}$ panel. The data were gathered by S-Pol at 0616:06 UTC.
plots are typical for S-Pol data. Figure 4 is similar to Fig. 3, except it is from the above SHV data. The scatter is rather tight about the one-to-one line for \( f_{dp} \), but for \( f_{dp} > 70^\circ \), the computed \( f_{dp} \) are biased low. We believe that this is due to biased SHV Z\( _{dr} \) caused by antenna polarization errors.

To further illustrate this SHV Z\( _{dr} \) bias, Z\( _{dr} \) is averaged under the constraint of 20 dBZ < Z < 25 dBZ for different ranges of \( f_{dp} \). The \( f_{dp} \) ranges reflect the different bias characteristics at different \( f_{dp} \) values shown in Fig. 4. Therefore, the data are partitioned into the following three categories: 1) 20° < \( f_{dp} < 40^\circ \), 2) 40° < \( f_{dp} < 70^\circ \), and 3) 70° < \( f_{dp} < 100^\circ \). The results are given in Table 1.

For low \( f_{dp} \), the SHV and FHV Z\( _{dr} \) values are approximately equal; for 40° < \( f_{dp} < 70^\circ \) they differ by 0.11 dB, and for 70° < \( f_{dp} < 100^\circ \) they differ by 0.27 dB. This increasing difference between FHV and SHV Z\( _{dr} \) as a function of \( f_{dp} \) is consistent with the Z\( _{dr} \) bias predicted for antenna errors of radar systems with an LDR limit in the 230 to 235 dB range. Note that the Z\( _{dr} \) values in Table 1 are not corrected for differential attenuation; hence, measured Z\( _{dr} \) decreases with increasing \( f_{dp} \).

c. Quantifying and correcting Z\( _{dr} \) bias caused by antenna polarization errors

To support the assertion that the FHV and SHV Z\( _{dr} \) differences seen above are a result of antenna polarization errors, the S-Pol antenna errors calculated in Part I are now used in the model to compute an estimated SHV Z\( _{dr} \) bias. The errors are \( \alpha_h = 0^\circ \), \( \epsilon_h = -0.91^\circ \) and \( \alpha_v = 90^\circ \), \( \epsilon_v = 0.69^\circ \), which corresponds to \( \xi_h = -j0.0159 \) and \( \xi_v = -j0.0120 \). This is not to say that these are the actual S-Pol antenna errors. For example, there is, no doubt, some small amount of tilt angle error; however, as shown in Part I, the ellipticity angle errors must dominate because of the nature of the measured \( \Omega \) (the H-to-V correlation coefficient from solar scans; see Part I) and the LDR system limit. These estimated antenna errors are used in the model and the results are shown in Fig. 5. There are no transmit errors [i.e., \( E'_h = E'_v \) (see Part I for definitions)], the mean canting angle of the propagation medium is 0, and the backscatter medium is drizzle. As is seen, the Z\( _{dr} \) bias becomes more positive with increasing \( f_{dp} \) in a similar fashion to that in the above experimental data. The model also predicts that in FHV mode, the measured \( LDR_h \) (LDR for H polarization transmission) decreases with increasing \( f_{dp} \) instead of increasing resulting from differential attenuation, as is normally expected. This type of LDR\( _h \) behavior is observed with S-Pol data for long paths of increasing \( f_{dp} \). Thus, the model predicts the general behavior of the observed SHV Z\( _{dr} \) bias and FHV LDR\( _h \) well. A more precise estimate of the antenna errors could be made if the

<table>
<thead>
<tr>
<th>Total ( f_{dp} )</th>
<th>Mean Z( _{dr} ) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FHV</td>
</tr>
<tr>
<td>Between 20° and 40°</td>
<td>0.17</td>
</tr>
<tr>
<td>Between 40° and 70°</td>
<td>0.15</td>
</tr>
<tr>
<td>Between 70° and 100°</td>
<td>-0.07</td>
</tr>
</tbody>
</table>
transmit polarization state could be measured and if the differential phase shift incurred from the reference plane to the I and Q samples were determined. While in principle this can be done, in practice it is not straightforward. To do this, the impedance mismatch of the measurement system and waveguide coupler to the radar system would need to be determined; this would require a vector network analyzer, and such a measurement was not attempted. However, the present analysis demonstrates the magnitude and the general character of antenna polarization errors, and their deleterious effect on SHV mode $Z_{\text{dr}}$.

Finally, the SHV experimental data of Fig. 4 are corrected using the modeled $Z_{\text{dr}}$ bias values from Fig. 5 as a function of measured $\phi_{\text{dp}}$. The self-consistency technique is then again applied to the corrected data and the result is shown in Fig. 6. As can be seen the data are now better clustered around the one-to-one line as compared to the uncorrected data of Fig. 4.

3. KOUN data example of antenna polarization errors

The following section uses data gathered by KOUN, NSSL’s S-band research radar, on 30 March 2007 through a convective line that produced over 300 mm of the $f_{\text{dp}}$ increase and serves as another example of SHV $Z_{\text{dr}}$ bias caused by antenna polarization errors. This rain event was described by local meteorologists as being more tropical in nature, with fewer large drops than typically occur in Oklahoma rainstorms (T. Schuur, Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, 2008, personal communication).

This is confirmed by the National Weather Service (NWS) sounding data for the time period that shows a moist profile through a deep layer, low vertical wind shear, and relatively low convective available potential energy (CAPE = 834 J). Furthermore, there were no hail reports in Oklahoma from the National Weather Service or the Community Collaborative Rain, Hail and Snow Network (CoCoRaHS). Thus, this is an excellent data-set for the analysis of antenna polarization errors. The KOUN antenna is similar to the antennas used on the NWS’s operational radars [i.e., Next Generation Weather Radar (NEXRAD)] except it has a dual-polarized feed horn. It has a center-fed parabolic reflector with three support struts. The $1.5^\circ$ elevation angle data are used in our analysis to avoid the influence of partial beam blockage.

Because KOUN does not operate in FHV mode, only the SHV data are available and no FHV mode data are available for comparison. Nevertheless, the self-consistency $Z$ calibration technique can be used to ascertain the presence of $Z_{\text{dr}}$ bias resulting from the cross coupling between the H and V channels. To calibrate KOUN data, plan position indicator (PPI) plots of $Z$ and $Z_{\text{dr}}$ are inspected in regions of light rain/drizzle with low reflectivity and very low $\phi_{\text{dp}}$ accumulation, so that intrinsic $Z_{\text{dr}}$ should be about 0 dB. From this data, the $Z_{\text{dr}}$ bias is estimated to be 0.6 dB. Next, using the self-consistency principle, the scatterplot of $\phi_{\text{dp}}^{\text{cal}}$ versus $\phi_{\text{dp}}^{\text{act}}$ is calculated using only data with $\phi_{\text{dp}}^{\text{act}}$ less than 50°, which yields a $Z$ bias of 4.7 dB. To verify these estimated calibration numbers, a scatterplot of $Z_{\text{dr}}$ versus $Z$ is made for data with $\phi_{\text{dp}} < 30^\circ$ (to minimize possible bias caused by the measurement system and waveguide coupler to the radar system).
by the antenna polarization errors), which is shown with the solid line in Fig. 7. The experimental data are put into 5-dBZ bins and averaged, and the standard deviations are then calculated. The solid vertical lines represent the standard deviations plotted at the midpoints of the 5-dBZ bins. For comparison, the curve found by Illingworth and Caylor (1989) is plotted in Fig. 7 as the dashed line. The corrected data compare well with the line from Illingworth and Caylor (1989).

The method of Vivekanandan et al. (2003) is applied to the KOUN data that are calibrated as described above. Once again, the scatterplot of \( \phi_{dp} \) calculated from \( Z \) and \( Z_{dr} \) versus measured \( \phi_{dp} \) should cluster around the one-to-one line. Figure 8 shows this plot for the KOUN data. The data points are clustered around the one-to-one line for measured \( \phi_{dp} \) less than about 50°, but data points are biased low for measured \( \phi_{dp} \) greater than about 50°. Because there are no reference FHV data for comparison, data self-consistency is used to demonstrate the \( Z_{dr} \) bias in the KOUN data.

The \( Z_{dr} \) attenuation correction as well as the \( Z \) correction for attenuation will affect the nature of the scatter, and there is a degree of uncertainty to these corrections. However, Vivekanandan et al. (2003) show that the scatterplots of \( \phi_{dp}^c \) versus \( \phi_{dp}^m \) for both 1) poorly calibrated \( Z \) data and 2) non-attenuation-corrected data remain scattered about a mean straight line, which has a significantly different slope as compared to 1. Thus, if the scatter of \( \phi_{dp}^c \) versus \( \phi_{dp}^m \) do not cluster well about a straight line, this indicates a \( Z_{dr} \) bias caused by antenna polarization errors. Assuming that the KOUN data are well calibrated for \( \phi_{dp}^m < 50° \), the data of Fig. 8 shows a negative bias of the \( \phi_{dp}^c \) for \( \phi_{dp}^m > 50° \). This in turn indicates that \( Z_{dr} \) is biased high [see Eq. (16) of Vivekanandan et al. (2003)].

**Estimating KOUN antenna polarization errors**

While it is impossible to calculate the KOUN antenna polarization errors, as was done for S-Pol, a rough estimate can be made based on the data displayed in Fig. 8 using trial and error and the model described in Part I. The antenna polarization error parameters are varied and the model is used to generate \( Z_{dr} \) bias curves. The KOUN \( Z_{dr} \) is then corrected and scatterplots of \( \phi_{dp}^c \) versus \( \phi_{dp}^m \) are calculated. The \( Z_{dr} \) bias curve that best aligns the scatter of such plots around the one-to-one line is judged to yield the best estimate of the KOUN antenna errors. This \( Z_{dr} \) bias curve is shown in Fig. 9 and the antenna errors are \( \alpha_h = 1.7°, \epsilon_h = -0.7°, \alpha_v = 91.7°, \) and \( \epsilon_v = 0.7° \). The transmit polarization ellipse is characterized by \( \alpha = 45° \) and \( \epsilon = -30° \). The true KOUN antenna errors may be significantly different and still result in a \( Z_{dp} \) bias curve similar to that in Fig. 9. Nevertheless, inevitably KOUN does possess antenna polarization errors because all center-fed parabolic antennas must. Furthermore, the magnitude of the errors must significantly bias SHV \( Z_{dr} \) as evidenced by the radar model given in Part I, unless the cross-polar isolation is better than 40 dB. Without a concerted design and development effort, this is extremely unlikely.

The suggested \( Z_{dr} \) bias correction curve of Fig. 9 is now used to correct the KOUN \( Z_{dr} \) data. As can be seen in Fig. 10, the character of the self-consistency plot has
improved: the scatter points are now more closely distributed around the one-to-one line as compared to the uncorrected data of Fig. 8. Thus, these estimated antenna errors are judged to be reasonable approximations of the true KOUN antenna errors.

Additional evidence of the validity of the antenna error corrections is provided by Figs. 11a,b. The data in both figures were corrected for attenuation and differential attenuation using Eqs. (17) and (18) from Vivekanandan et al. (2003). Figure 11a shows a scatter-plot of uncorrected mean $Z_{\text{dr}}$ versus $Z$ in 5-dB reflectivity bins for $\phi_{\text{dp}} > 175^\circ$ (thick solid line) and $\phi_{\text{dp}} < 175^\circ$ (thin solid line). The relationship of Illingworth and Caylor (1989) is again plotted as the dashed line in both panels of Figs. 11a,b. Figure 11b is similar to Fig. 11a, except $Z_{\text{dr}}$ has now been corrected for antenna polarization errors by using the curve from Fig. 9. Figure 11a shows that the thin and thick plotted lines are significantly above and below, respectively, the theoretical dashed line. The observed bias is consistent with $Z_{\text{dr}}$ being biased high, where $\phi_{\text{dp}}$ is less than $175^\circ$, and biased low, where $\phi_{\text{dp}}$ is greater than $175^\circ$, as predicted by Fig. 9. In comparison, the corrected data of Fig. 11b now yield curves that are much more consistent and agree with the theoretical curve of Illingworth and Caylor (1989). Note that there are fewer data available for $\phi_{\text{dp}}$ greater than $175^\circ$ than for $\phi_{\text{dp}}$ less than $175^\circ$, resulting in the smaller data coverage of the thick black lines in Figs. 11a,b.

4. Summary and conclusions

Simultaneous transmission of H and V polarized waves (the SHV mode) is now a popular way to construct dual-polarization radar systems, largely because of the lower cost and technical simplicity: an expensive, fast, high-power polarization switch is avoided. This paper has shown that data quality issues will likely limit the cost–benefit of the SHV technique unless antenna polarization errors can be reduced so that the cross-polar isolation is better than 40 dB, which is a figure that is difficult to achieve for center-fed parabolic reflector antennas.

S-Pol data from the Terrain-Influenced Monsoon Rainfall Experiment (TiMREX) were used to demonstrate the $Z_{\text{dr}}$ bias in both the ice phase of storms and in pure rain. S-Pol SHV data were compared to fast alternating H and V transmit (FHV) data, which are relatively free of biases caused by interchannel cross coupling (Wang and Chandrasekar 2006). S-Pol SHV mode $Z_{\text{dr}}$ bias was shown to be about 0.3 dB after about 80 dB of $\phi_{\text{dp}}$ accumulation in pure rain. Fortunately, small antenna polarization errors such as those found on S-Pol do not significantly bias either $K_{\text{dp}}$ or $\rho_{hv}$. For the antenna errors considered in this paper, the radar model showed that biases in $K_{\text{dp}}$ or $\rho_{hv}$ are both within about 2% of their nominal unbiased values.

SHV radar data from KOUN were also analyzed for antenna polarization errors. This was more difficult because there is no FHV truth data for comparison. Nevertheless, the antenna polarization errors were estimated using the radar model and the principle of self-consistency among $Z$, $Z_{\text{dr}}$, and $\phi_{\text{dp}}$, and $Z = Z_{\text{dr}}$ scatterplots. The KOUN analyzed data contained over 300 dB of accumulative $\phi_{\text{dp}}$, and therefore they made an excellent case for
examining $Z_{dr}$ bias in rain caused by antenna polarization errors. Using the radar model, $Z_{dr}$ biases were shown to be positive (about 0.5 dB maximum) for $\phi_{dp} < 180^\circ$ and negative (about $-0.5$ dB minimum) for $\phi_{dp} > 180^\circ$.

Mitigation of the SHV mode $Z_{dr}$ bias caused by antenna errors will be difficult. First of all they are very difficult to quantify precisely. If the errors were known exactly, then the data could be corrected. This would only be valid in regions of homogeneous distributions of precipitation particles because antenna errors are not constant across the antenna beam. Thus, reflectivity gradients will affect the magnitude of the $Z_{dr}$ bias. Additionally, radome seams and irregularities as well as radome wetting will also cause polarization errors and measurement biases. Such errors were not considered here (S-Pol operates without a radome and hence is free of these errors). The most promising path to reducing the SHV mode $Z_{dr}$ bias is to reduce the antenna polarization errors via antenna design. However, our model shows that if $Z_{dr}$ bias is to be kept below 0.2 dB, assuming antenna polarization errors are similar in character to S-Pol’s antenna errors, the system LDR limit must be reduced to about $-40$ dB. This is largely in agreement with Wang and Chandrasekar (2006) who quote a similar requirement of a $-44$ dB system LDR limit. Our estimated antenna errors are not worst case as was used by Wang and Chandrasekar (2006). Such a low LDR limit figure may not be cost effective to achieve with center-feed parabolic antennas, and this cost must be considered against the above-mentioned cost–benefit of implementing SHV mode dual polarization.

Acknowledgments. This research was supported in part by the Radar Operations Center (ROC) of Norman, Oklahoma. The authors thank Terry Schuur of the Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, for supplying the KOUN data, software assistance, and technical discussions. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

REFERENCES


