The Joint Polarization Experiment:

Polarimetric Radar in Forecasting and Warning Decision-Making

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Abstract

To test the utility and added value of polarimetric radar products in an operational environment, data from the KOUN polarimetric WSR-88D radar were delivered to the Norman, Oklahoma National Weather Service Weather Forecast Office (WFO) as part of the Joint POLarization Experiment (JPOLE). KOUN polarimetric base data and algorithms were used at the WFO during the decision-making and forecasting processes for severe convection, flash-floods, and winter storms. The delivery included conventional WSR-88D radar products, base polarimetric radar variables, a polarimetric hydrometeor classification algorithm, and experimental polarimetric quantitative precipitation estimation algorithms. The JPOLE data collection, delivery, and operational demonstration are described, with examples of several forecast and warning decision-making successes. Polarimetric data aided WFO forecasters during several periods of heavy rain, numerous large-hail-producing thunderstorms, tornadic and nontornadic supercell thunderstorms, and a major winter storm. Upcoming opportunities and challenges associated with the emergence of polarimetric radar data in the operational community are also described.
1. Introduction

Through several decades of studies, researchers worldwide have demonstrated the ability of polarimetric radars to provide improved rainfall estimates (e.g., Seliga and Bringi 1976, 1978; Ulbrich and Atlas 1984; Sachidananda and Zrnić 1987; Brandes et al. 2002; Ryzhkov et al. 2005a), classification of bulk hydrometeor characteristics (e.g., Hall et al. 1980, 1984; Höller et al. 1994; Vivekanandan et al. 1999; Liu and Chandrasekar 2000; Straka et al. 2000; Zrnić et al. 2001; Schuur et al. 2003a), and better data quality through the recognition and elimination of nonmeteorological echoes (e.g., Ryzhkov et al. 2002; Zrnić and Ryzhkov 1999, 2004). These results, however, were mostly obtained using much different scanning strategies than required by Weather Surveillance Radar - 1988 Doppler (WSR-88D) guidelines.

In the spring of 2003, the National Severe Storms Laboratory (NSSL) in Norman, Oklahoma conducted the Joint Polarization Experiment (JPOLE), which was designed in part to test in an operational environment the utility and added value of real-time polarimetric data and products collected by a prototype polarimetric WSR-88D radar (hereafter referred to as KOUN). This paper reports on the results of the JPOLE operational demonstration, during which real-time polarimetric data and products were delivered to forecasters at the Norman, Oklahoma National Weather Service Weather Forecast Office (WFO). An overview of JPOLE as a whole, including a discussion of polarimetric rainfall estimation and hydrometeor discrimination techniques, can be found in Ryzhkov et al. (2004).
In preparation for JPOLE, polarimetric radar data and products from the NSSL Cimarron research polarimetric radar were delivered to the WFO beginning in the spring of 2001. The data feed was switched to the KOUN radar in the spring of 2002, upon completion of the polarimetric upgrade (Melnikov et al. 2003). After approximately three months of evaluation and testing, the first high-quality KOUN dataset was delivered to the WFO on 16 June 2002. Fairly regular real-time data delivery began that fall. Data were delivered on an event-driven basis through the winter of 2002–2003, as work continued to enhance algorithm performance and streamline the real-time data processing and delivery system. All data delivered during this early JPOLE period were collected with volume coverage patterns (VCPs) that included only a few low-altitude elevation angles. Much of the early data analysis focused on developing techniques to assure high-quality radar calibration.

The JPOLE Intense Observation Period (IOP) was conducted from 15 March through 15 June 2003 in an effort to provide data in real-time to forecasters on a regular basis, and to gather their feedback and evaluation. VCPs used during the IOP were designed to emulate the elevation angles, scanning rates, and volume coverage times of the standard WSR-88D (up to 14 elevation angles every five to six minutes). In addition to the qualitative and quantitative analyses of polarimetric base data and algorithms, the data were examined to assure no degradation to conventional reflectivity and velocity information occurred.

In this paper, the operational benefits provided by polarimetric radar data and products are demonstrated. These benefits include immunity of polarimetric rainfall
estimators to partial beam blockage, mitigation of bright-band contamination and drop-size distribution variability in rainfall estimation, and the ability to remotely classify particle type, improving detection of hail, tornadoes, winter storms, and nonmeteorological echoes. Examples of enhancements to WFO warnings and forecasts will show the operational benefits radar polarimetry can provide. Finally, other possible applications in operational meteorology are discussed.

2. Overview of JPOLE Data Collection and Operational Delivery

a. KOUN data

Several “base” polarimetric products from KOUN were delivered to WFO forecasters during JPOLE. Differential reflectivity ($Z_{DR}$) is the reflectivity-weighted mean axis ratio of scatterers in a sample volume. Negative values of $Z_{DR}$ denote vertically-oriented scatterers, while positive values signify a horizontal orientation. The correlation coefficient ($\rho_{hv}$) describes the similarities in the backscatter characteristics of the horizontally- and vertically-polarized echoes. Progressively smaller $\rho_{hv}$ values indicate a progressively greater mixture of scatterer shapes, sizes, orientations, and eccentricities. Finally, specific differential phase shift ($K_{DP}$) describes the difference between propagation constants for horizontally- and vertically-polarized radar echoes over a given range interval. $K_{DP}$ values for isotropic bulk scatterers, such as falling hail, are typically near 0 deg km$^{-1}$, but can become quite large (to over 4 deg km$^{-1}$) in heavy rain. A summary of polarimetric variables and their relationship to bulk hydrometeor properties is provided by Zrnić and Ryzhkov (1999).
As noted in Ryzhkov et al. (2004), the KOUN data archive contains a collection of 98 cases, including both warm- and cold-season weather events, as well as meteorological and nonmeteorological echoes. Among the warm-season events are tornadic events on two consecutive days in the Oklahoma City area, several nontornadic supercells, a severe storm that produced hail over 13 cm in diameter, numerous other damaging hail events, and convective cells producing high rainfall rates. Among the cold-season events are a major winter storm with mixed precipitation types, two significant snowfall events on consecutive days, and several systems producing stratiform precipitation and “bright-band” reflectivity signatures. The database provides a unique opportunity to examine the accuracy and skill of the quantitative precipitation estimation algorithms (QPEAs) and hydrometeor classification algorithm (HCA) on storms having significant economic and societal impacts. Furthermore, since several tornadoes occurred near the KOUN radar, these data set the stage for studying the potential use of polarimetric signatures to improve tornado warning lead time.

A variety of nonmeteorological echoes were also observed by KOUN, including those due to anomalous propagation, birds, insects, and chaff. Many of these nonmeteorological echoes were observed by KOUN in clear air conditions (15 events), whereas others were concurrent with precipitation (31 events). Some of the nonmeteorological echoes were embedded within precipitation while others were not. This archive provides ample data to establish the efficacy of the dual-polarimetric-based HCA in identifying and mitigating the effects of ground clutter, anomalous propagation, and biological scatterers.
Verification of observed polarimetric signatures was a major focus of JPOLE. Two hail-intercept vehicles were available from 28 April through 13 June 2003. During the course of the project, cars were staffed by University of Oklahoma students and two members of the operational demonstration team. The purpose of the hail-chase effort was to intercept thunderstorm cores that had the potential to produce hail at the surface. Observations from the chase teams were compared with KOUN HCA output at low levels to verify the algorithm’s ability to discriminate between rain and hail. The vehicles collected more than 28 hours of data on five separate days, and these data continue to aid in the analysis of JPOLE data sets and will lead to improvements in the HCA (Heinselman and Ryzhkov 2004).

b. Operational Data Delivery

Since the insight of operational forecasters was vital to the evaluation of polarimetric WSR-88D radar products and display concepts, great emphasis was placed on forecaster interactions during the IOP. NSSL observers were scheduled to assist WFO forecasters in the analysis and interpretation of the polarimetric radar data and products for each significant weather event. Feedback and comments from WFO forecasters were compiled from evaluation forms that were designed to determine the usefulness and performance of each polarimetric measurement and product (Schuur et al. 2003b). This information was used to improve polarimetric system performance.

Table 1 describes the KOUN data and products delivered to WFO forecasters. These data were successfully delivered to the WFO for about 480 hours during the IOP.
The data were viewed at the WFO on two Linux workstations that ran the NSSL Warning Decision Support System - Integrated Information (WDSS-II) software package (Hondl 2002). An NSSL representative was at the WFO for at least a portion of 22 separate significant weather events.

During severe weather events, the NSSL representative would simultaneously observe the data and update forecast staff on polarimetric signatures and products potentially useful in the warning decision process. The WFO and NSSL meteorologists were asked to record instances of KOUN data integration into WFO operations, note polarimetric characteristics in hazardous weather (including winter storms, flooding rains, squall lines, supercells, tornadoes, and hail), and evaluate the performance of the polarimetric QPEAs and HCA. Additionally, NSSL meteorologists were asked to coordinate KOUN usage and calibration issues with radar operators, assist WFO staff in collecting verification information, and give “on-the-fly” training to forecasters on polarimetric theory, signatures, and WDSS-II software.

3. Rainfall Estimation

In their written feedback, WFO forecasters strongly agreed that polarimetric radar provided significantly improved rainfall accumulation estimates during JPOLE. Several forecasters remarked this capability will likely be a significant benefit to operational meteorology. Forecasters used and evaluated the traditional $R(Z)$ QPEA, which estimates rain rate $R$ using only reflectivity $Z$, and three QPEAs using polarimetric variables: one using reflectivity and differential reflectivity $Z_{DR}$, $R(Z, Z_{DR})$, a second using only specific
differential phase shift $K_{dp}$, $R(K_{dp})$, and a third using specific differential phase shift and differential reflectivity, $R(K_{dp}, Z_{dr})$. After the JPOLE IOP, a “synthetic” $R(Z, K_{dp}, Z_{dr})$ algorithm was developed, as described by Ryzhkov et al. (2005a), which uses $R(Z, Z_{dr})$ in areas of light rain, $R(K_{dp}, Z_{dr})$ in moderate rain, and $R(K_{dp})$ in areas of heavy rain.

Experience during JPOLE suggests polarimetric radar QPEAs outperform the traditional $R(Z)$ algorithm in several regimes. Later statistical study of the JPOLE data confirmed these observations (Ryzhkov et al. 2004). First, bright-band echoes, or regions of enhanced radar reflectivity associated with the melting of snow and graupel aloft, typically cause an overestimate of rain amounts by the traditional $R(Z)$ algorithm. Second, $R(Z)$ typically underestimates precipitation due to attenuation, which is frequently observed when the radar signal propagates through heavy precipitation or when the radome is wet. Finally, the $R(Z)$ relation is often variable in both time and space due to variability in the drop-size distribution (DSD). Since polarimetric variables help mitigate uncertainties due to DSD variability and hail contamination, polarimetric QPEAs show much improved rainfall estimation (Ryzhkov et al. 2004). This is a major advantage in regions of complex precipitation regimes (e.g., in mixtures of stratiform and convective precipitation or in regions with hail).

The flexibility and superior performance of polarimetric QPEAs have major implications for operational meteorologists and their users. In warning for flash-floods, forecasters can exhibit better confidence in the provided radar rainfall estimates and potentially reduce false alarms. The polarimetric QPEA output from a rainfall event can be used more effectively in water-resource management and remote estimations of soil
moisture content. These improvements will help hydrological models produce better flash-flood guidance and river-forecast information, aiding forecasts for flooding in the one- to three-day period. Three cases during JPOLE highlight the advantages of polarimetric rainfall estimation.

a. 18–20 October 2002: Heavy Rain and Bright-Banding

A heavy rain event in the Red River valley of southern Oklahoma, a sensitive area for water-resource management and hydrologic modeling, began late on 18 October 2002 and ended early on 20 October, in a region centered about 180 km south and southeast of KOUN. The bulk of the heavy rain, with reported amounts up to 80 mm (3.15 inches), fell during the daylight hours of 19 October. Conventional $R(Z)$ estimates were considerably higher than the polarimetric $R(K_{dp})$ estimates in this case (Fig. 1); $R(Z)$ values near 150 mm and $R(K_{dp})$ values near 80 mm were observed in the vicinity of the highest reported rainfall total. Further, the $R(Z)$ algorithm suffered from regions of partial beam blockage, revealed by azimuths with anomalously low $R$ compared to adjacent azimuths. $K_{dp}$ is immune to partial beam blockage, so the $R(K_{dp})$ algorithm did not show such abnormalities.

As a result of the enhanced reflectivity in the bright-band, the $R(Z)$ estimates were significantly inflated above the reported totals. Although $R(Z)$ estimated rain accumulations were near or slightly above the “flash-flood guidance” available to forecasters (rainfall rates estimated to be sufficient to cause local flash-flooding, as determined by National Weather Service River Forecast Centers), forecasters reported
they were able to use the polarimetric QPEA output to be confident flash-flooding was not a major concern; forecasters could instead focus staffing resources on other forecast issues. With the polarimetric data, users could be more confident in rainfall accumulations than they could be with only $R(Z)$ data and avoid over-forecasting the resultant river and lake levels.

b. 8 September 2002: Rain in a “Tropical” Environment

The air mass over Oklahoma on 8 September 2002 was maritime tropical, according to observed regional soundings. Scattered thunderstorms and larger areas of light, stratiform precipitation were observed. The $R(Z, K_{DP}, Z_{DR})$ algorithm showed important differences from the traditional $R(Z)$ algorithm (Fig. 2). In areas affected by convection, $R(Z, K_{DP}, Z_{DR})$ showed up to 40% higher rainfall accumulation than $R(Z)$. On the other hand, during the same period, the $R(Z, K_{DP}, Z_{DR})$ algorithm showed up to 25% less accumulation than $R(Z)$ in regions characterized by lighter, stratiform precipitation. Available gage measurements showed better agreement with $R(Z, K_{DP}, Z_{DR})$ algorithm output than $R(Z)$ output.

The different behaviors of the algorithms in this case are explained by the DSDs typical of precipitation in tropical air masses (Bringi et al. 2003). The $R(Z)$ algorithm underestimated the rainfall accumulations in the convective regions due to a DSD characterized by a relatively high concentration of small drops compared to typical continental convection. $R(Z)$ overestimated accumulations in the stratiform region where the DSD was dominated by a relatively sparse concentration of larger drops. In cases of
light ambient winds and a tropical air mass, heavy precipitation may persist in some areas for many hours, and these $R(Z)$ errors can accumulate to become quite large. These improvements can give forecasters and other data users better confidence in remote rainfall accumulation estimation in tropical environments than the $R(Z)$ estimator alone can provide.

c. 14 May 2003: Heavy Rain and Hail in Supercellular Convection

A northwest-southeast oriented line of supercell thunderstorms was observed by KOUN on the morning of 14 May 2003. These thunderstorms produced wide swaths of damaging hail over a 6-h period. The supercells moved from northwest to southeast, so some locations were affected by several different supercells in a short amount of time, and flash-flooding became a major warning concern at the WFO. The conventional $R(Z)$ algorithm showed accumulations 50% to 75% higher than $R(Z, K_{DP}, Z_{DR})$ in the heavy rain areas (Fig. 3). The water coats around melting hailstones in free fall can grow very large compared to the average rain drop size, yielding a DSD that causes the $R(Z)$ algorithm to severely overestimate the rain rate (despite the 53-dBZ “cap” on reflectivity in the $R(Z)$ relation). As discussed in Ryzhkov et al. (2005b), in heavy rain rates the rainfall estimator $R(K_{DP})$ is most reliable, and was the output used by forecasters during the 14 May 2003 event.

The amounts depicted by $R(Z)$ in the 14 May case reached or slightly exceeded the flash-flood guidance values available to WFO forecasters. Forecasters were able to
use the superior polarimetric QPEA output to be assured the flash-flooding threat did not require the issuance of warnings, and no flash-flooding was reported.

4. Signatures Related to Deep Moist Convection

a. The “$Z_{DR}$ column” signature

Another unique polarimetric radar signature often observed is a vertical area of enhanced differential reflectivity above the ambient melting level, often called a “$Z_{DR}$ column” (e.g., Bringi et al. 1991; Brandes et al. 1995). The $Z_{DR}$ column is a region of enhanced $Z_{DR}$ values extending above the freezing level, associated with rising motion. Enhanced $Z_{DR}$ and low $Z$ implies the presence of oblate hydrometeors (liquid drops), and in situ data confirm the presence of low concentrations of 1–3 mm diameter liquid drops or drops with ice cores and rising motion within $Z_{DR}$ columns (Loney et al. 2002; Schlatter 2003, among others).

The precise placement of $Z_{DR}$ columns relative to the updraft differs from storm to storm. For example, Bringi et al. (1991) studied a Florida multicell storm and found the $Z_{DR}$ columns and main updrafts collocated, while studies from supercells in Oklahoma and Colorado have found a $Z_{DR}$ column on a flank of the main updraft (e.g., Conway and Zrnić 1993; Askelson et al. 1998; Hubbert et al. 1998). The drops within any $Z_{DR}$ column are either advected into an updraft from elsewhere below the 0°C level, or may grow in situ. $Z_{DR}$ columns are therefore good indicators of regions of updraft in any particular storm, and the further above the 0°C the column extends, the more vigorous the updraft.
The case of the afternoon of 10 May 2003 is an excellent example of the operational utility of the \( Z_{DR} \) column signature (Fig. 4). Available model guidance and observational data indicated that severe storms were likely to develop along a dryline in central Oklahoma during the afternoon hours. If storms developed, very favorable low-level wind shear and thermodynamic profiles were expected to sustain significant tornadic supercells in the region for the third consecutive day. Thus, before and during the beginning stages of the 10 May event, WFO forecasts reflected a substantial threat of “high-end” severe weather, including the possibility of long-track and violent tornadoes. Forecasters were also more likely to issue tornado warnings earlier and at lower radar-based thresholds than on most other typical severe weather days.

Although thunderstorms did develop and propagate off the dryline into the warm sector as expected, forecasters using KOUN data noted that \( Z_{DR} \) columns associated with strong convective updrafts weakened as they propagated east and away from the dryline circulation (Fig. 4a), and did not resemble the well-defined \( Z_{DR} \) columns typically associated with supercells (e.g., Fig. 4b). This strongly suggested the vigorous updrafts that were being forced by the dryline circulation were unable to be maintained in the warm sector, despite the continuing high reflectivity values observed in some storm cells. Within two hours after initial storm development WFO forecasters had deduced something was wrong with the initial forecast of a high-end event, and enhanced situation awareness aided by KOUN data initiated a rapid and significant change in the forecast philosophy. Forecasts from WFO Norman were changed from ones representative of a “high-end” severe weather day to ones more representative of a typical severe weather
day. Accomplishing such a successful change in overall office forecast philosophy is often a very challenging goal to achieve in mid-event in a timely manner (Quoetone et al. 2001).

b. Polarimetric hail detection

Researchers have long demonstrated an enhanced ability to discriminate hail using polarimetric radar data (e.g., Aydin et al. 1986; Balakrishnan and Zrnić 1990; Bringi and Chandrasekar 2001). Hail is usually recognized by low $Z_{DR}$ combined with high $Z$, due to the bulk isotropic profile of hailstones in free-fall. In many cases storms with high $Z$ values exhibit a local minimum in $Z_{DR}$, indicating the presence of hail, while storms with similar $Z$ characteristics do not show a minimum in $Z_{DR}$. In the case of Fig. 5, at 2300 UTC on 10 June 2003, the thunderstorm's core is marked by reflectivity to 60 dBZ, corresponding with a local minimum in $Z_{DR}$. HCA output alerted forecasters to the presence of hail, and hail larger than 2 cm in diameter was observed by one of the JPOLE hail-intercept vehicles in the vicinity of the signature from 2327 to 2339 UTC.

These signatures allow forecasters and the HCA to determine with higher confidence whether hail is present. Typically, $\rho_{hv}$ is also reduced in rain/hail mixtures due to diverse hydrometeor shapes and sizes, and in areas of large hail due to resonance scattering. One storm observed during JPOLE, responsible for producing hail at the surface over 13 cm (5.25 inches) in diameter, exhibited $Z$ values near 70 dBZ, $Z_{DR}$ near -0.5 dB, and $\rho_{hv}$ as low as 0.7. This combination of values strongly suggested the
presence of giant, water coated hail, and forecasters issued strongly-worded warnings, alerting users to the likelihood of destructive hail.

While traditional WSR-88D hail detection algorithms, by design, offer one value for probability of hail for an entire storm, polarimetric variables can yield a three-dimensional mapping of hail location, allowing more specific hail threat information to be passed from forecasters to users. Fig. 6 illustrates how the explicit hail mapping information polarization information can aid forecasters. While the legacy WSR-88D hail detection algorithm outputs one probability of hail number for an entire large thunderstorm (100%), the HCA output correctly detected no hail above the location of a JPOLE hail-intercept vehicle.

During JPOLE, the HCA offered forecasters algorithm guidance with explicit mapping of hail location, and scored a higher probability of detection and lower false alarm rate than the legacy hail algorithm. Quantitative analyses of HCA skill can be found in Ryzhkov et al. (2004) and Heinselman and Ryzhkov (2004). Using the JPOLE data set, investigators are also attempting to employ polarimetric variables in the improvement of hail size estimation and forecasting.

c. Tornado debris signature

Polarimetric radar information can help alert forecasters to the presence of tornadic debris. Significant tornadoes struck the Oklahoma City area twice in a 30-h period, on 8 May 2003 and 9 May 2003 (10 May UTC). Both of these tornadoes were relatively close to the radar and produced well-defined debris signatures in the
polarimetric and conventional reflectivity fields, as discussed in detail by Ryzhkov et al. (2005b). It is presently unclear to what distance and tornado intensity this signature can be expected to be identifiable.

The 8 May 2003 tornado lofted substantial amounts of debris within 15 km of the radar, allowing very easy identification. The second tornado occurred after local sunset in an area with numerous trees, thus storm spotters faced difficulty confirming the presence of a tornado. Although a tornado warning was already in effect when the signature was observed in both cases, the debris detection increased confidence at the WFO that a damaging tornado was in progress, and forecasters were able to use enhanced wording in follow-up statements.

5. Winter Storms

Operational advantages of polarimetric radar are not limited to warm-season convective events. The altitude of the melting layer or freezing level can be critical to operational meteorologists needing to forecast precipitation type (Scharfenberg and Maxwell 2003), and can be well-observed by polarimetric radar (Ikeda and Brandes 2003). Such capability may also prove critical in determining the altitude of the snow level in mountainous terrain.

Polarimetric classification capability proved to be particularly beneficial during a winter storm on 24–25 February 2003 in southern Oklahoma. Snow was the primary precipitation type produced by this storm in the affected areas of southern Oklahoma, with a 65 km-wide area where storm total accumulations were in excess of 10 cm (4 in.),
and maximum amounts were near 25 cm (10 in.). Despite some sampling limitations due to range, real-time evaluation of KOUN data was quite helpful to WFO forecasters during this event (Miller and Scharfenberg 2003).

The synoptic situation was typical for a heavy snow event in Oklahoma (Branick 1985): A strong baroclinic zone extended from northwest Texas into Arkansas, with a mid-tropospheric shortwave trough moving eastward into the region. Although only a weak surface reflection of this feature was noted, lower- to mid-tropospheric deformation within the baroclinic zone resulted in strong frontogenetic forcing and ascent. However, up until the onset of precipitation, forecast confidence in heavy snow accumulation was low, due to forecast thermodynamic profiles that were considered borderline regarding precipitation type. A winter weather advisory was issued at 2036 UTC on 24 February for ~2.5 to 5 cm (one to two inches) of total snow accumulation in southern Oklahoma, with a significant amount of the precipitation expected to fall as freezing rain and/or ice pellets, greatly limiting snow accumulations. Forecasters did acknowledge, however, that sufficient atmospheric cooling due to strong deep-layer ascent, and/or diabatic cooling from melting snow (Kain et al. 2000), could change the dominant precipitation type to snow.

Precipitation developed over southern Oklahoma during the mid- to late-afternoon hours on 24 February, and rapidly increased in areal coverage and intensity between 2030 and 2130 UTC. During this time, forecasters monitored both traditional WSR-88D imagery from KTLX, and Z, ZDR and ρcv data from KOUN (Fig. 7a). Several calls were made to spotters to ascertain precipitation type. During the early stages of the event, one
spotter report confirmed a mixture of freezing rain, ice pellets, and snow (marked by the arrow in Fig. 7a).

Over the next two hours (Fig. 7b), forecasters observed a decrease in $Z_{DR}$ and increase in $\rho_{hv}$, signaling a change in the precipitation regime from mixed-phase to a single precipitation type. The changes in KOUN polarimetric radar data prompted additional calls to spotters, one of whom confirmed most of the precipitation had changed to snow by 2345 UTC (arrows in Fig. 7b). WFO forecasters successfully upgraded to a heavy snow warning based on this new information. Up to 25 cm (10 inches) of snow was reported, a climatologically rare event in the southern part of Oklahoma (Branick 2002), underscoring the importance of an early warning. KOUN’s depiction of the rapidly evolving precipitation type in this case led to greatly increased situation awareness and likely resulted in several hours additional lead time in upgrading to a heavy snow warning.

Polarimetric radar data also may be used to differentiate between regions of snow dominated by dry crystals and regions dominated by wet aggregates. These different types of crystals have very different liquid equivalents (Ryzhkov et al. 1998) for a given radar reflectivity factor, and the ability to discriminate between them using polarimetric variables will improve the performance of radar-based snow accumulation algorithms and potentially aid in detecting conditions favorable for hazardous aircraft icing. Such improvements may have major benefits in water-resource management, particularly in areas dependent on seasonal snow melt.
6. Benefits and Other Applications

Polarimetric radar data provided numerous benefits to Norman, Oklahoma WFO forecasters during JPOLE. The explicit depiction of features such as hail cores, tornadic debris, and heavy rain cores, which are much smaller than the overall storm scale, frequently aided in enhanced forecaster situation awareness. Perhaps most importantly, identification of these very small-scale signatures associated with dangerous weather enabled forecasters to issue warnings, statements, and graphical guidance for these events with greater spatial and temporal precision and with a higher level of confidence than ever before.

Other areas of research were too nascent during JPOLE to be tested operationally, but also show potential benefit to the operational community. A small number of observations suggest that the melting hail associated with wet microbursts has an identifiable polarimetric signature (Scharfenberg 2003). The water-coated, melting hail aloft in wet microbursts has a clear signature of enhanced $Z$, lowered $Z_{DR}$ and $\rho_{hv}$, and very high $K_{DP}$. Microbursts produced by severe thunderstorms are a difficult warning problem, and such a signature may provide additional warning lead time. In addition, the microphysical evolution near the upshear flank of supercell thunderstorms is being carefully scrutinized to determine if these data may be used to delineate between tornadic and nontornadic supercells. Further, polarimetric data input into storm-scale models may prove helpful in modeling the behavior of supercell convection (Weygandt et al. 2002).

Improvements to radar data quality, including the discrimination of nonmeteorological echoes, are expected to have a wide-ranging impact. For example,
many users (aviation and others) want a radar display showing only meteorological echoes. The HCA shows great skill in discriminating nonmeteorological echoes such as anomalous propagation, birds, and insects (Schuur et al. 2003a), ground and sea clutter (Ryzhkov et al. 2002), and chaff (Zrnić and Ryzhkov 2004). Successfully classifying birds would allow these scatterers to be removed from velocity azimuth display (VAD) wind profiles, thus eliminating a frequent source of contamination. Partial beam blockage in heavy precipitation often has unwanted effects on radar reflectivity. Differential phase measurements from polarimetric radar may be used to quantify these effects and correct the displayed reflectivity field.

The ability to discriminate nonmeteorological scatterers is well-illustrated by the case of 6 February 2003. On that date, a band of snow was moving across northern Oklahoma. A region of echoes that had similar $Z$ characteristics appeared in southwestern Oklahoma (Fig. 8). The polarimetric data revealed these echoes were not meteorological; $\rho_{hv}$ values were considerably lower and $Z_{DR}$ considerably higher than in the snow echoes. These echoes were found to be the result of chaff released upstream.

7. Concluding Remarks

Data delivered to the National Weather Service Weather Forecast Office (WFO) in Norman during the Joint Polarization Experiment (JPOLE) demonstrated the ability of a polarimetric WSR-88D radar to: (1) improve radar rainfall estimation, (2) accurately discriminate hydrometeor type and identify nonmeteorological scatterers, and (3) improve
data quality. Polarimetric radar can be a major asset to operational meteorologists on a national scale and benefit users in a variety of other fields.

A final goal of JPOLE was to provide research and analysis that could be used to conduct a cost/benefit study and to demonstrate the economic benefits provided by a potential national network of polarimetric WSR-88D radars. The possible economic benefits of such a network are substantial, and a number of industries can benefit from polarimetric radar. For example, improved detection of nonmeteorological echoes has the potential to greatly enhance data quality and improve rainfall accumulation estimates, aiding hydrologic interests. Improved detection of precipitation type may benefit transportation administration capabilities (through, for example, airspace recovery times and highway closures).

Feedback from operational users will be an integral part in developing this rapidly emerging technology. On evaluation forms, WFO forecasters strongly agreed polarimetric data were a valuable addition to operations (Schuur et al. 2003b). The polarimetric QPEAs received particularly high marks, and in several cases, forecasters said these algorithms were used specifically in the decision not to issue flash-flood warnings in regions where the traditional $R(Z)$ rainfall accumulations were incorrectly inflated. Several forecasters used $Z_{DR}$ to identify regions of enhanced hail threat and areas of supercooled water above the melting level in convective updrafts. Forecasters showed a great deal of confidence in the HCA output, particularly regarding the discrimination between rain and hail, and between precipitating and nonprecipitating scatterers.
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Table 1. Partial list of products made available to WFO Norman forecasters from KOUN polarimetric WSR-88D radar, and their abbreviations. Doviak and Zrnić (1993) and Bringi and Chandrasekar (2001) provide detailed descriptions of $Z$, $Z_{DR}$, $K_{DP}$, and $\rho_{hv}$. Schuur et al. (2003a) details the HCA, and the Quantitative Precipitation Estimation (QPE) Algorithms are described by Ryzhkov et al. (2003).

<table>
<thead>
<tr>
<th>Product</th>
<th>Abbreviation</th>
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</thead>
<tbody>
<tr>
<td>Reflectivity Factor at Horizontal Polarization</td>
<td>$Z$</td>
</tr>
<tr>
<td>Differential Reflectivity</td>
<td>$Z_{DR}$</td>
</tr>
<tr>
<td>Specific Differential Phase Shift</td>
<td>$K_{DP}$</td>
</tr>
<tr>
<td>Correlation Coefficient</td>
<td>$\rho_{hv}$</td>
</tr>
<tr>
<td>Hydrometeor Classification Algorithm</td>
<td>$HCA$</td>
</tr>
<tr>
<td>QPE Algorithm using $Z$</td>
<td>$R(Z)$</td>
</tr>
<tr>
<td>QPE Algorithm using $Z$ and $Z_{DR}$</td>
<td>$R(Z, Z_{DR})$</td>
</tr>
<tr>
<td>QPE Algorithm using $K_{DP}$ and $Z_{DR}$</td>
<td>$R(K_{DP}, Z_{DR})$</td>
</tr>
<tr>
<td>QPE Algorithm using $K_{DP}$</td>
<td>$R(K_{DP})$</td>
</tr>
<tr>
<td>QPE Algorithm using $Z$, $K_{DP}$, and $Z_{DR}$</td>
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</tr>
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</table>
Figure Captions

**Fig 1.** (a) KOUN radar rainfall accumulation estimation using the standard WSR-88D $R(Z)$ relation from 18 October 2002, 1400 UTC, to 20 October 2002, 1400 UTC in a region of reflectivity “bright-band” echoes. Overlaid numbers indicate rainfall accumulation reports (inches) from rain gage data courtesy of the Oklahoma Climatological Survey’s Oklahoma Mesonet. (b) As in (a), but the KOUN polarimetric radar rainfall accumulation estimation using specific differential phase shift, $R(K_{dp})$. Rainfall estimates based on data collected at approximately 3.5 km altitude above radar level (ARL) (180 km range at 0.5 degrees elevation angle).

**Fig. 2.** (a) KOUN radar rainfall accumulation estimation using the standard WSR-88D $R(Z)$ relation, 8 September 2002 from 1720 UTC to 1820 UTC, depicting precipitation areas in a tropical air mass. Circles represent areas of convection and arrows represent regions of stratiform precipitation. (b) As in (a), but the KOUN polarimetric $R(Z, K_{dp}, Z_{dr})$ algorithm. Rainfall estimates based on data collected at approximately 3.5 km altitude ARL (180 km range at 0.5 degrees elevation angle).

**Fig. 3.** (a) KOUN radar rainfall accumulation using the standard WSR-88D $R(Z)$ relation, 14 May 2003 from 0653 UTC to 0953 UTC, in a region of supercell convection. Overlaid numbers indicate rainfall accumulation reports (inches) from rain gage data courtesy of the Oklahoma Climatological Survey’s Oklahoma Mesonet. (b) As in (a), but the KOUN
polarimetric \( R(Z, K_{DR}, Z_{DR}) \) algorithm. Rainfall estimates based on data collected at approximately 0.4 km altitude ARL (40 km range at 0.5 degrees elevation angle).

**Fig. 4.** (a) Reflectivity (Z, left) and differential reflectivity (Z_{DR}, right) for a severe nonsupercell thunderstorm on 10 May 2003 at 1831 UTC, at an altitude of approximately 6.0 km ARL (92 km range at 3.5 degrees elevation angle). According to a sounding launched from KOUN at 1700 UTC, the temperature at this altitude (1.5 km above the 0°C level) was -11°C. (b) As in (a), but for a tornadic supercell on 8 May 2003 at 2151 UTC, and altitude 6.1 km ARL (24 km range at 14 degrees elevation angle). According to a sounding launched at 1700 UTC on this date, the temperature at this altitude (1.7 km above the 0°C level) was -12°C.

**Fig. 5.** (a) Reflectivity (Z, left), differential reflectivity (Z_{DR}, center), and hydrometeor classification algorithm output (HCA, right) images from KOUN polarimetric WSR-88D, 10 June 2003 at 2300 UTC. Data height approximately 0.9 km ARL (0.0 degree elevation angle at 124 km range). (b) As in (a), but a different thunderstorm at a similar range from the radar.

**Fig. 6.** (a) Reflectivity (top) and storm cell attributes table (bottom) from KTLX WSR-88D, 2301 UTC, 10 June 2003. The attributes table indicates the legacy hail detection algorithm has a calculated probability of hail (POH) for cell 68 (circled) of 100%. The location of a JPOLE hail-intercept vehicle is marked by the star. (b) Hydrometeor
classification algorithm output from KOUN polarimetric WSR-88D radar at approximately the same time as the image in (a). Data height in both (a) and (b) is about 0.9 km ARL (0.0 degrees at 124 km range).

**Fig. 7.** (a) Reflectivity ($Z$, left), differential reflectivity ($Z_{DR}$, center), and correlation coefficient ($\rho_{hv}$, right) images from KOUN polarimetric WSR-88D, 24 February 2003 at 2141 UTC. An area of enhanced $Z$ is associated with high $Z_{DR}$ and low $\rho_{hv}$. A weather spotter is located at the location marked with the arrows. Data height is approximately 2 km ARL (125 km at 0.5 degrees elevation angle). (b) As in (a), but at 2333 UTC.

**Fig. 8.** Reflectivity ($Z$, left), differential reflectivity ($Z_{DR}$, right) and correlation coefficient ($\rho_{hv}$, right) from KOUN polarimetric WSR-88D on 6 February 2003 at 2343 UTC. Echoes over the northern half of the radar range are the result of light snow, while echoes over southern Oklahoma are due to a cloud of chaff. No ground clutter filtering was applied to these radar data; the echoes near the center of the image are ground clutter. Data height at the chaff cloud is approximately 3 km ARL (165 km at 0.5 degrees elevation angle).
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