NEXT GENERATION WEATHER RADAR PROGRAM

OPERATIONAL SUPPORT FACILITY

A REVIEW OF RESEARCH AND DEVELOPMENT ACTIVITY RELATED TO WSR-88D ALGORITHMS

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1 INTRODUCTION

This year's research survey was conducted as in previous years. A total of 99 survey announcements were mailed to individuals and organizations who had responded in the past and to organizations engaged in radar-based research. Responses were received from 16 organizations (including research laboratories, universities, and operational groups).

Now that the operational network of WSR-88D's is in place, there is considerable local effort to evaluate algorithms and to enhance them through adaptable parameter studies. Much of this activity is summarized in conference proceedings of the American Meteorological Society and in a special issue of Weather and Forecasting (June 1998). Among papers in the special issue is an update on the Next Generation Radar (NEXRAD) and a visionary look into the future (Crum et al., 1998).

Research topics of recent heightened activity are hail detection, precipitation measurement, and radar polarimetry. Several studies examine the utility of the current WSR-88D Hail Detection Algorithm. Findings indicate that the algorithm offers important guidance, especially if combined with other data sources. Interest also continues in the use of vertically-integrated liquid (VIL) and "VIL density" for hail detection and size estimation.

A number of groups are involved with improving the WSR-88D Precipitation Processing System. Studies reported here evaluate current products, seek to optimize adaptable parameters, and explore other approaches to rainfall measurement. Several organizations are developing correction schemes for mitigating bright band effects on rainfall estimates.

Polarimetry is a popular area of basic research. Applications include precipitation type (rain/snow) characterization, quantitative precipitation estimation, hail detection, attenuation correction, designation of hydrometeor types, and the detection of insects and birds.

New and growing activities are the production of radar mosaics, the development of bistatic radar systems for realtime wind field analysis, and rainfall "prediction" by echo extrapolation.

The format of this report closely follows that of the past several years. The Topical Activities Summary (Section 2) roughly conforms with the technical needs identified by the NEXRAD Technical Advisory Committee (Appendix A). A description of on going research at responding organizations is presented in Section 3. Brief reviews of recently published papers and conference presentations relevant to WSR-88D algorithms can be found in Section 4.

2 TOPICAL ACTIVITIES SUMMARY

2.1 Archive of Storm Phenomena

The National Severe Storms Laboratory has been maintaining an archive of severe weather events (hail, tornadoes, and wind storms) for algorithm development and research (Section 3.3.3.4). The Level II database now consists of more than 1200 data tapes. Ground truth information is available for 1995 and prior years.

2.2 Velocity Dealiasing and Range Unfolding

Simulated radar echoes were used in a study by Strauch and Frehlich (1998) to determine if single-pulse velocity estimates provide sufficient accuracy to resolve ambiguities inherent in pulsed Doppler radar measurements. Rather than the usual sampling at a particular range location once after each pulse, single-pulse estimation uses a broadband receiver and averages samples spaced at intervals much less than the pulse duration. Unfortunately, results indicate that a large number of spatial samples would be required.

Zhang et al. (1997) propose that ambiguities arising from range and velocity folding be mitigated simultaneously by phase coding (i.e., transmitted pulses have a specific identification code) and staggered pulses. They show that phase coding and staggered pulse repetition times (PRT's) are compatible and that the standard deviation of the mean velocity estimate is within 10 m s^{-1} at low signal-to-noise ratios. The tested combination purportedly extended the unambiguous range and velocity from 150 km and 25 m s^{-1} to 350 km and 75 m s^{-1}. Other methods for retrieving overlaid second trip echoes with phase coded radar signals are described by Liu and Liu (1997) and Sachidananda and Zrnić (1997) (Section 4).

2.3 Anomalous Propagation and Clutter Removal

Recognizing that other sources of information besides radar reflectivity can be helpful for detecting anomalous propagation (AP) echoes, a method is being developed (Pamment and Conway 1998) to include surface weather reports, infrared satellite observations, AP climatology, and lightning strike locations. The procedure is applied to individual radars and to composite reflectivity maps intended for producing precipitation analyses and initializing numerical weather prediction models. The scheme replaces an interactive system called FRONTIERS. Individual data points are assigned a "dryness" probability which is modified through a multistep Bayesian process that weights each of the input parameters. Pixels with an overall probability above some threshold are checked against a lightning map before final designation. The scheme depends primarily on the availability of satellite and surface observations. A pixel is deemed wet if the present weather code indicates precipitation, showers were reported in the vicinity, or precipitation occurred during the past hour. A distance weighing function is applied to determine the probability of dryness away from a surface report. Infrared temperatures from earth satellite are quantized into 16 classes and compared to quality controlled precipitation maps to determine the probability of precipitation for each class. A climatology in the form of the probability of precipitation echoes at a dry pixel was determined with hourly data corresponding to synoptic reporting times. All echoes within the position error of lightning strike locations are assigned an AP probability of 0.01, which forces their retention as precipitation. Case studies indicate that ~90% of all echoes are correctly designated. The inclusion of visual satellite images and pattern recognition routines for AP are listed among planned upgrades.

Operationally oriented research directed toward clutter detection and removal is progressing at several institutions. The NEXRAD OSF is improving the "tilt test" logic that removes clutter at the lowest elevation angle by comparing echo coverage at the lowest two tilts (Section 3.5.7.1). A Lincoln Laboratory algorithm that removes ~2/3 of the AP and clutter from radar composites has been installed in Build 10 (Section 3.8.4). A neural network scheme for AP detection is described by the University of Iowa (Section 3.10.1, see reference 9 abstract). A clutter detection procedure developed at McGill University incorporates local averages of radial velocity, vertical reflectivity gradients, and horizontal gradients of reflectivity (Section 3.11.5.2). Pixels where radial velocities average <1 to 2 m s^{-1} and vertical and horizontal reflectivity gradients exceed prescribed thresholds are considered to be clutter. "Holes" in the precipitation pattern are filled by interpolation in the horizontal.

May and Strauch (1998) describe a simple spectral processing procedure for removing clutter from wind profiler measurements. Compared to weather radar, clutter removal with profilers is facilitated by longer dwell times, smaller spectral clutter widths, and broader spectrum widths for "clear air" signals. This is because profiler beams are fixed and clutter is not broadened by antenna motion. On the other hand, the greater beam width of profilers widens the spectral width of clear-air returns. Nonetheless, the technique may be applicable for weather radars, particularly if the data are filtered in azimuth. Previously proposed algorithms for suppressing clutter have incorporated least squares and neural network approaches. Techniques applied to mean velocity estimates are ineffective because clutter biases and meteorological signals are often mixed. Notch filters cause significant weather signal to be lost. The technique applied by May and Strauch (detrending) assumes that clutter signals fade linearly and removes the trend from the spectra. The time series must be reasonably long (128 samples were used). Simulations revealed that the detrending technique improved clutter suppression over window (Hanning and rectangular) filtering methods. The method is also compared to the a finite impulse response (FIR) filter widely used on weather radars. Velocity biases with detrending approached that for FIR filtered data when the detrending resolution was increased.

Polarimetric measurements offer new approaches for detecting ground clutter and AP as well as for mitigating clutter effects on rainfall estimates. Ryzhkov and Zrnić (1998c; Sections 2.13 and 4) show how the cross-correlation coefficient between radar reflectivity measurements at horizontal and vertical polarization (ρ_{HV}), can be used to identify ground echoes. They also show that when ground and precipitation echoes are mixed the differential propagation phase (ϕ_{DP}) contains enough signal that specific propagation phase (K_{DP}) rainfall estimates can still be made in the clutter region.

2.4 Severe Weather Detection

2.4.1 MESOCYCLONES

Research has shown that a high percentage of thunderstorms with mesocyclonic circulations having diameters of <10 km produce severe weather and that a significant subset spawn tornadoes. Hence, there has been considerable effort to automatically detect these circulations. National Severe Storms Laboratory (NSSL) researchers, Stumpf et al. (1998), describe a new Mesocyclone Detection Algorithm (MDA) which features lowered thresholds for initial classification and performs a diagnosis in four dimensions for broad detection of weak and strong circulations. Other algorithm features include range-dependent strength thresholds, a more robust two-dimensional circulation identifier, improved vertical association, and trend information. The algorithm is designed to detect shallow circulations and larger scale circulations associated with bow echoes. The proposed algorithm processes data at the radial level to find shear segments which are combined to form two-dimensional features that are subsequently checked for vertical and temporal continuity. Other algorithm parameters are the rotational velocity, the shear, and the radial convergence. Using a comparative dataset, the NSSL MDA was found to be superior to the current WSR-88D algorithm even when the current algorithm threshold values are optimized (their Table 14). Probabilities of detection for mesocyclones with tornadoes were 46.3 to 57.6% for the proposed algorithm and 32.8 to 69.3% for various configurations of the WSR-88D algorithm. Most significant differences between the algorithms were in the Heidke skill scores (31.1 to 35.7% for the proposed algorithm and -21.9 to 24.9% for the WSR-88D algorithm).

A similar comparison of WSR-88D and NSSL Mesocyclone Detection Algorithm performance was conducted by Stuart et al. (1997; also Section 3.4.4.1). Although details of the comparison are not given, the NSSL algorithm produced many more mesocyclone detections, including some that did not produce severe weather, and tended to give detections to farther ranges. The authors attribute the improved performance of the NSSL algorithm to an ability to detect weaker circulations.

Because the NSSL MDA does not indicate severity (i.e, whether or not tornadic or damaging winds are present), a second algorithm was developed to designate those circulations with strong winds (Marzban and Stumpf 1998). The approach employs a neural network (also Section 2.11). Results with 23 storm attributes as input yielded critical success indices (CSI's) of ~50% and Heidke skill scores of 60%.

A refinement to vortex detection is undergoing testing in Japan. Both radial and azimuthal shears are computed in the study of Haneda and Uyeda (1997). Particular shear zone configurations represent vortex signatures. The zone of maximum azimuthal shear and the locations of radial convergence zones specify the vortex center and its diameter (their Figure 1).

Discrete azimuthal sampling effects on the inferred intensity of vortices observed by radar have been investigated by Wood and Brown (1998). A combined Rankine vortex was simulated and then sampled at varying radar ranges and for different beam positions relative to the vortex center. Depending on the relative location, the diameter of maximum mesocyclone winds can be over or underestimated. The latter is likely at far distances and for increased separation between the vortex core and the beam center. While the maximum rotational velocity is always underestimated and the underestimate increases with range due to smoothing within the radar beam, the relative location of the vortex to the beam also influences the radar-measured intensity. Because of their small size, the diameter of tornadic vortices is always overestimated and the peak velocity is greatly underestimated. The caution with discrete sampling is that observed changes in intensity may simply reflect sampling location randomness.

Usually, the strength of vortices is estimated by the velocity difference between the two extrema which form a velocity couplet. The procedure is subject to bias errors due to sampling (e.g., Wood and Brown 1998). Davies-Jones and Stumpf (1997) compute circulation and rate of expansion to estimate vortex strength. Circulation should have less range dependence than velocity differences. Also, the combination of significant circulation and a contracting surface would be a predictor of further intensification. The parameters are computed as the integral of tangential and normal components of velocity about a closed curve. Unobserved components of the wind are initially set to zero. Calculations were made for a test case with a tornado having a circulation of 10^5 m^2 s^{-1} at a radius of 200 m. The tornado was 51 km from the radar. Circulations were computed for radii of 0.5 to 3 km. After doubling the results to account for the unobserved wind components, it was found that the circulations and divergences were fairly independent of the averaging radius; and the circulations were close to the tornado values.

Compared to the United States, tornadoes and damaging winds are relatively rare in Canada. Nevertheless, a mesocyclone detection algorithm, based on the "pattern vector" technique has been implemented on the McGill University radar. Vaillancourt et al. (1997) present verification of the algorithm for reported tornadoes and observed winds >90 km h^{-1}. As might be predicted, preliminary results show that low threshold values detected most events (13 of 14 tornadoes) but had relatively high false alarm rates (FAR's). High thresholds reduced the FAR substantially but resulted in an increased number of missed tornadoes.

2.4.2 TORNADOES

Matson (1998) evaluated the MESOcyclone/Tornadic Vortex Signature (MESO/TVS) algorithm with data collected by the NWS Forecast Office in Little Rock, Arkansas. Archive Level II data were replayed on the WSR-88D Algorithm Testing and Display System (WATADS). The dataset was first scored on default parameters (Threshold Pattern Vector, TPV=10; Threshold TVS Shear, TTS=72 h^{-1}). The critical success index was 10%. At optimum parameter values, TPV=7 and TTS=45 h^{-1}, the algorithm CSI was 37%. The probability of detection (POD) increased from 11 to 38%. Algorithm improvement was tempered somewhat by an increase in false alarm rate (from 42 to 50%). Other benefits with the optimum parameters were an increase in lead time from 3 to 6 min and a 13% increase in tornado detections beyond 110 km. An evaluation of the Build 10 Tornado Detection Algorithm (TDA) was also conducted. A fundamental difference between the algorithms is that the TDA examines radial velocity differences at constant range (gate-to-gate) whereas the MESO/TVS algorithm examines shear between minimum and maximum velocities within a mesocyclone. The TDA was run at default settings. The POD and CSI were little changed from optimum MESO/TVS values, 41 and 37%, respectively; but the FAR fell to 14%.

Tests of the Build 10 TDA with varying reflectivity thresholds have been conducted by the NEXRAD Operational Support Facility (Section 3.5.5). Best results were for a 0 dBZ threshold (CSI's of ~0.50). Algorithm outputs for two WSR-88D's separated by 18 km had similar CSI's, but inexplicable differences were found in the POD's and FAR's. An ongoing study of the impact of the Velocity Dealiasing Algorithm on the performance of the new TDA (Section 3.5.6) found that receiver saturation can cause false TVS detections in close proximity to a radar.

2.4.3 MICROBURSTS

Smythe et al. (1997) present an independent evaluation of the Integrated Terminal Weather System (ITWS) microburst/windshear detection algorithm being developed by Lincoln Laboratory for the Federal Aviation Administration. Radial velocity and signal-to-noise ratios are the input measurements. Outputs are the location, areal extent, and intensity of divergent wind features at 0.3° antenna elevation. Interlaced sampling permits updates at 1 min intervals. Windshear is defined as velocity changes >8 m s^{-1} over distances ≤4 km; a microburst is a velocity difference of ≥15 m s^{-1} over the same distance. There is also a predictive component that incorporates sounding and VIL information. Probabilities of detection for microbursts and windshear events are very high (≥93%) and false alarm rates are low (generally <20%). For three sites, 23 to 31% of all microbursts were correctly predicted with an average lead time of 215 s.

The microburst study at the Salt Lake City NWSFO continues (Section 3.4.3.1). The work combines radar observations with stability analyses from a one-dimensional cloud model.

2.4.4 HAIL

The current WSR-88D hail algorithm is described in the recent paper of Witt et al. (1998a). The algorithm features the Probability of Hail (POH) of any size and the Probability of Severe Hail (POSH). Severe hail is defined as hail with diameters ≥19 mm. Hail occurrence is determined largely from the extension of 45 dBZ echo above the melting level. A Severe Hail Index (SHI) parameter is computed from radar reflectivity and the temperature lapse rate. Predictions of Maximum Expected Hail Size (MEHS) are also given. Verification for the probability of any-size hail is lacking, but good results are reported for Colorado. [Problems encountered when verifying algorithms are discussed in Witt et al. (1998b).] Performance of the SHI varies considerably by geographical area. Critical success indices are typically 16 to 55%. Hail size increases with the Severe Hail Index in the mean but the unexplained variance is high. Hence, the predictions may have little value [see the study of Edwards and Thompson (1998) described below and in Section 4.]

The Build 9 Hail Detection Algorithm has been evaluated for northern Ohio and northwestern Pennsylvania by Barjenburch and LaPlante (1997). The analysis was performed on archive Level II data with the WSR-88D Algorithm Testing and Display System (WATADS). The dataset consisted of 46 severe hail events on 16 days. Verification data were taken from *Storm Data*. (The usual caveats about maximum hail size estimates and likelihood of reports apply.) Algorithm output for each storm with a POSH ≥10% was scored on a scan-by-scan basis rather than the window method. Statistics were generated for a POSH ≥50%. The HDA significantly overestimated the occurrence of severe hail. For example, for populous counties and a POSH of ≥50% the observed frequency of severe hail was actually 37%. The observed ≥50% hail frequency occurred with a POSH of 70%. At this threshold the algorithm had a POD of 36%, a FAR of 58%, and a CSI of 24%. The average lead time was 16 minutes. The authors conclude that the HDA should be used only for guidance.

The vertically-integrated liquid (VIL) water is frequently used by operational meteorologists to "predict" hailstone size. The parameter is computed by vertically integrating the radar reflectivity. The presence of hail and the 6th power dependence of reflectivity on particle diameters dictates that hail associates with high reflectivity and consequently large VIL values. A number of formal and informal studies have attempted to exploit this association for estimating maximum hail size. Edwards and Thompson (1998) examined hail size relationships with VIL and thermodynamic variables for a large dataset from several geographical regions and for different seasons. Parameters such as VIL, VIL normalized by a sounding-determined equilibrium level, and VIL divided by maximum parcel level were computed and compared to the maximum reported hail size. While some parameters increased with hail size in the mean, the data reveal considerable scatter. Correlation coefficients between tested variables and hail size were insignificant (≤0.17). The lack of correlation led the authors to conclude that tested parameters had no operational value. Hailstone sizes considered in the report were well within the Mie scattering range. Failure to "predict" hail diameters may be due to the resonance between hail diameter and radar wavelength that occurs in the Mie range.

An assessment of the Build 9 Hail Detection Algorithm (the Probability of Severe Hail or POSH component) and VIL was made for a small dataset (consisting of 16 severe hail events on 6 days) in the Tallahassee, Florida area (Lenning et al. 1998). The study optimizes warning thresholds for both the POSH and VIL techniques and seeks other methods for finding thresholds. The default POSH threshold of 50% was verified indicating that the freezing level yields a reasonable estimate of the best Severe Hail Index (SHI). However, the average wet-bulb temperature in the 1000 to 700 hPa layer gave slightly better estimates of the best daily SHI threshold. Correlation coefficients between the best SHI determined from the freezing level and the low-level wet-bulb temperature were 0.55 and 0.59, respectively. Wet-bulb temperatures also improved VIL of the day estimates (a correlation coefficient of 0.68). For the six days in the study, the optimized VIL parameter seemed to have a slight edge over the optimized SHI. However, poor performance with one parameter was matched with poor performance of the other.

A study at the NWSFO in Charleston, West Virginia evaluated the VIL density parameter to detect severe hail (≥19 mm in diameter) (Section 3.4.1.1). At a threshold of 4 g m^{-3}, the POD for large hail was 91% and the FAR was 1.9%.

An evaluation of VIL density for hail detection and size estimation was conducted by Turner and Gonsowski (1997). Their data show that a VIL density threshold of 3.25 g m^{-3} identified 91% of the severe hail storms (≥19 mm) but mis-identified 43% of non-severe hail storms as severe. Maximum hail size grew with increasing VIL density. A similar study by Troutman and Rose (1997, 28th Radar Conference) shows a linear relationship between VIL density and hail size. However, no information is given concerning the scatter within the dataset.

Thunderstorms producing large hail (in the Mie scattering range) often exhibit elongated regions of radar reflectivity and radial velocity that protrude radially from the far side of the radar echo. These echoes, dubbed "hail spikes" or "hail flares", are commonly seen at elevation angles of 2 to 6° and may extend for 10 km or more beyond the storm's reflectivity core. Lemon (1998) asserts that hail flares precede the occurrence of large hail at ground by tens of minutes. Flare echoes are usually characterized by weak reflectivity (<25 dBZ). Radial velocity signatures can be complex but often show weak flow toward the radar; spectrum widths are large. Hail flares are artifacts created by three-body scattering in which transmitted energy is scattered by hail to the ground, a portion of the scattered energy is backscattered to the hail region, and the energy is scattered a third time back to the radar. Importantly, the hail resides in the storm's reflectivity core) not within the flare echo. While hail flares at S-band are sure indicators of hail, the author points out that there could be substantial melting before the hail is deposited at the earth's surface. Also, hail may exist even though a hail flare is not detected. The paper includes a discussion of operational implications.

Hubbert et al. (1998) report on a study of hail detection with polarimetric radar. Golfball-sized hail coincided with large linear depolarization ratios (LDR $\geq$-18 dB), slightly negative differential reflectivity values ($Z_{DR} \leq$-0.5 dB), and relatively low copolar correlation coefficients ($\leq$0.93). The measurements and dual-Doppler analyses suggest that raindrops, beginning as graupel in the forward anvil, and later recycled in the storm's updraft served as hail embryos.

An automated hail mapping system that uses polarimetric radar data has been developed by Colorado State University (Section 3.9.4). The algorithm, based on the hail signal of Aydin et al. (1986, J. Climate and Appl. Meteor.), utilizes reflectivity and differential reflectivity measurements and looks for departures from established relationships between these parameters for rain. Inconsistencies between observed differential phase shifts and shifts calculated from radar reflectivity and differential reflectivity measurements are the basis of a University of Reading hail detection algorithm (Section 3.13.3).

2.4.5 TURBULENCE

The Turbulent Kinetic Energy (TKE) distribution in a stratiform rain event was computed from radar measurements in the study of Kim et al. (1997). The computational method is that described earlier by one of the authors (Campistron; J. Atmos. Sci., 1991). Results show that the TKE concentrated at and just below the melting layer. A rapid increase in TKE coincided with the development of heavy rain. Richardson's numbers were greater than 2, suggesting that turbulence generated by shear was suppressed by negative buoyancy.

2.4.6 FLASH FLOODS

The performance of the WSR-88D Precipitation Processing System (PPS) in flash flood cases has been examined by Baeck and Smith (1998). They found that significant underestimates of the rainfall occurred in every case. Reasons for the underestimates varied from storm-to-storm (see also Section 2.6). In a similar study of a flash flood, Vieux and Bedient (1998) reduced the underestimates significantly with the tropical Z-R relationship $Z=250R^{1.2}$.

The flash flood which struck Fort Collins, Colorado with more than 10 inches of rain on 28 July 1997 is being studied by researchers at Colorado State University (Section 3.9.1). They implicate coupling between warm and ice processes (deduced from polarimetric measurements), topography, and interaction with the outflow from another storm complex as causes of the heavy rain.

In an attempt to add a predictive component to radar-derived rainfalls, necessary to increase flash flood warning lead times, Pereira Fo and Crawford (1997) have been developing a scheme that linearly extrapolates radar reflectivity patterns according to observed trends and hourly wind information. Error levels are high but believed to be less than those for short-term numerical forecasts.

2.4.7 TROPICAL CYCLONES

Gall et al. (1998) present a new analysis technique for studying the fine structure of hurricanes and tropical storms. Perturbation radar reflectivity fields are generated whose features are then enhanced by correlation analysis in which a cosine function is fit to the perturbations. The wavelength of the applied cosine function is varied to reveal different scales. The correlation patterns depict persistent spiral features that are distinct from larger scale rainbands. The bands are characterized by rope-like regions of high correlation that are ~10 km in width and can extend for 100 km or more. They propagate outward in a clockwise sense at speeds on the order of 10 m s^{-1} while rotating in a counterclockwise direction about the storm. Vertical cross-sections reveal that they may extend to heights of 6 km. The bands, which are roughly aligned with the low-level wind, contain updrafts and are postulated to be similar to boundary-layer rolls. Their role in storm intensification is not known.

2.4.8 SNOWFALL

Quantitative snowfall estimation with radar is complicated by the variety of hydrometeor types, shapes, and densities which can cause radar reflectivity-based estimates to differ from observed snowfalls by a factor of 10 or more. A novel approach to estimate snowfall with a neural network was recently described by Xiao et al. (1998). The method, based on a multilayer feed forward network, did not assume a particular Z-S relationship but mapped the time evolution of radar reflectivity profiles to snowgauge measurements. The profiles had 0.5 km vertical spacing for heights of 0.5 to 5 km and were found by averaging measurements over 9 km^2 areas. Predictions of 15 min liquid equivalent accumulations were then made at three verifying gauge sites located ~75 km from the radar. Different combinations of training and test datasets were examined and compared to snowfall estimates with the Marshall-Palmer relationship. Network-derived Z-S relationships for two storms had a much smaller exponent for Z_H than the Marshall-Palmer relationship and had smaller bias errors. Correlation coefficients between the radar estimates and the gauge amounts were about the same for the optimized and fixed Z-S relations. The technique has already been successfully applied for rainfall estimation [see Xiao and Chandrasekar (1997), 1998 Survey Report].

Operational algorithms for snowfall estimation are under development at the Bureau of Reclamation (Section 3.1.1) and at the National Weather Service Forecast Office in Salt Lake City

(Section 3.4.3.2). Both efforts report considerable storm-to-storm bias variation in estimated liquid equivalents and attempt to reduce the bias with gauge adjustment procedures.

Radar reflectivity from low elevation scans do not generally exhibit characteristic signatures for rain and snow. Further, bright bands may not be present in vertical cross-sections when rain forms from the melting of compact ice particles. Ryzhkov and Zrnić (1998) examine polarimetric measurements in snow storms and show that melting layers are characterized by a pronounced minimum in the cross-correlation coefficient between radar echoes at horizontal and vertical polarization (ρ_{HV}) and a maximum in the differential reflectivity (Z_{DR}). The signature is created by wet aggregates which also cause the specific differential phase (K_{DP}) to be large. The authors also find that the transition from snow to rain in horizontal cross-sections is marked by a minimum in ρ_{HV}. Snowflakes (aggregates) associate with a decrease in Z_{DR}.

Matrosov (1998) shows how dual-wavelength radar systems provide direct measurements of snowfall rate. Measurements are made both at a sufficiently long wavelength such that the snowflakes are within the Rayleigh range and at an attenuating wavelength such as K_a-band. The attenuation is used to find the median volume diameter of the snowflakes, and the snowfall rate (S) is then computed from a combination of the unattenuated radar reflectivity and D_o's expressed in the form $Z/S=AD_o^B$. Estimates are sensitive to particle density and can be refined by comparison with actual gauge amounts. Results for a dataset consisting of two storms and a single verification gauge show that dual-wavelength snowfall estimates were close to gauge amounts, while estimates with fixed Z-S relations underestimated the snowfall by a factor of 4.

2.5 Feature Detection, Tracking, and Forecasting

A capability to detect nonprecipitating clouds with the WSR-88D is compromised by Bragg scattering from refractive index inhomogeneities, residual ground clutter contamination, and biological targets. Nevertheless, there is interest in the utility of the WSR-88D to detect clouds, particularly in support of nowcasting operations and for the parameterization of clouds in forecasting models. Consequently, Miller et al. (1998) quantify WSR-88D cloud detection capabilities. The authors find that echoes of -25 dBZ (commonly observed with clouds) should be detectable with the WSR-88D in clear air mode (VCP 31) at a range of 74 km for elevation angles $\leq 2.5°$ and for 30 km in VCP 21 at angles $\leq 1.4°$. WSR-88D echoes were compared to those of a nearby vertically pointing cloud radar operating at 94-GHz. There are, of course, difficulties in comparing the discrete coarse measurements from the WSR-88D with the near continuous, high spatial resolution of the cloud radar; but reasonable agreement was found in most cases. At times, the WSR-88D detected low-level echoes >25 dBZ that were not seen with the cloud radar. Some echoes were thought due to residual ground clutter. Largest discrepancies, observed during afternoon hours, were attributed to Bragg scattering. Correlation coefficients between radar reflectivity values were rather low, 0.54 to 0.68, possibly caused by the more diverse echo sources with the WSR-88D and differences in measurement spatial resolution. The Level II data at the time of the experiments did not allow for the recording of radar reflectivities with signal-to-noise ratios <6 dB. Both systems detected echoes 82% of the time in March and 39% of the time in October.

The current WSR-88D Storm Cell Identification and Tracking (SCIT) algorithm is described by Johnson et al. (1998). To better isolate individual cells, storm tracks are computed from centroid locations rather than from cross-correlation statistics. Storm identification is based on volumetric reflectivity information. Storms are reconstructed from radial segments at various reflectivity thresholds. The segments are combined into 2D storm components which are checked for vertical continuity and for construction of 3D storm cells. Motion vectors are computed by applying a least squares fit to the cell's last position and up to 10 previous locations. POD's for cells with reflectivities >40 dBZ are 68%; POD's for cells >50 dBZ are 96%. Location errors vary from 2.0 km for 5 min forecasts to 22.8 km for 60 min forecasts.

2.6 Precipitation Analysis Techniques

The current WSR-88D rainfall estimation algorithm is described by Fulton et al. (1998). Key components are (1) a radar data preprocessing system, (2) rain-rate computation, and (3) accumulation. A realtime gauge-radar adjustment procedure is not currently operational. The preprocessing system produces a "hybrid" reflectivity scan near 1 km altitude from the lowest 4 elevation angles, performs biscan maximization (a procedure whereby the highest reflectivity from the 0.5 and 1.5° elevations is selected at distant ranges), corrects for partial beam blockage, and removes ground clutter and anomalous propagation. Shortcomings identified in the paper are the lack of objective procedures for adaptable parameter optimization, bright band mitigation, range bias correction, clutter suppression, and AP removal.

A discussion of capabilities and limitations of the current WSR-88D precipitation algorithm can be found in Hunter (1996). This study reviews the many potential sources of error in radar-derived rainfall estimates. The paper calls for specific improvements to the tilt test to prevent the loss of meteorological information at 0.5° elevation, implementation of a gauge-radar adjustment procedure, and techniques for extrapolating the vertical reflectivity profile to ground.

The performance of PPS products on two coexisting storm systems (a slow-moving multicellular storm and a fast-moving squall line) was examined by Bauer-Messmer et al. (1997). Rainfall from the multicell storm, some 120 km from the radar, was underestimated by 16%; while rainfall from the squall line, at roughly the same distance, was overestimated by 19%. Both storms produced large hail, leading the authors to hypothesize that estimate errors resulted from the "confounding influence of hail". However, no evidence is presented to support this argument.

Anagnostou and Krajewski (1998) report on efforts to optimize the selection of adaptable parameters within the WSR-88D Precipitation Processing System. The parameters can be set to account for different climates, seasons, and storm type. Anagnostou and Krajewski applied a global optimization technique designed for nonlinear multicomponent systems to two months of radar and raingauge data. The paper begins with a description of the PPS and the 12 parameters which control data quality, set thresholds for minimum rainfall rates and hail mitigation, and assign the coefficient and exponent of the Z-R relation. Performance of the parameter optimization procedure is weighed by minimizing the root-mean-square difference between gauge observations and radar estimates. Optimization is achieved in a probabilistic sense by the "shuffled complex evolution" method. Optimal parameters converged to values different than default values. For the ensemble dataset the reduction in RMSE was about 10%. Even more dramatic was the reduction in bias for ranges <100 km.

The performance of the WSR-88D PPS for estimating rainfall for 5 extremely heavy events was investigated by Baeck and Smith (1998). In each case the radar underestimated the rainfall. [The usual biases for the various radars are not discussed.] Biases increased with radar range. Bias sources, whose importance varied from storm-to-storm, were attributed to such factors as the growth of precipitation toward ground, inappropriate Z-R relations, and imposition of too low a hail threshold. Bright bands were observed with one event, but its impact was (perhaps fortuitously) to reduce the underestimate of the rainfall.

Vieux and Bedient (1998) evaluated rainfall estimates from the WSR-88D for a two-day flash flood event in which rainfall estimates from the Precipitation Processing System (PPS) were low with respect to gauge accumulations. Suspected causes were the use of an inappropriate Z-R relation and imposition of a 53 dBZ hail threshold. Another possible contributor to the underestimates mentioned in the paper is that default occultation parameters restricted realtime rainfall estimates to measurements from 2.3 and 3.3° elevation. The authors compute rain estimates with 0.5° data using both the default Z-R relation and $Z=250R^{1.2}$. The latter relationship produced underestimates of 6% on one day and overestimates of 14% on the other. Rainfall estimates with the default relationship were 55% less than those with the tropical relation. The hail threshold had little impact on the results.

The University of Iowa (Section 3.10) and Princeton University (Section 3.12) are heavily involved in efforts to improve the Precipitation Processing System with the WSR-88D. Activities at the NEXRAD OSF are described in Section 3.5.7.

Often operational users of WSR-88D Precipitation Processing System (PPS) products express the desire to specify Z-R relations. For example, users in more tropical regions wish to reduce radar underestimates characteristic of the default WSR-88D relation by applying the tropical relation of Rosenfield. The exponent of the latter relation (1.2) differs significantly from the default relation (1.4) and greatly enhances the intensity of high rain rates. Smith and Joss (1997) make a strong argument for a fixed exponent. They reason that in empirical DSD studies the exponent is often wrong because of truncation and posit that the exponent variation is at most 10%. They propose that the coefficient of the Z-R relationship be adjusted so that the median rainfall rate (defined so that values greater and smaller than the median contribute equally to the rainfall total) is unbiased. Rain rates far from the median rate will have relatively little impact on the total. They argue that exponent departures from a fixed value)they suggest 1.5)would have relatively minor impact on rainfall rates (<30% if the actual exponent differs by 0.2). Moreover, errors would tend to cancel if the exponent varies about the selected value. Thus, the problem of rainfall estimation is reduced to finding an appropriate coefficient. Empirical studies are needed to verify that a relationship exists between the median rain rate and the exponent and to find the best exponent.

Outputs from algorithms for estimating rainfall with radar are inevitably compared to raingauge measurements. Comparisons between "point" gauge observations and "volumetric" radar estimated rains are fraught with problems. For example, the sampling volumes differ by many orders of magnitude, the measurements are made at different heights, the radar makes measurements at discrete time intervals, and both gauge and radar amounts have significant error bars. Results are sensitive to how the comparison is made. Most often the gauge measurements are compared to averaged radar values. Bolen et al. (1998) seek to optimize the comparison by determining optimal, elliptically shaped regions that minimize the RMSE (difference) between the radar-derived and gauge rain rates. Because it is a relatively unbiased estimator, radar rain rates were determined from K_{DP} rather than radar reflectivity. First, a filter is applied to the gauge data to produce a time record having temporal resolution similar to that of the radar. Then the autocorrelation function is computed for the gauge data. The $1/e$ value determines the length of the radar time series for averaging. Histories of radar data at polar grid locations are then shifted in time and compared to the gauge record to find the minimum RMSE. The polar grid point with the minimum RMSE becomes the center of the ellipse. The RMSE difference field is recomputed using this distance. The procedure yields a region of minimum RMSE that is normally elliptical. One axis of the ellipse is directed from the minimum point toward the gauge; the other is in the orthogonal direction. The lengths of the axes are found by decorrelation distances. For the cases presented, averaging distances were ~1 km; and aspect ratios varied from 0.78 to 0.96. The authors state that the method provides a "meaningful" optimal area only when the radar rain-rate estimates are unbiased. If true, this would limit the utility of the method.

Pereira Fo et al. (1998) performed a detailed analysis of the stage III hourly rainfall product of the Arkansas-Red River Basin River Forecast Center (ABRFC) and compared results to a statistical analysis which combines gauge and radar information. The stage III analysis is a 4 km × 4 km regional radar mosaic constructed from stage II products (hourly, gauge-adjusted rainfalls for individual radars). In regions of overlapping radar coverage rainfall estimates are based on averages of non-zero amounts. Pereira Fo et al. compared the ABRFC product to a procedure which minimizes the error (variance) in raingauge and radar observations. Rainfall estimates are made by adding weighted differences between the two instruments to the radar-derived rain field. Weights are derived from the error variance of radar rainfall estimates. The resulting analysis error variance purportedly is less than the observation error variance. Inherent in the scheme are assumptions that biases have been removed and gauge observation and background errors (differences between the radar estimates and the true rainfall) are uncorrelated. Background error cross-correlations were found by examining a number of storm systems. The stage III ABRFC product rainfall amounts were generally lower (up to 40% for long-term accumulations) than those derived from the statistical analysis. A number of artifacts introduced into the stage III product by the ABRFC compositing process are also discussed.

The window probability matching method (WPMM) and regression analysis technique for estimating Z-R relationships were compared in a study of Rosenfeld and Amitai (1998). The WPMM pairs the probability distribution functions of radar reflectivity and gauge observations; the regression method is a straight forward analysis of rain rate and reflectivity. The evaluation was conducted with disdrometer measurements. The disdrometer-derived reflectivity estimates were averaged over a 3 min interval to simulate the larger radar sampling volume. To account for the effects of making measurements with an elevated radar beam and the difference in time for deposition at ground, temporal offsets were introduced into the reflectivity/rain rate pairs. The WPMM and regression method gave comparable results for accumulated rainfalls, but significant differences characterized instantaneous rain rates. An advantage with the WPMM is that the method automatically accounts for radar bias and for synchronization and geometric errors. When the latter errors are present, the regression analysis method tends to underestimate high rain rates and overestimate low rain rates. Apparently, as the data become more unsynchronous, the regression method degenerates to the conditional mean rainfall rate.

The change in radar reflectivity with height can be a major source of range dependent errors in rainfall estimates. If the radar beam intercepts the bright band, precipitation can be overestimated by a factor as large as 5. Errors are also introduced if rainfall estimates are made from radar measurements above the bright band and an adjustment is not made for the lower dielectric factor of ice. Consequently, bright band detection is critical for improving rainfall estimates with radar. Bright bands are most pronounced in stratiform rainfall and may be altogether absent in vigorous convection. Schemes have been developed based on discrete vertical samples of reflectivity at and above the bright band to estimate reflectivity at ground. To be effective the scheme must differentiate between stratiform and convective precipitation types. Smyth and Illingworth (1998b) describe a correction method that made use of the linear depolarization ratio (LDR) from a polarimetric radar to designate convective and stratiform rain types. This parameter is sensitive to hydrometeor wobble, shape, and phase. Graupel and snow, representative of convective and stratiform precipitation types, respectively, have characteristic signatures. Plots of LDR and Z_H for regions above the melting layer show that snow (and consequently stratiform rain) associates with radar reflectivity <30 dBZ and LDR >-18 dB. Reflectivity echoes >30 dBZ were dominated by graupel and deemed to be convection. Mean vertical reflectivity profiles for stratiform rain events show increased lapses as the intensity of the bright band increases. This result may be due to the increasing importance of aggregation relative to accretion and deposition as precipitation intensity increases. The considerable observed scatter among individual reflectivity profiles suggested that application of idealized mean profiles would not be beneficial. Instead, a near linear relationship (correlation 0.91) was found between the radar reflectivity at the melting layer and the reflectivity 500 m below the melting layer. The correlation falls off to ~0.5 at beam heights roughly 3 km above the melting level. The implication is that the observed profile can be used to extrapolate the measurements to ground. A smaller reduction in reflectivity with height for convective storms indicates that they must be treated separately. Three correction schemes are described in the paper. The method of Kitchen et al. (1994, Quart. J. Royal Meteor. Soc.) was tested for comparison purposes. The technique is based on the height of the freezing level, the maximum height of the precipitation, and the magnitude of the low-level reflectivity measurements. A modification used the 30 dBZ reflectivity threshold 1.5 km above the bright band to discriminate between precipitation types. A third method incorporated median reflectivity profiles according to 30 dBZ/1.5 km thresholds. The correlation between "predicted" and "observed" surface reflectivity for the two new schemes was about 0.95. See also Section 3.13.1.

A method for reducing bright band effects and accounting for phase differences for radar beams that rise above the freezing level is described by Gysi et al. (1997). The method examines measurements from low-elevation angles and searches for reflectivity maxima at heights typical of bright bands. Maximum reflectivity, band thickness, height, and the lapse rate of reflectivity above and below the maximum are examined. If maxima are found at a specified number of radials, the presence of a bright band is declared, and its intensity is subtracted from the data. An example shows a reduction of rainfall estimates close to the radar (presumably due to bright band mitigation) and a reduction in azimuthally oriented features. Rainfall estimates made from measurements obtained in ice regions increased.

McGill University (Section 3.11.5.1) routinely derives range-dependent reflectivity profiles and applies them to their rainfall products. A bright band mitigation effort at the Office of Hydrology/Hydrologic Research Laboratory is summarized in Section 3.5.7.2.

As radar estimates of rainfall continue to improve, attempts to make short-term forecasts are likely to increase and to be incorporated into flash flood warnings. Pereira Fo and Crawford (1997) made rainfall "predictions" by linear extrapolation from a time series of radar observations and hourly wind profiles. Bias adjustments were made based on 15 and 30 min periods from earlier times. Experiments show that forecasts for small watersheds beyond 15-30 min would be very difficult.

Rainfall estimation studies with polarimetric variables are summarized in Section 2.13.

2.7 Wind Analysis Techniques

Velocity azimuth display (VAD) techniques typically estimate the wind and divergence based on measurements from a ring-like region centered on the radar. The technique requires widespread echoes with returns from all quadrants. For small echoes, e.g., convective storms spanning small azimuthal sectors, the wind can be estimated with the volume velocity processing (VVP) method. Kinematic parameters are computed from the observations of a single radar by multivariate regression analysis, assuming that the wind varies linearly within the radar sub-volume. To reduce the variance in wind estimates, Xin and Reuter (1998) use simulated data to winnow the full set of eleven possible VAD parameters to seven and find that this subset minimizes the error in the kinematic terms. Experiments with different sized regions (30 to 40° in azimuth and 20 to 40 km in range) suggests that errors in the mean wind are small (<10%) but can be 25% for vertical wind shear and deformation terms. The technique was applied to a convective case. Divergence and deformation fields were computed by subdividing the echo volume into small, overlapping volumes. Standard errors for divergence, on the order of 10^{-5} s^{-1}, were small compared to typical values with convection. Trends in retrieved deformation and divergence mirrored changes in echo characteristics.

Three-dimensional wind field retrieval from single-Doppler measurements with the adjoint method continues to be investigated at the U.S. Naval Research Laboratory (Section 3.7).

Radial velocity measurements can be contaminated by birds. Problems arise during the spring (March to May) as birds migrate northward and in the fall (September and October) as the birds return southward. Contamination occurs predominately at night beginning 30 to 45 min after sundown and ending before dawn. Gauthreaux et al. (1998) report VAD wind speed errors as large as 12.9 m s^{-1} and directional errors as large as of 128°.

Chapman and Browning (1998) contend that vertical cross-sections of Doppler radar data can be important for the construction of streamlines in two-dimensional wind cases such as fronts, for the detection of Kelvin-Helmholtz billows, and for the identification of shear layers. While streamlines can be calculated from the radial velocity measurements, they maintain that the two-dimensional shear in the cross-sections is a first order approximation to the streamline pattern. Interestingly, observations from a front revealed that mixing occurred within a weakly stratified layer rather than at its periphery. Further, billows did not appear at the leading nose of a frontal surface but well to its rear.

Tests of a bistatic radar network for wind field and thermodynamic retrieval have been conducted by McGill University (Sections 3.11.1 and 3.11.2). A bistatic radar system is also under development in the United Kingdom (Eastment et al. 1997). They note problems with sidelobes and weak signals, but early results are prompting further development.

2.8 Icing Analysis Techniques

A scheme to diagnose supercooled liquid water in clouds is under development at McGill University (Section 3.11.3). Three-dimensional wind fields are constructed from single or multiple Doppler radar measurements. Icing conditions (supercooled water contents) are deduced from the derived vertical motion, a local temperature sounding, and a model which determines the proportion of condensate which exceeds depletion by the depositional growth of ice particles.

2.9 Data Acquisition Strategies

The rehosting of the WSR-88D presents an opportunity to rethink data acquisition strategies. Fabry (1997) notes that radar data collection and display is often dictated by tradition and should be rethought in terms of today's increased capacity to process radar information. An example, one of several, is presented in which the essential features of the radar reflectivity field are reproduced in measurements composed of a single radar sample. Reduced sampling may be adequate for many applications and volumetric products, thereby permitting more frequent temporal samples at low levels for other applications (e.g., rainfall estimation and monitoring tornadic storms).

It is often suggested that the detectability of shallow meteorological phenomena would be improved if the base elevation of the current VCP's were reduced. Smith (1998) shows that the sensitivity to near-horizon features (of infinitesimal thickness) could be increased by 6 dB if the base antenna elevation were lowered to 0°. Such an action would have the negative impacts of degrading reflectivity measurements (in theory one half of the power would be lost) and increasing the strength of ground-clutter echoes. At an elevation angle of 0.33°, a 3 dB enhancement of boundary-layer phenomena would occur. As the layer containing the feature of interest thickened, the advantage would be reduced. The theoretical reflectivity loss at 0.33° elevation due to the beam intersecting the ground would be ~0.8 dB. The increase in strength of existing clutter would be about 3.8 dB but could be greater for clutter below the current base angle. Overall, strong weather echoes will be minimally affected; but the (negative) impact on quantitative rainfall estimates and Doppler velocity could be significant.

2.10 Interpretive Techniques/Human Interface Techniques

No reviewed papers or reported research specifically addressed Interpretive Techniques or Human Interface Techniques.

2.11 Data Analysis Techniques

Because of the ease in application, neural networks are being applied in all aspects of signal processing, pattern recognition, time series analysis, signal compression, and signal coding. The advantages of neural networks are high speed computational processing, a capability to handle complex non-linear problems, inputs and outputs need not be specified a priori, and a capacity to include multidomain datasets. A Special Issue of *Signal Processing* (Volume 64, No. 3) presents a broad spectrum of papers devoted to signal detection and classification, "blind signal" processing, and applications.

Application of a neural network to snowfall estimation was described by Xiao et al. (1998). The method, based on a multilayer feed forward network does not assume a particular Z-S relationship but maps the time evolution of the three-dimensional reflectivity field to snowgauge (liquid equivalent) measurements at ground. The network consists of an input layer (vertical reflectivity profiles), a hidden layer of radial-basis functions, and an output layer that yields the snow liquid equivalent. The radial-basis function is Gaussian with a variable center and spread factor. Training includes forward and backward propagation steps in which the connectional weights between layers are updated. Different combinations of training and test datasets were examined. Snowfall estimates from network-derived Z-S relationships had much smaller bias errors than those for a fixed (Marshall-Palmer) relationship.

The current NSSL Mesocyclone Detection Algorithm (MDA) is designed to detect a broad spectrum of circulations which are not necessarily tornadic or producing damaging winds (Marzban and Stumpf 1998). Hence, an algorithm was need to designate those circulations with strong winds. The method adopted was that of a feed forward neural network. Inputs consisted of 23 scaled storm attributes defined from radar measurements (e.g., the maximum rotational velocity, maximum diameter, height of the circulation, ... etc.). Outputs were constructed to produce yes/no predictions. Networks with two hidden nodes generally gave higher performance at a probability parameter of 0.2 (close to the climatological probability). This optimum number of hidden nodes was found by nearly all performance measures. CSI's approached 50%. The network was not tested on an independent dataset.

2.12 Radar Analysis Techniques

Gauthreaux and Belser (1998) and Gauthreaux et al. (1998) have been using WSR-88D reflectivity and VAD products to monitor spring and fall bird migrations. In the spring, birds cross the Gulf of Mexico and typically arrive along the Texas and Louisiana coasts during the afternoon and early evening hours. The transgulf migrants land in forests just beyond the coast. Upon recuperation subsequent migration occurs primarily at night, beginning 30 to 45 min after sundown and continuing until dawn. The movements of birds at dawn as they leave their night time roosts and begin their daily foraging are also readily detected with the WSR-88D. The departing birds appear as a reflectivity annulus that grows in diameter and decreases in intensity with time.

Storms with intense reflectivity are frequently associated with severe weather. Apparently, extreme reflectivity values are evidence of strong updrafts. In an attempt to quantify this association, Gerard (1998) examined storms with maximum reflectivity ≥65 dBZ, stratifying them according to whether the strong echo extended above or below the freezing level. A storm was considered severe if there was a report of severe weather (hail, strong winds, and tornadoes) within one hour after the reflectivity threshold was met. (The reflectivity threshold was not exceeded by every severe thunderstorm, and some storms produced severe weather before the threshold was met.) For an ensemble of 64 classifiable storms with extreme reflectivity, 55 (86%) were severe. Of the 54 storms with echo ≥65 dBZ extending above the freezing level, 52 (96%) were severe. Only 3 of 10 storms with extreme reflectivity below the freezing level were severe. The study would seem to confirm notions that the probability of severe weather increases with reflectivity.

The TRMM radar footprint (4.3 km) is large with respect to tropical convection; hence, there is concern that rainfall estimates may have considerable bias. The problem, arising from taking averages of nonlinear processes, was modeled by Durden et al. (1998) and results compared to observations from an airborne radar. (The TRMM problem is further complicated by attenuation losses.) Durden et al. show examples where the reflectivity and rain rate can be over or underestimated depending on the amount of attenuation, the rain rate intensity, the distribution of rain, and the standard error. As an example, the simple binary problem where one half of the beam has one value of reflectivity and the remainder has a different reflectivity leads to an overestimate of the rainfall rate within the combined beam. Errors are typically <10%.

To aid in the interpretation of radar signals and to permit examination of hydrometeor effects on the propagation of radar signals, a radar simulator has been developed by Capsoni and D'Amico (1998). Model inputs include radar characteristics (peak transmitter power, antenna gain, frequency, ... etc.) and particle distributions. Phase (I) and quadrature (Q) signals are generated. Particle positions and characteristics can then be updated for pulse-to-pulse examination.

2.13 Polarimetric Radar

Because of sensitivity to particle size, shape, orientation, and composition, measurements from polarimetric radars give additional information about hydrometeors and, hence, offer hope for physically-based approaches for improved rainfall estimation. Bringi et al. (1998) present a study in which the mass-weighted median drop diameter (D_o) is computed from differential reflectivity. [The relationship between axis ratios and volume-equivalent spherical diameters is critical for successful application. Often, radar-measured axes ratios suggest that small droplets may be less spherical than found by wind tunnel experiments.] Detailed comparison between aircraft and radar measurements show regions of high radar reflectivity that correspond to relatively high and low rainfall rates. In the latter case, Z_{DR} tends to be large indicting that the rain is composed of small numbers of large drops. Comparisons of penetration-averaged radar reflectivities and DSD-computed radar reflectivities show excellent agreement (the radar was 0.41 dB low) with a fractional standard error of 4%. Radar estimates of D_o had a bias of 0.07 mm and a fractional standard error of 13.7%. From this the authors conclude that overall collision-induced large drop oscillations are not significant in this case. Several rain rate relations based on Z_H alone and in combination with Z_{DR} were then tested. Results for a sample of nine penetration-averaged rain rates indicate that estimators which combine the two measurements have fractional standard errors that are about one half that found with reflectivity alone. The primary source of the error in the reflectivity estimates stems from bias.

Ryzhkov and Zrnić (1998a) studied snow storms with polarimetric radar and found that melting layers are characterized by pronounced minima in the correlation coefficient between horizontally and vertically polarized signals (ρ_{HV}) and maxima in Z_{DR}. For warm and cold snowfall events, both Z_{DR} and the specific differential phase (K_{DP}) increase with height, indicating that pristine ice crystals dominate both storm types aloft. Compared to rain, Z_{DR} and K_{DP} for warm and cold snow show little change as size (reflectivity) increases. Discrimination between pure rain and snow is possible with K_{DP} and Z_{DR} for Z_H >30 dBZ. For lower reflectivities, precipitation with a Z_{DR} <0.2 dB can be classified as snow. The authors also find that the transition from snow to rain in horizontal cross-sections is marked by a minimum in ρ_{HV}. The signature comes from large wet aggregates. Corresponding values of Z_H and K_{DP} are large. A clear demarcation line between rain and snow was not evident in the Z_{DR} measurements, rather there was a gradual decrease in Z_{DR} as rain changed to snow.

Field work has uncovered situations where rainfalls derived from specific differential propagation phase (K_{DP}) and from Z_H differ significantly and situations where strong gradients of Z_H and negative K_{DP} are observed. The problem is examined in detail by Ryzhkov and Zrnić (1998b) who simulate radar response at distant ranges to small isolated storm cells and to gradients of reflectivity. Rain rates within the isolated cells are assumed to be Gaussian and axisymmetric. For cells on the radar bore sight, rainfall rate profiles derived from Z_H and K_{DP} are similar in shape and magnitude. Cells off the bore site exhibit large negative K_{DP}'s (and consequently negative rainfall rates) at the rear of the simulated cells and significant overestimates of the rain rates at the cell core. For cells within the azimuthal gradient of the differential propagation phase (ϕ_{DP}), rain patterns are distorted with negative K_{DP}'s appearing at the cell's leading and trailing edges. Again, positively biased values of K_{DP} overestimate the rain rate in the cell core. Importantly, area integrations of the rainfall patterns are unbiased, i.e., the negative K_{DP}'s and the overestimated positive values tend to balance. Reflectivity gradients within the radar beam, common with squall lines or bright bands, cause similar problems. Although rain estimates derived from specific differential phase may have less spatial resolution than reflectivity and may be affected by the nonuniform beam filling problem, the authors maintain that K_{DP} rainfall estimates should be more reliable than those derived from radar reflectivity measurements that suffer from radar miscalibration, attenuation, and beam blockage. When nonuniformities within the radar beam are significant, they suggest that the integral of the K_{DP} rainfall might serve as a constraint for reflectivity estimates.

Smyth and Illingworth (1998a) present a technique based on the linear depolarization ratio (LDR) measurement for making improved radar reflectivity estimates at ground when the radar beam passes through the bright band. Characteristic LDR signatures exist for snow and graupel which permit the discrimination of stratiform and convective rain types and the derivation of median reflectivity profiles (see also Section 2.6).

One of the basic limitations in radar rainfall estimation is the natural variability in drop-size distributions within rain storms and consequently in the relationship between radar reflectivity and rainfall rate. Estimates from fixed Z-R relations are susceptible to this variation. Dual-polarization measurements, because of their sensitivity to hydrometeor shape and orientation, offer the possibility of monitoring the drop-size distribution in real time. Richter and Hagen (1998) retrieved the intercept parameter N_o and the median volume diameter D_o of an exponential DSD from polarimetric radar data and compared results with similar estimates determined from a vertically pointing wind profiler, in situ particle measurements, and a disdrometer. There was a tendency to overestimate N_o and to underestimate D_o, but overall there was good quantitative agreement between the radar estimates and the validating measurements. Errors in Z_H and DSD departures from an exponential model are potential problems. Further improvements may be possible with a gamma DSD and computing the shape parameter μ by adding the K_{DP} measurement to the procedure. Hence, it may be possible to improve rainfall estimates by continuously monitoring spatial and temporal changes in DSD's.

The full suite of polarimetric measurements (radar reflectivity, differential reflectivity, linear depolarization ratio, specific differential propagation phase, and copolar correlation coefficient) were utilized by Hubbert et al. (1998) in an interesting study of hydrometeor distributions and their evolution within a hailstorm. Large hail was depicted by relatively high LDR (>-18 dB), slightly negative Z_{DR} ($\leq$-0.5 dB), and low ρ_{HV} ($\leq$0.93). A negative Z_{DR} value is an indication that the major axes of the hailstones were vertically aligned in the mean. Storm features depicted in the measurements included a positive Z_{DR} column that was connected to the storm's updraft and contained supercooled raindrops; mixtures of supercooled raindrops, partly frozen drops, and wet graupel above the Z_{DR} column; and regions in which large drops may have been shed by melting hail. Dissected hailstones disclosed that 30-40% of the largest stones had frozen drop embryos which may have originated in the Z_{DR} column.

With polarimetric radar measurements it is possible to designate hydrometeors as either liquid or frozen and determine the relative contribution of each phase to radar reflectivity. Tong et al. (1998) extend this capability to the computation of water budgets and heating rates within convective storms. Liquid and ice contributions to reflectivity are found with the difference reflectivity parameter, defined as $Z_{DP} = 10\log(Z_H - Z_V)$. The key assumption is that ice particles tumble and, hence, $Z_{H,ice} = Z_{V,ice}$. For rain, $Z_{H,rain} > Z_{V,rain}$. Consequently, the Z_{DP} signal is due only to rain. The relation between Z_{DP} and $Z_{H,rain}$ is linear (for measurements in dB). Departures from the rain line signify the presence of ice and represent the ice contribution to reflectivity. Liquid water contents (LWC's) for ice and rain were calculated from reflectivity with empirical relationships. Vertical profiles of layer averaged ice fractions and LWC's are presented. The latter required adjustments for the index of refraction and an assumption regarding ice particle density. The time history of an observed cell shows an increase in the fraction of ice water content with time and domination by glaciation in the declining stage. Latent heating estimates are based in part on time variations of water content and rainfall. Latent heating dominates early, while cooling dominates in storm decline. Net heating of the atmosphere was attributed to the fact that more water vapor is condensed than falls to ground as rain. Verification would be very difficult with observations.

Biological targets can seriously degrade Doppler velocity and radar reflectivity measurements. Gauthreaux and Belser (1998) and Gauthreaux et al. (1998) note that insects can fly at speeds of up to 6 m s^{-1} and bird velocities can exceed 15 m s^{-1}. Thus, biological targets can have a serious adverse effect on radial velocity measurements and cause spurious VAD wind estimates. Radar reflectivity measurements can also be corrupted. With polarimetric radar it is possible to detect biological targets and to distinguish between insects and birds (Zrnić and Ryzhkov 1998b). Insects are generally within the Rayleigh scattering range at S-band. When aligned in the mean, they produce differential reflectivity signatures that can exceed 10 dB. Often the signatures appear in radar reflectivity as well. While large insects can produce a backscatter differential phase (δ), the propagation (forward-scattering) component is usually small. Cross-correlation coefficients (ρ_{HV}) are typically <0.8, compared to those for rain (usually >0.95). Bird sizes well exceed the limits of Rayleigh scattering. Compared to insects their Z_{DR} signature is relatively small and may even be negative. The primary distinguishing characteristic of birds is a large backscatter propagation phase which is inversely proportional to Z_{DR}. The authors suggest that, because the azimuthal dependencies for Z_{DR} and δ are more sensitive to scatterer size than to their concentrations, it may be possible to estimate the size of the biological scatterers.

Anomalous propagation effects on rainfall estimates with radar can be very serious if the ground echoes are interpreted as precipitation. The mitigation procedure on the WSR-88D applies a high-pass filter in the frequency domain to remove stationary echoes. The procedure readily removes clutter but has the undesirable effect of removing power in precipitation regions with near zero radial velocity. With a polarimetric radar the cross-correlation coefficient (ρ_{HV}) can be used to identify clutter. This parameter is inversely related to the standard deviation of the differential propagation phase measurement. The differential phase of ground clutter is uniformly distributed over the interval $\pm$ 180°. For precipitation fluctuations are relatively small. Ground targets typically have ρ_{HV} values <0.7. Ryzhkov and Zrnić (1998c) show this parameter alone is very effective in distinguishing between precipitation and clutter echoes that are separated in space. This simple scheme may fail if hail is present or the radar beam rises through the melting layer. The latter conditions are detectable with the Z_{DR} parameter. When precipitation and AP echoes are mixed, the ϕ_{DP} measurement may become noisy; but the authors show enough signal remains that trends can be established and K_{DP} can be computed in areas of mixed echoes.

While attenuation of reflectivity at S-band is usually small, losses of even 1 dB can be significant for rainfall estimation. Consequently, there is interest in the development of correction schemes. Techniques based on radar reflectivity, generally applied gate-by-gate, are inherently unstable. Moreover, it's simply not possible to correct for attenuation when returns fall below the minimum detectable signal. Other complications are a sensitivity to temperature and the presence of hail. The advent of polarimetry offers additional options for attenuation correction which are exploited in papers by Gorgucci et al. (1998) and Smyth and Illingworth (1998a). Gorgucci et al. examined attenuation correction methods based on radar reflectivity, reflectivity and differential reflectivity, and specific differential phase using both simulations and radar observations. The simulations show that for a variety of DSD's the combination Z_H and Z_{DR} provides a good estimate of Z_H attenuation and the differential attenuation in Z_{DR} and gives substantial improvement over attenuation estimates from Z_H alone. Fractional standard errors were also somewhat smaller than attenuation estimates derived from K_{DP} (see Gorgucci et al. 1998, Table 5). Estimates from K_{DP} do have an important advantage with operational radars in that the measurement is immune to hardware calibration errors. Experiments with radar data showed that in practice attenuations computed from the combination Z_H and Z_{DR} and from K_{DP} were comparable.

Smyth and Illingworth (1998a) present calculations showing that a simple linear relationship does not exist between attenuation and K_{DP} and that to accurately correct for attenuation N_o and D_o must be known. To over come these difficulties and the temperature dependence, Smyth and Illingworth use the specific differential phase parameter and the differential attenuation, i.e., the difference in radar reflectivity at horizontal and vertical polarization, measured on the far side of storms. The differential attenuation, manifest as negative Z_{DR}, is partitioned among data bins where $K_{DP} > 1° \text{ km}^{-1}$ according to the magnitude of K_{DP}. The DSD parameters N_o and D_o are then computed from the differential attenuations and K_{DP} values. Finally, the attenuation at horizontal polarization is computed; and radar reflectivity and differential reflectivity are adjusted according to the accumulated attenuations. The relationship between attenuation and K_{DP} is sensitive to D_o. Results from a storm with rain rates >250 mm h^{-1} and a differential attenuation of ~1.5 dB show significant improvement in rainfall estimates and in the reduction of negative Z_{DR} values at low radar reflectivity. It is not clear what impact overestimates of positive K_{DP} and the presence of negative K_{DP} values (Ryzhkov and Zrnić 1998b) will have on the correction scheme.

Bistatic radar systems built to date are designed to transmit and receive signals at a single polarization. Aydin et al. (1998) explore potential applications such as rain/hail discrimination with transmission at a single polarization and passive receivers capable of making dual-polarization measurements. Exponential size distributions were modeled for rain, hail, and mixtures. Retrieved radar parameters were the bistatic-to-backscattering reflectivity ratios, linear depolarizations ratios (for horizontally and vertically transmitted signals), cross-polarized coefficients, differential reflectivity, and the copolarized correlation coefficient. (The latter two parameters require that the transmitter be dual-polarized.) When combinations of cross-polarized and copolarized parameters are plotted, rain and hail generally lie in different parts of the parameter space, which may be useful for differentiating them. The amount of separation is dependent on the incident and scattering angles. Ratios of various parameters are functions of the median drop diameter (D_o) and are independent of the distribution intercept (N_o) making them useful for computing D_o. (Note that D_o can also be computed for monostatic polarimetric radars and that N_o can then be found from the combination Z_H and D_o.) Not all solutions yield unique estimates of D_o. There may be limitations to using horizontally polarized waves at low signal levels and at low elevation angles. The technique represents a possible compromise to modifying the WSR-88D for polarization capability.

Properties of polarimetric signals at linear vertical and horizontal, slant linear +45° and -45°, and left-hand and right-hand polarization are compared in a recent study by Torlaschi and Holt (1998). The equations for radar covariances and cross-covariances are presented for a model that assumes a uniform distribution of canting angles along the beam. Observations confirm that depolarization is stronger at slant linear polarization than at linear vertical/horizontal polarization, particularly in ice. The data also indicate that particles may change their canting angles as they melt.

2.14 Data Compaction and Transmission Techniques

The Forecast Systems Laboratory has been developing a procedure for constructing regional three-dimensional composites of radar reflectivity and velocity data. Some preprocessing steps are performed at individual radar sites to reduce the amount of data that must be sent to a central facility where the mosaics are produced (Section 3.2.1).

The Iowa Institute of Hydraulic Research remains active in data compaction and database organization for the support of large dataset analyses (Section 3.10.7).

3 ACTIVITIES ACCORDING TO ORGANIZATION

3.1 Bureau of Reclamation

3.1.1 SNOW ACCUMULATION ALGORITHM

The Bureau of Reclamation (Reclamation) has developed a Snow Accumulation Algorithm (SAA) for the WSR-88D (NEXRAD) radar network as discussed by Super and Holroyd (1996, 1997a, 1997b, 1998). This effort received primary support from the WSR-88D Operational Support Facility. Additional support has been provided by Reclamation and, more recently, by the NOAA/Office of Global Programs/GEWEX Continental-Scale International Project office.

The SAA is intended for dry snowfall. No attempt has been made to deal with the complexities of "bright band" contamination. However, the effects are often evident as a ring of unusually high snowfall accumulation around the radar at ranges where the radar beam illuminates the melting layer.

Hourly observations of snow water equivalent (SWE) and snow depth were obtained during one winter period at several locations scanned by WSR-88D's. The sites were near Albany, New York; Cleveland, Ohio; Denver, Colorado; Minneapolis, Minnesota; Grand Mesa, Colorado; the Sierra Nevada of California; the Cascades of Washington; and Anchorage, Alaska. High resolution precipitation gauges were installed near the radars in Colorado, Minnesota, and Ohio. These gauges were protected from serious wind effects by trees and buildings. Hourly snow board data were provided by the Albany, New York NWS Forecast Office from a large volunteer network of similarly protected locations.

Usually, storm total accumulations of SWE, as estimated by radar and observed on the surface, were within 0.2 inches for sites within 60 km range of the radars. Corresponding correlation coefficients ranged between 0.83 and 0.96 providing further evidence that the SAA provides useful approximations of snowfall. This agreement is especially gratifying when the huge differences between radar and gauge sampling volumes are considered, and when the difficulties of obtaining accurate surface snowfall measurements are appreciated.

Radar comparisons with surface observations made by existing gauge networks in the Sierras, Cascades, and near Anchorage have been less successful. Part of the problem with these locales is the considerable blockage at low antenna elevation angles by mountainous terrain. Additional complexity may be caused by less than ideal surface observations in some cases, although attempts were made to include only gauges protected from the wind. Ongoing work in Minnesota with volunteer gauges reveals that exposed (windy) gauge locations have substantially reduced agreement between surface and radar SWE estimates. The importance of obtaining accurate snowfall measurements for comparison with radar cannot be overemphasized.

An optimization scheme matches hourly observations of SWE with Z (radar reflectivity factor) measurements by the radars to determine best fit coefficients for the commonly-used equation

$$Z = \alpha SWE^{\beta} \quad .$$

This scheme consistently provides β values near 2.0 and corresponding α values in the 50 to 250 range. The lowest α value was over the Grand Mesa where the lowest available beam tilt was likely to have been above the important snow particle growth zone. The highest α value is from a radar suspected to be miscalibrated. The most appropriate α value appears to be ~150 for non-mountainous regions, although real regional differences may exist.

Underestimation of SAA-estimated SWE occurs beyond approximately 70 km range because of earth's curvature, beam widening, and possible incomplete beam filling at greater ranges. The underestimation problem is severe with shallow lake-effect storms but less apparent with large synoptic storms. Realtime testing of the SAA was accomplished at Cleveland and Minneapolis during the 1996-97 winter. While forecasters found the SAA estimates to be useful, they noted that lack of a range correction scheme was a shortcoming with the prototype algorithm. A correction scheme, based on earlier comparisons between radar estimates and surface observations, was used during 1997-98 testing at Albany. It significantly reduced the range underestimation. The challenge is to determine appropriate range corrections for locations lacking suitable surface observations. Reclamation has suggested use of the vertical profile of reflectivity as sampled by the 5 lowest beam tilts. A seasonal correction scheme was successfully applied to several Minnesota snow storms (Super 1998).

Realtime tests at Cleveland and Minneapolis affirm the need for customizing the "hybrid scan" to use the lowest practical radar beam tilt at all locations. As with the NEXRAD rain algorithm, the SAA uses a hybrid scan file to select beam tilts for each range bin location. Higher tilt beams are used in regions with persistent ground clutter. But over terrain with limited relief, it is possible to use the lowest tilt (0.5°) within 10-20 km of the radar for snowfall estimates, thereby scanning near the surface where Z tends to be highest. Anomalous propagation does not appear to be a serious problem with dry winter snowfalls.

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3.2 NOAA/Forecast Systems Laboratory

3.2.1 A Technique for Interpolating Full-Volume Level-II Data for Regional Radar Products

The Forecast Systems Laboratory (FSL) is developing a regional radar volume (RRV) mapping capability initially using measurements from three WSR-88D's covering northeastern Colorado. Data are collected in real time and combined to create full three-dimensional volumes of reflectivity and Doppler winds on a 5 km, 20 level grid. The RRV design combines on-site and central processing (Roberts et al., 1995 and 1997). On-site processing includes remapping measurements to a common conterminous United States (CONUS) Cartesian grid. Remapping reduces the volume of data transmitted to the central facility and eases the merging of data from multiple radars. At the central site data from the individual radars are combined to produce a mosaic of reflectivity and Doppler winds. The RRV data are used as input for operational mesoscale numerical models and for display on forecaster workstations.

On-site processing uses the Radar Interface and Data Distribution System (RIDDS) and circular buffer software, developed at the National Severe Storms Laboratory, as an interface to the Level II data. Remapping techniques, developed for the Local Analysis and Prediction System (LAPS), are used for data interpolation. The remapping algorithm computes reflectivity by taking the mean radar reflectivity value of all data gates within a grid volume centered on the grid point. When the mean reflectivity is less than 0 dBZ, it is set to a flag value of -10 dBZ, thus avoiding problems with electronic noise and non-hydrometeor scatterers. The radial velocity is averaged similarly. Several quality checks are performed on the velocity data. One requirement is that 40% of all gates located within a grid box or at least 4 of them, whichever is greater, must contain valid velocity data (i.e., are not flagged as ground clutter or range-folded). If a threshold velocity standard deviation is exceeded, the grid box is assigned the missing data value. The sparsely packed arrays of gridded reflectivity and velocity are easily compressed for transmission and sent real time via voice-grade phone lines to the central facility at FSL. Compressed files average about 40 Kbytes in size.

All of the RRV processing steps are currently being done outside the operational WSR-88D system. In the future, these steps could be tied directly into operational systems with the remapping component executed on the Open Radar Products Generator (ORPG). Improved remapping techniques which preserve more of the base data resolution are being evaluated and could be implemented when additional processing power and transmission bandwidth are available.

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3.3 NOAA/National Severe Storms Laboratory

3.3.1 Introduction

The National Severe Storms Laboratory (NSSL) conducts research and development to utilize Doppler radar data and to enhance hazardous weather detection and prediction algorithms. Testing is accomplished both in a post-analysis research environment and in real time at NWS forecast offices and at FAA Integrated Terminal Weather System (ITWS) prototype test sites. Several unique and innovative display products have been created to help evaluate algorithm performance and to test potential products in operational environments before transferring them to the National Weather Service for inclusion in the WSR-88D system and the Automated Weather Interactive Processing System (AWIPS), to the FAA for inclusion in the Weather and Radar Processor (WARP) and ITWS, and to the Department of Defense (DOD) for inclusion in the Open Principal User Processor (OPUP).

In addition, NSSL is developing pre-production software for the Open Radar Products Generator (ORPG), developing a prototype hardware/software system for the Open Radar Data Acquisition (ORDA), and developing pre-production software for Open PUP (OPUP).

3.3.2 Algorithm Development and Enhancement

3.3.2.1 Storm Cell Identification and Tracking (SCIT) Algorithm

The Storm Cell Identification and Tracking (SCIT) algorithm is currently part of the Build 10 software suite of the Radar Products Generator (RPG) of the WSR-88D system. The current version identifies cells using multiple reflectivity thresholds and is capable of identifying embedded cells in multi-cellular storms. The algorithm also provides time and time-height trends of various storm attributes.

As a result of work being conducted on the Damaging Downburst Prediction and Detection Algorithm (DDPDA), resolution output from the SCIT algorithm has been increased to improve the detection of downburst precursors. This change has also improved the tracking of reflectivity cores.

The SCIT algorithm has recently been modified to permit continuous updating of storm cell locations. The process of "building" three-dimensional storms from two-dimensional components now is attempted as each elevation sweep is completed, providing updated locations of storm cells more often than at the end of a volume scan.

NSSL is integrating a correlation-tracking and a storm growth and decay algorithm developed by MIT/Lincoln Laboratory into the SCIT algorithm. This software promises to improve the tracking of multi-cellular storm complexes, and will be tested during the 1999 convective season.

3.3.2.2 Mesocyclone Detection Algorithm (MDA)

The NSSL Mesocyclone Detection Algorithm is expected to appear in the WSR-88D system in the 2nd or 3rd Builds of the Open-RPG. The MDA allows for the detection of storm-scale vortices of various sizes and strengths, and classifies them into different vortex types (mesocyclone, low-topped mesocyclone, etc.). Trends of vortex attributes are also computed.

Algorithm testing continues on an ever-expanding database of tornadic and non-tornadic supercells that now contains more than 50 individual storm days (over 250 tornadoes and over 300 hours of radar data) from a variety of geographical locations. The database serves as input to a neural network (NN) being developed to determine the probability of tornadoes or severe weather associated with each mesocyclone detection.

Enhancements to the MDA include the addition of several diagnostic parameters (such as mesocyclone ascent/decent trends) and slight modifications to detection techniques. A number of new input parameters for the NN have been added, including trend information, output from a bounded weak echo region (BWER) detection algorithm, and a variety of near-storm environmental parameters. The NN now also incorporates information from the Tornado Detection Algorithm (TDA) in its diagnosis of storm-scale vortices.

The MDA has been reconfigured for updating mesocyclone locations after the first (low altitude) elevation. Mesocyclone detections from the previous volume scan are associated with two-dimensional detections from the lowest elevation in the current volume scan, and the position of the old detection is updated. Future work will combine the detection capabilities of the MDA and TDA into a storm-scale Vortex Detection and Diagnosis Algorithm (VDDA).

3.3.2.3 Tornado Detection Algorithm (TDA)

The Tornado Detection Algorithm (TDA) was successfully transferred to the OSF and included in Build 10 RPG software release. NSSL continues to test the TDA in real time at select NWS forecast offices. A version was added to the WSR-88D Algorithm Testing and Display System (WATADS).

New techniques for detection and diagnosis of tornadic vortices within storms using WSR-88D data have been created. One technique involves the computation of azimuthal and radial shear using a linear least-squares method. Initial results with simulated and actual WSR-88D data show that the shear term may complement current techniques used within the TDA and the Mesocyclone Detection Algorithm to identify potentially hazardous vortices within storms.

The TDA has also been altered for updating vortex locations after the first (low-altitude) elevation. TVS detections from the previous volume scan are associated with two-dimensional detections from the lowest elevation in the current volume scan, and the position of the old detection is updated. Continuing work includes building three-dimensional detections of TVS's as each elevation is completed.

3.3.2.4 Hail Detection Algorithm (HDA)

A performance evaluation of the Hail Detection Algorithm (HDA), part of the Build 9 RPG software suite, was conducted in response to users' perceptions that the algorithm over-warned in summertime storm situations. A total of 78 storm days (hail and non-hail) from four locations (Melbourne, Florida; Fort Worth, Texas; Sterling, Virginia; and Chicago, Illinois) were analyzed to determine forecast bias. Analysis of the warning threshold selection model for 51 days at Melbourne showed no apparent over or under-forecasting bias. Performance statistics for the algorithm were calculated at various population density thresholds, and the optimum population density threshold was chosen to determine the reliability of the Probability of Severe Hail (POSH) parameter. It was concluded that during summertime storm situations the algorithm could be improved by altering the POSH equation from

$$POSH = 29\ln(SHI/WT)+50$$

to

$$POSH = 29\ln(SHI/WT)+30,$$

where SHI is the Severe Hail Index, and WT is the Warning Threshold.

A planned future enhancement is based on cloud modeling studies which show that mid-altitude rotation in storms may play a significant role in the growth of very large hail. Use of the MDA to quantify the rotation should improve the accuracy of the maximum hail size estimates and reduce instances where very large hail (i.e., larger than two inches) is predicted for non-supercell storms. Second, the calculation of a volumetric (3D) Severe Hail Index, versus the one-dimensional SHI that is now used, should allow better discrimination between large, severe hailstorms and relatively small cells that may be producing little, if any, severe hail, in spite of having similar one-dimensional vertical reflectivity profiles. Third, NSSL plans to add a terrain model to the HDA, which should provide more accurate accounting for the differential melting that occurs in regions where terrain height varies substantially across the radar domain.

3.3.2.5 Damaging Downburst Prediction and Detection Algorithm (DDPDA)

NSSL is developing an algorithm which has the capability to both predict and detect damaging wind events using Doppler radar reflectivity and velocity data. The Damaging Downburst Prediction and Detection Algorithm (DDPDA) scans through radar data to locate downburst precursors) events that can be detected in the middle and upper altitudes of a storm which may precede the onset of strong surface winds. Early algorithm versions focused on predicting damaging wind events from short-lived "pulse" thunderstorms. A prediction equation was developed by analyzing approximately fifty convective cells which produced outflows of varying strength.

The DDPDA has undergone a number of improvements, especially to the routines that analyze downburst precursors. The resolution of the output from the Storm Cell Identification and Tracking (SCIT) algorithm, used as input to the DDPDA's core-tracking routine, was increased. The number of reflectivity cores correctly tracked increased from 64 to 78%. Additionally, environmental data have been added as input to the DDPDA, and the radial velocity processing routines have been improved. We will investigate methods to unambiguously score downburst occurrence, using Low-Level Windshear Alert System (LLWAS) and Terminal Doppler Weather Radar (TDWR) product data.

3.3.2.6 Near-Storm Environment (NSE) Algorithm

The goal of the Near-Storm Environment (NSE) algorithm is to provide information about a storm's environment, such as shear and stability parameters. Currently, NSE uses output from the Rapid Update Cycle - II (RUC-II) model to determine the environment of storm cells. Recently, the capability for incorporating surface observations was added.

Future plans include investigating the use of the Local Analysis and Prediction System (LAPS) as input into the NSE algorithm. In addition, new parameters will be derived as needed for further WSR-88D algorithm development.

3.3.2.7 Neural Network (NN) and Statistical Analyses

The original neural networks (NN's) developed for diagnosis of tornadic and damaging wind circulations have been supplemented by additional NN's. Currently, NN's examine circulations detected by the NSSL Mesocyclone Detection Algorithm (MDA), the Tornado Detection Algorithm (TDA), and circulations detected by both the MDA and TDA.

The NN's were designed to yield occurrence probabilities for tornadic and damaging wind phenomena. Other statistical techniques have also been examined. Mathematical analysis shows that most, if not all, commonly used algorithm performance measures are unreliable for rare events. Several journal articles summarize these findings. Similar NN's may be developed for hail and precipitation estimation.

3.3.2.8 Vortex Detection and Diagnosis Algorithm (VDDA)

The groundwork is being laid to merge the TDA and MDA into a single algorithm called the Vortex Detection and Diagnosis Algorithm (VDDA). The new algorithm will allow for detection of a range of vortex sizes and for sharing of information (such as vertical association and time association) from the two algorithms. The integration of data from other radar-based algorithms and other sensors (such as near-storm environment data) will provide for a more thorough analysis of the vortices.

The VDDA will feature some techniques from both the MDA and TDA, as well as some new techniques such as the least-squares method to compute radial and azimuthal shear and a line-integrated method to diagnose rotation and divergence within detected vortices.

A database of simulated WSR-88D data consisting of vortices of varying, sizes, strength, and range from the radar; gust fronts; mesocyclones with embedded TVS's; and mesocyclones with rear-flank downdrafts has been assembled for testing. The MDA and TDA will be tested on the simulated data to determine the strengths and weaknesses of each algorithm and to develop new two-dimensional feature detection and diagnosis techniques. Plans include refinement of vertical and time association procedures.

A significant effort will be made to integrate output from the Near-Storm Environment (NSE) algorithm into the VDDA and the neural network. This will be the first step in integrating multiple data sources to obtain a more complete picture of the storm-scale situation for determining tornado and severe weather probabilities. This effort will hopefully lead to future data integration [i.e., satellite data, bounded weak echo region (BWER) information, multiple WSR-88D output, ... etc.].

3.3.2.9 Multi-PRF Dealiasing Algorithm (MPDA)

The Multi-PRF Dealiasing Algorithm (MPDA) is a WSR-88D scanning strategy and data processing package whose purposes are to minimize the amount of overlaid echoes (range folding) in velocity data and to produce dealiased velocity fields that are superior to those retrieved with the current WSR-88D Velocity Dealiasing Algorithm (VDA). We propose to collect data at different Nyquist velocities while maintaining a constant elevation angle. This provides the opportunity to acquire velocity estimates at gates that may be range folded at a given Nyquist interval. The algorithm has evolved from a prototype to a mature software package that is a viable addition to the WSR-88D open systems platform.

The infrastructure required to ingest and process realtime MPDA data is now in place. This task required streamlining of the MPDA software by changing floating point to integer processing where possible to keep pace with the realtime datastream. Output is available to both the Norman NWSFO and NSSL through the Warning Decision Support System (WDSS). Three significant convective events were captured in the past year using the realtime processing software.

A comparison between the speed of the MPDA software using floating point versus integer calculations and the conversion of high computationally intensive calculations to lookup tables have both been accomplished. Results show that software performance increases 10-20% using the integer format and another 10% using the lookup table procedure.

The environmental wind table (EWT) derived from the WSR-88D continues to play a crucial role in producing correct MDPA solutions. Although the decision of when to use the EWT estimates remains a complex issue, other software constraints developed for MPDA processing have provided significant fault reduction compared to the 1997 versions of the MPDA.

Future efforts will focus on a more robust two-dimensional dealiasing scheme and fault mitigation in areas where only single velocity estimates exist. Data collection strategies will also be examined to reduce collection times and noise levels in the velocity data.

3.3.3 RADAR DATA PROCESSING SYSTEMS

3.3.3.1 WSR-88D Radar Ingest and Data Distribution System (RIDDS)

The Radar Ingest and Data Distribution System (RIDDS) is a RISC-based workstation that provides users with access to the WSR-88D Level II datastream in real time. The system uses a Sun Sparc 5 workstation to communicate with the WSR-88D wideband user port to ingest the Level II data and distribute it over an Ethernet connection to other workstations for processing. The RIDDS system is also capable of archiving Level II data. There are currently 31 NWS and DOD sites which use the RIDDS software; eight more sites are planned for 1999.

3.3.3.2 Warning Decision Support System (WDSS)

NSSL's prototype WDSS combines enhanced or new WSR-88D severe weather algorithms and innovative display capabilities to support warning functions of meteorologists in severe or hazardous weather situations. The WDSS processes realtime Level II data from the WSR-88D and executes the algorithms described in Section 3.3.2. In addition to WSR-88D data, the WDSS can integrate surface observations, satellite imagery, ground strike locations from the National Lightning Detection Network (NLDN), and numerical model output. These data can be displayed for an integrated look at a potential warning situation and serve as environmental input to the algorithms.

NSSL continues to conduct realtime operational tests of the WDSS. In 1998, the WDSS was tested in Pleasant Hill, Missouri and Sterling, Virginia during the spring and summer convective seasons and is tested continuously at 11 other sites around the nation. The realtime operational tests are designed to obtain forecaster feedback to guide future algorithm and display upgrades.

Work is currently underway to integrate WDSS functionality into the Advanced Weather Interactive Processing System (AWIPS). The effort, targeted toward AWIPS Build 5, will include an interactive decision support table with environmental parameters, trends, rate-of-change alarms, tracking and trending of mesocyclone and tornado detections, and a ranking and sorting algorithm for tabular information that uses algorithm output from all locally available WSR-88D's. A test of the limited WDSS functionality being integrated into AWIPS will be conducted in real time at the NWS Forecast Office in Tulsa, Oklahoma, during the spring and summer of 1999.

3.3.3.3 WSR-88D Algorithm Testing and Display System (WATADS)

WATADS is an off-line version of the WDSS which can be used with Level II data to perform adaptable parameter evaluations on NSSL and WSR-88D algorithms. WATADS is commonly used by NWS science and operations officers to re-examine interesting weather events in detail. Users have the ability, through a graphical user interface, to change adaptable parameters and input environmental data (such as soundings) before executing the software. The WATADS software also includes a version of the radar analysis and display system created specifically to display output from both the WSR-88D and NSSL algorithms.

WATADS 10.0 was released in the summer of 1998 and includes the following changes: the Build 10 Tornado Detection Algorithm (TDA), a compressed file utility, and new versions of NSSL experimental algorithms. A WATADS 10.1 release is scheduled for winter of 1999 and will include Build 10 precipitation algorithm changes, the capability to run the Areal Mean Basin-Estimated Rainfall (AMBER) algorithm, and the Bureau of Reclamation Snow Accumulation Algorithm.

3.3.3.4 Inventory of WSR-88D Level II Data

The NSSL-OSF Level II database has grown to over 1200 tapes. The tapes have been acquired in cooperation with the NCDC and via tape archival of Level II data by NSSL during its testing of the Warning Decision Support System (WDSS). Ground truth data associated with the Level II data tapes from 1995 and before are contained within an associated events database. The ground truth data were obtained from the SELS (Severe Local Storms) smooth log and other data sources. A total of 6135 hail, 1504 tornado, and 4345 severe wind events are included in the database.

A web site which allows for systematic searching of the Level II database according to event, event intensity, radar site, date and time, is located at "http://codiac.nssl.noaa.gov/nexcat". Access to the Level II inventories, tape indices, and ground truth information can be found at "http://www.nssl.noaa.gov/~mitchell/l2_dbase.html".

3.3.3.5 Open System Radar Product Generator (ORPG)

A Memorandum of Understanding between the Environmental Research Laboratories and the National Weather Service has tasked NSSL to lead the software development efforts for the Open Systems Radar Product Generator (ORPG). Open Build 1, the first operational release of the ORPG, will feature the existing RPG's Build 10 functionality with some extensions. This release is currently scheduled to be delivered to the OSF for testing during the spring of 1999.

The ORPG is engineered to be expandable to accommodate future growth and resource demands. The ability to easily incorporate new meteorological algorithms, product generators, and functionality will be provided through the encapsulation of services and modules as well as the loosely coupled relationship of the processes making up the system. As resource demands (processing, memory, and storage) increase, the ORPG will be able to adapt through the addition of the required resources with no changes to the software. The ORPG software is also being developed to be portable, making relatively inexpensive hardware available for the ORPG and hopefully to reduce technological obsolescence.

An iterative development model was chosen for the ORPG project. This project is expected to be completed over five "Mini-Builds", each lasting approximately six months. Mini-Builds 1 through 3 have already been completed. The primary development activities have been in product distribution, RDA monitoring and control, communications, and graphical user interface (GUI) development. Further, the ORPG software has been ported to a PC platform running a Sun Solaris x86 operating system. Preliminary tests indicate a PC platform is a viable candidate for the ORPG.

3.3.3.6 Open System Radar Data Acquisition (ORDA)

Significant accomplishments have been made in the upgrade of the NOAA/ERL research and development WSR-88D. NSSL is developing a prototype ORDA hardware/software system, and is planning to add dual-polarization to the system during 2000. Detailed design of the synchronizer board for timing and an interface board have been completed. The boards have been wired and engineering tests are being conducted. A modern development environment and prototype signal processors and host computers have been acquired and integrated. Several base data estimation algorithms have been developed for the new digital signal processor. The building to house the radar and to provide a workshop and office space has been completed, and we plan to move in during early 1999. For a progress report of activities to modify the WSR-88D for polarimetric measurements see Section 3.3.4.

3.3.3.7 Open Systems Principal User Processor (OPUP)

The Open Systems Principal User Processor (OPUP) is being developed by NSSL to display WSR-88D data and products for Department of Defense users. NSSL began work on the OPUP system in 1997 in response to the U.S. Air Force requirements for a WSR-88D display system that could evolve under the open systems concept and the changing operational environment of the U.S. Air Force Weather Agency (AFWA). The OPUP software design will re-use infrastructure services developed for the Open Systems Radar Product Generator (ORPG) as applicable. The OPUP system is designed as a distributed computing client/server architecture in contrast to the current PUP system. Graphical user interfaces are being developed to replace the dedicated display hardware and alphanumeric menu systems of the current system with a UNIX workstation. Several new requirements for the OPUP system have also been identified by the AFWA and are integrated into the OPUP design. These new requirements include the ability for the OPUP system to connect to, and ingest data from, as many as 30 dedicated and 10 dial-in WSR-88D systems. The first mini-build of the OPUP system was completed in late 1998 and demonstrated the capability to connect to and receive products from multiple radars.

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3.3.4 WSR-88D: POLARIMETRIC UPGRADES

This summary focuses on activities at the National Severe Storms Laboratory to improve rainfall measurements by adding polarimetric capability to NSSL's research WSR-88D (designated KOUN1). One of the most important elements of a polarimetric radar is an antenna with low sidelobes and matched radiation patterns for horizontally and vertically-polarized waves. An engineering evaluation was made to determine if the existing antenna assembly could provide polarimetric measurements. Fortunately, this is the case and radar modification costs should be reduced accordingly.

Because pattern measurements had not made of a WSR-88D antenna on site, it was imperative to first evaluate the KOUN1 antenna before the feed was changed from one which transmits only horizontally polarized waves to one with a dual-port feed transmitting both horizontally and vertically polarized waves. The patterns, before change of feed, demonstrated that there had been no significant change in antenna quality since the 1988 installation. After changing the feed and one strut on the antenna assembly, the radiation pattern still satisfied the original WSR-88D specifications.

A dual-port antenna feed was purchased from Andrew Canada, Inc. (manufacturers of the WSR-88D antennas) and installed on the radar. Pattern measurements were made for the horizontal and vertical polarizations. The radiation patterns with the dual-port feed are very close to those with the single-port feed. Both horizontal (H) and vertical (V) polarization copolar patterns have low sidelobe levels and are well matched in the mainlobe. Beamwidths are 0.93° for the horizontal copolar and 0.90° for the vertical copolar patterns. Pattern match in the lower half of the vertical plane is excellent and even extends to several of the sidelobes. For the most part, the patterns agree within ± 1 dB; and the match is best where the gain is largest (i.e., near the beam axis). For points far removed from the axis, the differences are larger as expected, but because the antenna gain is much smaller in these regions, the differences are less significant than those close to the axis.

Cross-polarization patterns were also recorded, and it was observed that the WSR-88D specification of < -30 dB is met. The cross-polar pattern at vertical polarization matches in shape the cross-polar pattern at horizontal polarization, but the amplitudes are about 4 dB higher (still within the measurement uncertainty). The addition of the dual-port feed and the retention of the three struts had not degraded the patterns. Hence, this configuration is recommended for future polarimetric upgrades of the WSR-88D.

Of critical importance to polarimetric radar utility is the selection of an appropriate polarization basis and its practical implementation. Circular and linear polarimetric bases were examined. Circular polarization can, in principle, provide specific differential phase (K_{DP}) estimates without switching the transmitted polarization. In weak showers, these estimates are corrupted because the cross-polar signal is almost three orders of magnitude below the copolar signal. But with circular polarization, the cross-polar signal does not depend on hydrometeor orientation; and in combination with the copolar signal, it leads to the measurement of the mean canting angle. This apparent advantage vanishes in the presence of significant precipitation along the radar beam. A linear polarization basis is well suited for quantitative measurement of rainfall and classification of hydrometeor types without extensive correction of propagation effects. Therefore, the reasonable choice rests with linear H/V polarization.

A novel polarimetric scheme employing simultaneous transmission of horizontally and vertically polarized waves is being implemented on the KOUN1 radar. Principally, the motivation for simultaneous transmission is to do away with an expensive, high-power microwave switch which has been the key component in research polarimetric radars built during the 1980's and 1990's. The proposed design includes installation of two receivers that share several common components. With two receivers, the dwell time for computing polarimetric variables is reduced, the ground clutter filter is not affected, and maintenance is simpler. On the downside, the depolarization ratio cannot be measured simultaneously with other polarimetric variables; but if desired, it can be measured together with the standard spectral moments in separate volume scans. Having two receivers offers some redundancy that might be advantageous. For comparative testing, NSSL plans to incorporate two receivers in its radar and still provide full WSR-88D compatibility, i.e., all current data acquisition modes and scanning strategies are supported with minimal impact on existing algorithms and products.

A theoretical evaluation of the effects that feed alignment, drop canting, and backscatter depolarization have on the polarimetric parameters has been made for the simultaneous transmission and reception of H and V signals. This mode is not detrimental to the measurements of the specific differential phase and cross-correlation coefficient. Effects, however, on differential reflectivity by drop canting along propagation paths can be significant. But these effects are harmful only when differential attenuation dominates, which is a problem whether H and V signals are transmitted simultaneously or alternately. Differential reflectivity and the correlation coefficient could be affected by depolarization due to backscattering from hail mixed with rain. On the other hand, backscatter depolarization would accentuate the hail signature of low Z_{DR} and low ρ_{HV} (i.e., further reduce low Z_{DR} and ρ_{HV} values in hail regions). Thus, the effect might be beneficial.

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3.4 NOAA/National Weather Service Offices

3.4.1 CHARLESTON, WEST VIRGINIA

3.4.1.1 Severe Hail Detection with Cell-Based VIL Density

A preliminary study relating a cell-based "VIL density" to severe hail ($\geq$ 19 mm in diameter) events has been conducted by the Charleston, West Virginia NWSFO (KRLX). VIL densities were determined using archive Level II data processed by the WSR-88D Algorithm Testing and Display

System (WATADS). A total of 75 thunderstorms were analyzed, 56 of which produced hail. At a threshold cell-based VIL density of 4.0 g m^{-3}, warnings would have been issued for 51 storms, 5 hail storms would not have received warnings, and 1 non-hail storm would have prompted a hail warning. The corresponding probability of detection (POD) was 0.91, and the false alarm ratio (FAR) was 0.019. Results may be somewhat skewed by the small sample of non-severe hail storms and the fact that few of the non-severe hail storms crossed populated areas likely to produce hail reports. Findings are being used operationally at the NWSFO. Future plans call for enlarging the dataset of both severe and non-severe events, refining the POD's and FAR's, and finding the relation between VIL density and hail size for storms within the KRLX county warning area (CWA).

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3.4.2 GOODLAND, KANSAS

3.4.2.1 Summary of Tornado Detection Algorithm Study

A detailed analysis and optimization of the Build 10 Tornado Detection Algorithm is in progress at the Goodland, Kansas NWSO. The study involves 28 storm days and 50 tornadic events within the local county warning area. The study is about 70% complete and is expected to be finished by mid 1999. Adaptable parameters being examined are the minimum three-dimensional depth, the minimum three-dimensional low-level delta velocity, and the minimum TVS (Tornado Vortex Signature) velocity. Build 10 algorithm default parameters gave a false alarm rate of 54%.

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3.4.3 SALT LAKE CITY, UTAH

3.4.3.1 Microburst Studies

A joint investigation between the National Severe Storms Laboratory and the National Weather Service office at Salt Lake City for predicting dry microburst storms continues. Radar, sounding, and surface data have been analyzed for 4 cases. The microburst-producing storms often have low reflectivities which require modification of WSR-88D Storm Cell Identification and Tracking (SCIT) thresholds. The work incorporates a one-dimensional cloud model (Srivastava 1985). Examples of the SCIT algorithm performance on dry microburst storms appear in the Western

Region Technical Attachment TA98-24 "Use of thermodynamic information to predict low-reflectivity microbursts" by Vasiloff and Stewart. This report can be found on the NWS Western Region homepage at "http://www.wrh.noaa.gov".

3.4.3.2 Radar Snowfall Measurement

The National Center for Atmospheric Research's Warning Support to Deicing Decision Making system is being evaluated for snowfall estimation with the WSR-88D. An important component of the system is a dynamic adjustment of the radar reflectivity-snowfall rate equation coefficient and exponent. The system incorporates realtime snow gauge data from up to 8 locations at various ranges and altitudes. Preliminary results show that in order to accurately predict a 30 min snowfall liquid equivalent, it may be necessary to vary the Z-S coefficient by an order of magnitude. An example of the methodology appears in the Western Region Technical Attachment TA97-35 "Interpretation of radar data during snow events in mountainous terrain" by Vasiloff. This report is also on the NWS Western Region homepage.

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3.4.4 WAKEFIELD, VIRGINIA

3.4.4.1 Mesocyclone Detection Algorithm Performance during Tropical Storm Bertha

Mesocyclone Detection Algorithm (MDA) performance during tropical storm Bertha (July 1996), which spawned 4 confirmed tornadoes within the Wakefield county warning area (CWA), has been examined. Maximum rotations for the mesocyclonic circulations were 12-15 m s^{-1}, minimum diameters were 2-2.5 km, and highest shears were > 0.014 s^{-1}. The highest rotational and shear values were found at 0.5° elevation. The WSR-88D MDA failed to detect mesocyclonic circulations beyond 65 km. Overall performance of the MDA was judged to be poor.

In a related study, detections with the WSR-88D Mesocyclone Detection Algorithm were compared to those from the NSSL Storm Scale Vortex (SSV) algorithm. The WSR-88D MDA detected only 9 circulations)all within 55 km of the radar. The NSSL algorithm found 39 SSV's)some at distances of 170 km. The NSSL algorithm indicated > 90% probability of a tornado 5 to 10 min prior to tornado observance in 2 of the 10 cases. Of the 10 tornadic SSV's, 5 were not detected by the WSR-88D MDA. A feature of the NSSL algorithm thought to have contributed to its superior performance in detecting shallow circulations is the application of a storm-relative depth threshold rather than an absolute depth threshold. An electronic summary of this study can be found at http://www.nssl.noaa.gov/swat/cases_071296_kakq.html".

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3.4.4.2 Characteristics of Mesocyclones Associated with Landfalling Tropical Cyclones

Statistics have been compiled for mesocyclones associated with 9 confirmed tornadoes occurring with landfalling tropical cyclones within the Wakefield CWA. Parameters studied include maximum rotation, diameter, and shear at the 0.5 and 1.5° elevation angles from four volume scans prior to tornado touchdown (T-4) to a volume scan after touchdown (T+1).

All confirmed tornadoes occurred in the cyclone's right front quadrant. The WSR-88D Mesocylone Detection Algorithm (MDA) failed to detect a circulation with 4 of the 9 confirmed tornadoes.

Generally, for the period T-4 to T+1, the average rotational velocity at 0.5° elevation for the 9 mesocyclones increased, the average diameter decreased, and the average shear increased. The trends were less distinct at 1.5° elevation angle suggesting that the 0.5° scan may provide the best predictor for tornadogenesis. Every confirmed tornado possessed shear values > 0.01 s^{-1}.

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3.5 NOAA/NEXRAD Operational Support Facility

3.5.1 Operational Needs for Custom Volume Coverage Patterns

An investigation (in collaboration with Dale Sirmans, System Technology Associates) is underway to determine operational needs for additional Volume Coverage Patterns (VCP's). A report, "Operational Needs for Custom Volume Coverage Patterns," was written, in part, to accompany NSSL 1998 Memorandum of Understanding VCP tasks. The report explores ways to modify VCP's for meteorological purposes and to validate operational needs. Four experimental Volume Coverage Patterns, based on meteorological factors, are listed in the appendices of the report. Two custom VCP's feature dense sampling of the lower atmosphere, one VCP is designed for rapid update, and yet another custom VCP yields dense sampling with a 5 minute throughput.

The dense sampling VCP parameters were devised as a way to effectively detect lake-effect snow (LES) events. The procedure to develop a LES VCP began with the selection of several sites with detection problems. VCP parameters were carefully established. For example, variation of the tilt elevation angles, antenna rotation rate, and signal estimate requirements were matched against the meteorological phenomenon of interest. The effort to alleviate LES detection problems represented a general solution to many other low-level meteorological phenomena and far-range events.

We were compelled to devise a "standard" VCP, generalizing the particular solution for LES detection, for broad application at other sites. With a well designed VCP, the development effort would require fewer VCP parameter changes at "problem" sites. Using U.S. Geological Survey terrain data, the beam blockage at selected sites was calculated at 0.1° steps from 0.1 to 0.7° and occultation files were generated. Stanford Research Institute visual and digital profile data were inspected. Azimuthal extents of importance to the LES problem for each site were established. The 0.3° elevation angle was quite acceptable as a standard solution. Radar sensitivity requirements typical of LES events were a basis for determining antenna rotation rates and pulse repetition frequencies. For radar sites with flat terrain, the physical basis for a 0.3° minimum elevation angle has been established (Smith 1998).

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3.5.2 WSR-88D ALGORITHM SURVEY

In March 1998, NEXRAD OSF personnel polled WSR-88D users to evaluate Build 9 software installed during the winter of 1996. The survey examined perceived algorithm performance, frequency of use, field use of certain adaptable parameters, and the effectiveness of new algorithms and products.

Forecasters are comfortable with most WSR-88D algorithms and products, find them accurate and reliable, and consult them often. Algorithms and products new to Build 9 [Storm Cell Identification and Tracking (SCIT), Hail Detection Algorithm (HDA), and Cell Trend (CT)] are used often by a majority of forecasters. User Selectable Precipitation (USP), also a new product, was little used by survey respondents.

Older products, Severe Weather Analysis (SWA), Velocity Azimuth Display (VAD), Combined Shear (CS), Layer Composite Reflectivity-Average (LRA), Severe Weather Probability (SWP), Spectrum Width (SW), and Echo Tops Contour (ETC), were also infrequently consulted. Of the little utilized algorithms and products, SW probably holds the greatest potential for forecasters. In recent years, this Doppler moment has found application in the detection of turbulent regions associated with deep convergence zones; thunderstorm inflows, updrafts, and downdrafts; large hail through three-body scattering; tornadoes associated with tropical storms; depth of orographic turbulence; eye walls of deepening or filling hurricanes; gust fronts; and determining the quality of velocity data (Lemon, personal communication).

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3.5.3 TDA ADAPTABLE PARAMETER STUDY

A new Tornado Detection Algorithm (TDA) is part of the WSR-88D Build 10 software release. Thirty adaptable parameters used by the algorithm specify program memory limits, modify data processing thresholds, and establish criteria for detecting two-dimensional (2D) and three-dimensional (3D) vortex features. The TDA is designed to detect a full spectrum (large, small, weak, and strong) of 3D circulations. Three adaptable parameters filter 3D features by depth and gate-to-gate velocity differences.

Thirty-four cases were categorized by storm type (15 isolated supercells, 13 squall lines, 6 tropical storms), and algorithm performance was analyzed as a function of the three adaptable parameters that govern algorithm detections. This analysis yielded parameter values for optimizing TDA performance for each storm type. OSF and NSSL personnel are working to define sets of adaptable parameters that minimize false alarms and maximize probability of detection, thus providing optimum algorithm performance.

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3.5.4 ALGORITHM EVALUATION

The NEXRAD/OSF has been evaluating WSR-88D baseline algorithm performance in tornado/severe storm situations and comparing results with that of NSSL experimental algorithms. This project involves staff from the Applications and Operational Training Branches of the OSF and NSSL. Results from the Hall/White county, Georgia tornado of 20 March 1998 are included in an online training module developed by the Operational Training Branch located at "http://www.osf.noaa.gov/otb/tngmat/tutorials/mar20/intro.htm".

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3.5.5 PERFORMANCE OF THE NEW WSR-88D TORNADO DETECTION ALGORITHM FOR THE OKLAHOMA TORNADIC STORMS OF 13 JUNE 1998

The performance of the recently installed Build 10 Tornado Detection Algorithm (TDA) was assessed for tornadic storms occurring in Oklahoma on 13 June 1998. In particular, algorithm performance was evaluated (1) for two closely-placed WSR-88D's, (2) for range coverages to 100 and 150 km, and (3) for velocity data thresholds of 0 and 20 dBZ. Both the range of coverage and the reflectivity threshold are controlled by adaptable parameters that field sites will have authority to change through the Unit Radar Committee.

Level II data were archived in Volume Coverage Pattern (VCP) 11 using the Operational Support Facility's testbed WSR-88D (KCRI) in Norman, Oklahoma. A second set of Level II data was archived in VCP 21 using NSSL's Warning Decision Support System (WDSS) attached to the Twin Lakes WSR-88D (KTLX) operated by the Norman, Oklahoma National Weather Service Forecast Office. KTLX is about 18 km east-northeast of Norman. The analysis period was from 2200Z on June 13 to 0200Z on June 14. Level II data were replayed using the Build 10 version of the WSR-88D Algorithm Testing and Display System (WATADS). The tornadoes were rated F1 to F2. Tornadoes from one storm that struck the northern fringes of Oklahoma City produced four distinct damage tracks and caused an estimated $25 million in damage. Other tornadoes were reported near the towns of Guthrie and El Reno.

The best TDA performance was obtained using data from KCRI with a 0 dBZ reflectivity threshold and a range of 100 km. The KCRI detections had a critical success index (CSI) of 0.54, while with the KTLX radar it was 0.50. Although the CSI's were similar, the probabilities of detection (POD) and the false alarm ratios (FAR) differed considerably. On KCRI the TDA had a POD of 0.79, while the KTLX radar had a POD of 0.62. The algorithm had a higher FAR with the KCRI data than with the KTLX data (0.37 versus 0.28). When the range of coverage was extended to 150 km, the FAR's increased for both radars. There was no change in the POD's because no tornadoes were reported beyond 100 km. The CSI's for the increased range were 0.30 and 0.33 for KCRI and KTLX, respectively. Imposition of a 20 dBZ reflectivity threshold reduced the number of detections by one half and increased the number of misses by more than a factor of two. Within 100 km, the CSI's for KCRI and KTLX at the 20 dBZ threshold were 0.30 and 0.28. With the extended range the CSI's fell even lower (0.20 and 0.19, respectively).

The difference in the TDA's performance for the two radars is not easily explained. KTLX had a slightly longer viewing distance. Most false alarms lay beyond 80 km and were associated with strong, easily identified circulations in the velocity data. Generally, the TDA requires that there be at least three vertically correlated regions of high gate-to-gate velocity difference and that the base region be on the lowest elevation scan to identify a feature as a Tornadic Vortex Signature (TVS). Because VCP 11 and VCP 21 have the same five lowest elevation angles, differences in coverage should not be a factor. This and other studies by the Applications Branch indicate that the new TDA will yield a larger number of TVS detections than the old algorithm.

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3.5.6 Study of Velocity Dealiasing Algorithm Changes on the Performance of the Build 10 Tornado Detection Algorithm

The Applications Branch has begun a study to document the occurrence of false alarms with the Build 10 Tornado Detection Algorithm. A preliminary look at the Spencer, South Dakota tornadic storm of May 30, 1998 revealed a large number of false Tornadic Vortex Signatures (TVS's). Many were beyond the default range limit of 100 km and would not normally be identified or displayed. There were, however, a large number of false TVS's identified as storms moved over the Sioux Falls, South Dakota WSR-88D. They were not confined to outflow regions but also occurred within the storm core. Examination uncovered a "speckling" of near zero Doppler velocity bins that were embedded within the storm's flow field. The near zero values presumably represent residual ground clutter. Prior to Build 10, the Velocity Dealiasing Algorithm (VDA) would have removed the ground clutter-contaminated bins from the velocity field. However, in the Build 10 version of the VDA, SAVE/REPLACE logic attempts to restore bins removed during dealiasing. This logic was requested by the NSSL source scientist and added specifically to support the TDA. (Missing velocity data within mesocyclones could be indicative of a strong circulation and require close scrutiny by forecasters.) The number of false alarms can be mitigated by disabling the SAVE/REPLACE logic (effectively restoring Build 9 performance levels), but a small percentage of TVS signatures would be lost.

When the storms passed over the Sioux Falls WSR-88D, high spectrum widths of 16 m s^{-1} appeared in regions with reflectivity >40 dBZ. A possible explanation is that, if the receiver A/D saturates before the Automatic Gain Control steps in, there may be a spurious increase in spectrum width and residual clutter. With more residual clutter embedded within precipitation, there is greater likelihood that velocity dealiasing will restore values that don't fit the overall flow pattern, thus leading to false TVS detections by the TDA. Ensuring good receiver calibration should reduce the false TVS signatures. The Applications Branch is continuing this investigation of saturation issues with cases from other WSR-88D's.

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3.5.7 Short-Term WSR-88D Precipitation Processing System Refinements

The OSF and NWS Office of Hydrology (OH) Hydrologic Research Laboratory (HRL) are coordinating plans to enhance the WSR-88D Precipitation Processing System (PPS). Enhancements will entail significant changes to the PPS preprocessing software that will be made possible by improved data processing capabilities in the Open Radar Product Generator (ORPG) environment.

3.5.7.1 Ground Clutter Removal

Currently, the PPS uses fairly crude (Tilt Test) logic to mitigate clutter contamination effects on radar precipitation estimates. The logic simply compares the area of reflectivity coverage at the first and second tilts. If the second tilt coverage area is significantly smaller than that at the first tilt, the PPS considers the lower tilt to be contaminated and rejects the reflectivity information. The Tilt Test logic frequently rejects regions of significant precipitation and is particularly ineffective in removing clutter embedded in precipitation.

We are planning to replace the Tilt Test with logic that utilizes the bin by bin clutter identification output from the Radar Echo Classifier (REC) algorithm (Section 3.5.7.3). This should allow the PPS to be far more precise in removing clutter contamination and decrease the rejection of significant precipitation echoes.

3.5.7.2 Vertical Reflectivity Profile

It has been well documented that vertical gradients of radar reflectivity due to bright bands, partial beam filling, and hydrometeor phase can significantly degrade the accuracy of radar precipitation estimates in orographic and stratiform storms. The errors are compounded in mountain sites with elevated radar locations. A primary cause of the errors is the physical inability of the radar to sample representative volumes of hydrometeors, particularly at ranges far from the radar. Scientists at HRL (led by Dr. D.-J. Seo) are developing an operational technique to calculate the vertical profile of reflectivity (VPR) in real time and to apply the VPR in the PPS software to improve precipitation estimates. Preliminary results show that the VPR can extend the range of meaningful precipitation estimates in stratiform and orographic events and may provide reliable realtime bright band detection. Knowing the bright band height should enable the correction of some anomalously high rainfall estimates and assist in realtime recognition of rain-snow lines.

3.5.7.3 Radar Echo Classifier

The National Center for Atmospheric Research (NCAR) and Environmental Research Laboratories (ERL) Forecast System Laboratory (FSL) are developing software to classify radar echoes in real time. The first operational implementation of the Radar Echo Classifier (REC) software generates a product that depicts the bin by bin likelihood of each measurement being ground clutter. It is expected that the clutter identification product will assist operators in applying clutter filters, particularly in regions of clutter caused by anomalous propagation. Additionally, the PPS is being redesigned to use the clutter identification product for mitigating ground clutter and anomalous propagation contamination in precipitation estimates.

3.5.7.4 Terrain-Based Hybrid Scan Data Files

Following successful tests earlier this year, the OSF generated modified (terrain-based) Hybrid Scan data files for each WSR-88D site and distributed them for operational use. The distribution was completed in November 1998.

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3.6 NOAA/Techniques Development Laboratory/Office of Systems Development

3.6.1 Synopsis of WSR-88D Research and Development Activities

Efforts during 1998 focused on operational implementation of various analyses and nowcasting products within the System for Convection Analysis and Nowcasting (SCAN), a part of the Advanced Weather Interactive Processing System (AWIPS) (Smith et al. 1998a,b). Also under development are a radar and satellite-based 0-3 hour rainfall prediction algorithm, and a twice-per-hour, 10 km national radar mosaic. For a detailed description of current Techniques Development Laboratory projects and operational products see the web site "http://www.nws.noaa.gov/tdl/".

3.6.2 SCAN Implementation

SCAN products provide analyses and nowcasts of various convective phenomena, combining various datastreams available within AWIPS. These include:

1. Thunderstorm products (Churma and Smith 1998) utilizing radar reflectivity and lightning data to detect thunderstorms and to display information on storm location, movement, and intensity;

2. Severe weather and large hail probabilities derived from vertically-integrated liquid (VIL) and upper-air information such as freezing level height and wind velocity; and

3. 0-1 hour forecasts of rainfall amount and rainfall probabilities exceeding various thresholds for each box of a 4 km, radar-centered grid. The forecasts also give the probability that individual storm cells will produce more than 1 inch (25 mm) in the next hour.

As of November 1998, the AWIPS release featuring these products had been fielded at several NWS sites, with full implementation scheduled during early 1999. For more information on SCAN see the web site "http://www.nws.noaa.gov/tdl/scan/scan2.html".

3.6.3 0-3 Hour Rainfall Prediction

This algorithm, destined for AWIPS implementation, will provide forecasts of heavy rainfall potential based on automated interpretation of radar echo intensity and velocity, satellite-detected cloud-top temperature, and upper-air humidity and stability from numerical weather prediction models. Specifically, the algorithm produces probabilities of rainfall exceeding 0.1, 0.5, 1, and 2 inches in 3 hours, at some place within each box of a 40 km grid. A categorical rainfall amount forecast is also produced by comparing the probabilities to preset thresholds.

3.6.4 National Radar Mosaic

An effort is underway to rehost the production of a 10 km radar mosaic for the conterminous United States. This mosaic, derived from radar coded messages obtained from all WSR-88D sites, is produced operationally at the NWS Aviation Weather Center; production will be relocated to a facility within NWS headquarters. The rehosted mosaic will be produced twice per hour, and will indicate temporary and permanent gaps in radar coverage due to radar outages, radar siting, and terrain occultation.

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3.7 U.S. Naval Research Laboratory

3.7.1 Summary of Recent Algorithm Research

This past year collaborative work continued with colleagues at the University of Oklahoma/Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) on Doppler radar data assimilation. Efforts were directed toward improving the analysis packages described in the following two subsections.

3.7.2 Simple Adjoint

We modified the simple adjoint (SA) code in order to retrieve the vector wind field directly on conical surfaces. The modified SA code was applied to Doppler data collected during the 21 August 1996 rain storm on the eastern coast of U.S. The method was found to be useful when the radar data are available at a single or very few elevation angles.

3.7.3 The Coastal Ocean/Atmospheric Mesoscale Prediction System

We performed test runs of the Navy's Coastal Ocean/Atmospheric Mesoscale Prediction System (COAMPS) to examine the impact of WSR-88D radar and surface mesonet observations on the short-term prediction of storms observed on 7 May 1995 during the Oklahoma Vortex Field Experiment. Results show that introducing the mesonet data into the analysis improves the short-term storm prediction of clouds and precipitation, and adding the Doppler radar data retrievals in combination with mesonet data further improves the prediction. Both fine grid (5 km) and relatively coarse grid (15 km) COAMPS background fields have been used in the analyses and test runs. However, since the analysis was not updated through data assimilation cycles, the analysis with the fine grid (5 km) COAMPS background field suffered a phase-error problem in terms of storm position and structure due to a mismatch between the model background and the observations. Predictions significantly improved when the 15 km COAMPS background field was used in the analysis. Based on these tests, a strategy was outlined for the development of an analysis system called "Shipboard Mesoscale Data Assimilation System Using Doppler Radar". Currently we are working on upgrading the wind retrieval codes with COAMPS terrain coordinates.

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3.8 Massachusetts Institute of Technology/Lincoln Laboratory

3.8.1 GUST FRONT DETECTION/PREDICTION

Detecting and predicting gust fronts (including the straight line wind speeds behind a front) would provide a number of benefits including: (1) improved forecasting of damaging winds, (2) wind shear information for airports without Federal Aviation Administration (FAA) wind shear detection systems, and (3) improved forecasts of convective weather initiation.

The FAA has implemented the Machine Intelligent Gust Front Algorithm (MIGFA) on the Terminal Doppler Weather Radar (TDWR) and it will be a part of the Integrated Terminal Weather System (ITWS). Typical MIGFA probability of detections (POD's) on TDWR data is 80% with a false alarm of 5%.

NEXRAD base data currently differ from TDWR data in two important ways. NEXRAD has a much coarser range resolution (1 km for reflectivity and 250 m for velocity versus 150 m for both measurements with the TDWR). Generally, NEXRAD has much greater ground clutter contamination. (NEXRAD sites typically do not use the ground clutter filters as much as the TDWR sites, and NEXRAD does not have a clutter residue editing map).

Consequently, it is difficult to achieve the same gust front detection performance on NEXRAD data. Information on this use of MIGFA on NEXRAD is available in an American Meteorological Society (AMS) Interactive Information and Processing Sytems for Meteorology, Oceanography, and Hydrology (IIPS) paper which is referenced on the Lincoln Laboratory aviation weather web site "http://www.ll.mit.edu/AviationWeather/". This joint Lincoln Laboratory/NSSL effort to optimize MIGFA for use with NEXRAD is continuing.

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3.8.2 STORM MOTION/EXTRAPOLATED POSITION ESTIMATION

An innovative scale separation technique has been developed to provide 30-60 min forecasts of storm positions using NEXRAD data. Also, the correlation tracker used in ITWS for storm motion estimation on TDWR, NEXRAD, and ASR-9 reflectivity data continues to be refined. Information on these projects is available on the Lincoln Laboratory web site.

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3.8.3 GRIDDED WINDS ESTIMATION USING NEXRAD DATA

The ITWS terminal winds algorithm producing gridded winds by assimilation of Doppler radar data, aircraft reports, forecast winds from the rapid update cycle (RUC) model, and surface observations continues to be modified based on ongoing realtime testing and evaluation at New York, Memphis, and Orlando. See the web site for details.

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3.8.4 ANOMALOUS PROPAGATION AND CLUTTER REMOVAL FROM NEXRAD DATA

The Lincoln Laboratory algorithm to edit anomalous propagation (AP) and ground clutter from composite reflectivity products based on altitude and Doppler velocity data has been implemented in Build 10. This algorithm removes ~2/3 of the AP while removing about 4% of the valid weather returns.

The residual AP is due primarily to range folding and occurs principally at long range (> 115 km) from a NEXRAD site. Analysis has shown that virtually all of the unedited AP could be removed by incorporating information from an adjacent NEXRAD to validate returns.

Information on this use of adjacent NEXRAD's to improve data quality is available in an AMS IIPS paper which is referenced on the Lincoln Laboratory web site.

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3.8.5 REDUCING BRIGHT BAND CONTAMINATION IN COMPOSITE REFLECTIVITY PRODUCTS FOR USE BY AIR TRAFFIC

The FAA plans to provide NEXRAD composite reflectivities to en route and terminal air traffic personnel via the Weather and Radar Processor (WARP) and the ITWS. Recent tests at the ITWS sites (especially New York) have shown that the NEXRAD composite reflectivity levels in winter storms are biased significantly upward by bright band contamination. The resulting composite reflectivities approach those of summer convective storms. However, the weather is not convective; and the overestimation could result in the NEXRAD products being perceived as false alarms. We have also observed some anomalous storm motions using NEXRAD composite reflectivity in winter storms. In these cases, the NEXRAD apparent motions appear to be too high.

Investigations are underway to determine if an edited VIL product (using the NEXRAD composite reflectivity AP editing algorithm) would provide a more realistic storm intensity for use by air traffic personnel. Information on this use of VIL as an air traffic product is available in an AMS paper which is also referenced on the Lincoln Laboratory web site.

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3.9 Colorado State University

3.9.1 ANALYSIS OF THE FORT COLLINS FLASH FLOOD OF 28 JULY 1997

On the evening of 28 July 1997 the city of Fort Collins, Colorado experienced a devastating flash flood that caused five fatalities and over $100 million in damage. Six hour rainfall accumulations in western parts of the city exceeded 10 inches. A multi-scale meteorological overview of the event utilizing a wide variety of instrument platforms and data sources including raingauge, CSU-CHILL multiparameter radar, NEXRAD radar, National Lightning Detection Network, surface and ACARS observations, satellite observations, and synoptic analyses has been conducted.

Many meteorological features associated with the Fort Collins flood typify similar events in the western U.S. Prominent features included a 500 hPa ridge axis over northeastern Colorado, a weak shortwave trough on the western side of the ridge, post-frontal easterly upslope flow at low levels, weak to moderate southwesterly flow aloft, a deep moist warm layer, and a quasi-stationary rainfall system. In contrast to the Rapid City and Big Thompson floods, the thermodynamic environment of the Fort Collins storm exhibited only modest instability, consistent with low lightning flash rates and an absence of hail and other severe storm characteristics.

Radar, raingauge, and lightning observations provided a detailed view of the cloud and precipitation morphology. Polarimetric radar observations suggest that a coupling between warm-rain collision-coalescence processes and ice processes played an important role in rainfall production. Dual-Doppler radar and mesoscale wind analyses revealed that the low-level flow associated with a bow echo located 60 km to the southeast of Fort Collins may have been responsible for a brief easterly acceleration in the low-level winds during the last 1.5 hours of the event. The enhanced flow interacted with both topography and the convection located over Fort Collins, resulting in a quasi-stationary convective system and causing the heaviest rainfall of the evening.

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3.9.2 SIMULTANEOUS HORIZONTAL AND VERTICAL TRANSMISSION EXPERIMENTS CONDUCTED WITH THE CSU-CHILL RADAR

During the summer of 1998 test data were collected with the CSU-CHILL radar in which the antenna's horizontal and vertical ports were energized simultaneously. For the experiments, adjustable horn antennas were temporarily mounted in a clear area approximately 1.5 km from the radar site. Measurements of the transmitted signal at the remote site were used to optimally adjust the relative power levels and phase lag between the CSU-CHILL's dual transmitters. The general "simultaneous transmission" method permits polarimetric measurements to be made without the difficulties (expense, tuning, monitoring requirements, etc.) incurred by the use of a high power polarization switch. Two receiver configurations were tested:

1. A single receiver switched to alternately sample horizontally (H) or vertically (V) polarized return signals (STAR mode: Simultaneous Transmit Alternate Receive)

2. Dual receivers to simultaneously process H and V returns from each received pulse (STSR mode: Simultaneous Transmit Simultaneous Receive).

It should be noted that radar hardware configurations used in these experiments are under investigation at NSSL as possible upgrades that will permit WSR-88D radars to efficiently collect polarimetric measurements.

Data were collected with the CSU-CHILL radar operating in both simultaneous transmit and conventional alternate H/V transmission modes. Very good agreement was found between the differential propagation phase ϕ_{DP} and Z_{DR} measurements obtained with the two transmission schemes. The H/V correlation at zero lag $\rho_{HV}(0)$ was somewhat lower in STAR mode, presumably due to backscatter depolarization effects. Analyses of the test data are continuing both at CSU and at the University of Essex (United Kingdom) by Prof. Anthony Holt.

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3.9.3 Polarimetric Radar-based Fuzzy Logic and Neuro-Fuzzy Hydrometeor Classification Schemes

Research is underway that blends radar reflectivity measurements at horizontal polarization (Z_H), differential reflectivity (Z_{DR}), differential propagation phase (ϕ_{DP}), cross-correlation coefficient at zero time lag ($\rho_{HV}(0)$), linear depolarization ratio (LDR); as well as the ambient temperature at the altitude of the radar observations, in a neuro-fuzzy network for the discrimination of hydrometeor types. The network logic outputs are 10 possible hydrometeor classifications:

1. drizzle
2. rain
3. dry and low density snow/ice crystals
4. dry and high density snow/ice crystals
5. wet and melting snow/ice crystals
6. dry graupel
7. wet graupel
8. small hail
9. large hail
10. rain/hail mixture

Neural network methods are used to automatically adjust the "membership functions" that are applied in the fuzzy logic hydrometeor classification scheme. This is thought to be an improvement over classification systems based on fuzzy logic alone. Performance evaluations of the neuro-fuzzy system have thus far been promising.

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3.9.4 Testing of an Automated Hail Mapping System Based on Polarimetric Radar Classification Schemes

During the summer of 1998 the CSU-CHILL radar facility supported the Colorado Collaborative Rain and Hail Study (CoCo RaHS). A key project component was the organization of approximately 120 volunteer precipitation observers in the greater Fort Collins area. The observers were equipped and trained to make and report daily observations of rain and hail. Efforts were made to collect polarimetric CSU-CHILL radar data whenever intense convective echoes crossed the observer network. The primary objective was to develop hailswath maps that could be verified using observations from the CoCo RaHS network. Hailswaths were mapped using the H_{DR} hail signal of Aydin et. al (1986; J. Climate Atmos. Meteor.).

Individual range gate H_{DR} values from the lowest elevation sweep were calculated with a computer program which read the CSU-CHILL data tapes. Locations of $H_{DR} > 10$ dB were plotted on an electronic base map. The final swath map was then posted on the internet, usually the day following a hail event.

Experience to date indicates that clutter-contaminated gates must be removed before H_{DR} processing. Reasonably good clutter rejection was obtained by removing data bins where:

Z_H < 45 dBZ
$\rho_{HV}(0)$ < 0.88
Z_{DR} < -1.25 dB
LDR > -18 dB, and
radial velocity magnitude < 1.0 mps.

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3.10 University of Iowa/Iowa Institute of Hydraulic Research

3.10.1 SUMMARY

The primary focus of research related to WSR-88D algorithms at the Iowa Institute of Hydraulic Research is the improvement of the Precipitation Processing System (PPS). Specific tasks are directed toward refining bias adjustments, the optimization of PPS adaptable parameters, the development of new approaches for realtime rainfall estimation, anomalous propagation detection, the study of precipitation variability at small scales, and database organization. For additional information regarding the Institute and research projects see the web site "http//www.iihr.uiowa.edu".

3.10.2 MEAN BIAS ADJUSTMENT

We have investigated the performance of the PPS realtime mean-field bias adjustment algorithm with a data-based Monte Carlo simulation (Anagnostou et al. 1998a). An analysis was made of a two-year record of radar observations from the Tulsa, Oklahoma WSR-88D and rainfall measurements from a dense raingauge network under the radar umbrella. Data stratification disclosed that bias errors differed for warm and cold seasons and had marked range dependencies. We have also quantified the sampling error as a function of the raingauge network density. Results reveal that sampling error decreases proportionally with the square of the gauge density and that sampling errors are higher in the warm season. Finally, the performance of three mean radar-rainfall bias estimation and prediction algorithms have been examined. Methods tested included the NEXRAD precipitation adjustment procedure, an adaptive error parameter technique, and the maximum likelihood autoregressive model. Experiments for the two seasons; accumulation times of 1, 3, and 6 h; and prediction and update modes of operation show significant seasonal and time-scale effects.

3.10.3 ADAPTABLE PARAMETER OPTIMIZATION

The WSR-88D PPS is a multicomponent rainfall estimation algorithm with a large number of controlling parameters. Default values are based on limited experimental studies and do not account for rainfall regime differences. This translates potentially to uncertainty in system-estimated precipitation products.

To improve algorithm performance we have formulated PPS calibration as a global optimization problem (Anagnostou and Krajewski, 1998a) in which parameter values are determined at the hourly rainfall accumulation product level. The technique automatically accounts for parameter interactions. Performance was measured by the root mean square difference between hourly radar-rainfall products and rainfall accumulations from raingauges. The main advantages of our approach are the simultaneous estimation of all system parameters thereby providing an integral assessment of the algorithm's performance and an automatic evaluation of the relative importance of the PPS parameters in the full context of rainfall estimation.

The optimization approach was applied to two months of radar reflectivity data from the Melbourne, Florida WSR-88D and corresponding raingauge measurements. We determined improvements up to 22% with respect to the default parameter setup.

3.10.4 REALTIME RAINFALL ESTIMATION

A multi-component radar-based algorithm for realtime precipitation estimation, that emphasizes the combined use of weather radar observations and in situ rainguage measurements, is under development (Anagnostou and Krajewski, 1998b). Algorithm outputs are 1 h to storm-total accumulations for areas of 4 to 16 km^2. Processing steps include beam-height correction, vertical integration, convective and stratiform storm type classification, conversion from radar observables to rainfall rate, range correction, and transformation of estimated rainfall rates from polar coordinates to a Cartesian grid. The algorithm applies an advection scheme in an effort to minimize temporal sampling errors and incorporates different parameter values for convective and stratiform regimes. System calibration is formulated as a global optimization problem, which is solved with the Gauss-Newton adaptive stochastic method.

The algorithm was evaluated with the radar reflectivity and rainguage measurements from Melbourne, Florida (Anagnostou and Krajewski, 1998c). Performance statistics were the mean difference (bias), normalized root mean square difference, and the correlation coefficient between radar and gauge amounts. We have demonstrated the convergence properties of the algorithm's adaptive parameter estimation procedure, conducted a series of sensitivity tests, and compared major components of our algorithm to the operational WSR-88D Precipitation Processing System. Improvements up to 40% result from the new parameterization scheme and the realtime calibration procedure. When rainfall classification is included, the improvement is as much as 50%. Correction for rain field advection moderately improves estimation accuracy (up to 20%). The algorithm effectively removes systematic range errors in the radar observations.

3.10.5 ANOMALOUS PROPAGATION DETECTION WITH A NEURAL NETWORK

We have perfected a procedure for detecting anomalous propagation (AP) echoes with a neural network. The network, described by Grecu and Krajewski (1999), features efficient procedures for selecting input predictors and training datasets and is devised for situations where only single-scan data are available (as in most of the RADAP II data). System output is quantified into four classes corresponding to upper limits of 25, 50, 75 and 100% anomalous propagation echo per scan. The high dimensionality of the input data is reduced by feature extraction through fractal, statistical, and wavelet analyses. The procedure incorporates a feed-forward neural network for classification and a fuzzy logic strategy for network training. We have tested the methodology on real data and have made a comprehensive accuracy assessment.

Previous work shows that AP detection algorithms must be calibrated before application at new sites. The development of the calibration datasets can be laborious because it typically involves human experts. We eliminate this problem with an efficient calibration and validation methodology based on a neural network. Using volume scan radar reflectivity data from two WSR-88D's, we have demonstrated the utility of the calibration procedure and successfully applied the method to different sites (Grecu and Krajewski 1998).

3.10.6 Precipitation Variability at Small Scales

A fundamental problem in radar-rainfall estimation is the quantification of radar accuracy through comparison with raingauge data. Results can be misleading if one ignores small-scale rainfall variability (Ciach and Krajewski, 1998, 1999; Anagnostou et al., 1998b).

Consequently, an experimental facility is being established at the University of Iowa (Krajewski et al. 1998) to improve our knowledge of precipitation variability on scales of 10 to 1000 m. Collocated instrumentation includes a vertically pointing X-band radar, a two-dimensional video disdrometer, an optical rainguage, a standard tipping bucket rainguage, and high temporal resolution sensors for measuring wind velocity, temperature, humidity, and pressure. Planned upgrades are a Doppler processor, a mobile platform to enable participation in community-organized hydrometeorological experiments, and a network of 15 high-resolution rainguages. The gauge network will incorporate dual sensors connected to the same data logger. Observations, collected with gauges spaced at 10-1000 m, will support a broad spectrum of studies in rainfall and measurement variability.

3.10.7 Radar-Raingauge Comparison

A major problem in radar rainfall estimation is the lack of accurate reference data for area-averaged rainfalls. Radar-raingauge (R-G) comparisons are commonly used to assess and validate radar algorithms, but large differences in the spatial resolution between raingauge and radar measurements prevent straightforward interpretation of the results. We postulate that the R-G difference variance can be partitioned into the error of the radar area-averaged rainfall estimate and the area-point background originating from the resolution difference. A semi-parametric procedure to decompose these components, named the error separation method (ESM), is being tested. When applied to a sufficiently large sample, the decomposition permits the estimation of the radar error and describes the uncertainty of the hydrological radar products in rigorous statistical terms. An extensive dataset has been used to illustrate the ESM technique. The proportion of the error in the R-G difference variance has been studied as a function of rainfall accumulation time for intervals of 5 min to 4 days. Results (Ciach and Krajewski 1998) show that the area-point component is a dominant part of the R-G difference at short time scales and remains significant even for the 4 day accumulations.

The most common sensor for validation of radar-estimated rainfall products is the raingauge. However, the error in raingauge area-rainfall estimates imposes additional noise in the radar-raingauge difference statistics, which should not be interpreted as radar error. We propose to quantify the radar rainfall error variance by separating the raingauge sampling error variance from the variance of radar-raingauge ratio. The error is defined as the ratio of the "true" rainfall to the estimated mean-areal rainfall from radar and raingauge. Both radar and raingauge multiplicative errors are assumed to be stochastic variables, log-normally distributed, with zero covariance. Two methods for estimating the raingauge sampling error variance have been evaluated. The methods are based on the spatial correlation and the log of the gauge rainfall, respectively. The procedure emphasizes the range dependence of the radar error variance and produces error variance estimates for each radar rainfall product. The radar and raingauge data from Melbourne, Florida have been used to illustrate the method. Experiments with hourly rainfall accumulations at 2 and 4 km grid resolutions (Anagnostou et al. 1998b) show that the variance of raingauge sampling error can be as much as 65% of the radar rainfall error variance, depending on the product grid size, the location of the sampling point in the grid, and the distance from the radar.

An analytical model of the radar-raingauge comparison process, including measurement errors has been developed to study properties of different reflectivity-rainfall conversions with synchronized radar and raingauge data (Ciach and Krajewski 1999). Common Z-R adjustment schemes under investigation are direct and reverse nonlinear regression and the probability matching method. The three techniques yield different estimates of the Z-R relation exponent which are strongly dependent on system uncertainties. This partly explains the diversity of Z-R relationships encountered in the literature.

3.10.8 DATA COMPACTION

The format of archive Level II data and the volume of radar datasets makes it difficult to conduct studies on multi-year datasets. Hence, the Iowa Institute of Hydraulic Research is active in the development of techniques for radar data compression and database organization (Kruger and Krajewski, 1997; Software Practice and Experience).

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3.11 McGill University

3.11.1 Data Quality Study of a Bistatic Radar Network

The McGill bistatic radar network has operated during most of the past year in conjunction with the operationally used McGill S-band scanning radar. Experience is being gained on assessing the strengths and weaknesses of the bistatic approach for obtaining three-dimensional winds, including quantifying error sources.

Operational experience suggests that one of the most serious source of errors is the contamination of data by sidelobe echoes. To evaluate the magnitude of the problem and the possibilities for correction, a theoretical study as well as an analysis with real data were performed. A numerical model that simulates the bistatic reflectivity measurement has been developed. Assuming a monostatic reflectivity field, the model generates the reflectivity field seen by a bistatic receiver at a given location, taking into account the geometry of the network, the antenna patterns, as well as the polarization of the radar. Comparisons with real data are very satisfactory although some quantitative differences are present. It is believed that differences are due to uncertainties in the antenna patterns. Nevertheless, the simulations allow us to determine areas of different degrees of contamination and hence to select regions with the best data for three-dimensional wind field reconstruction.

Other work is addressing the presence of spurious errors in the bistatic Doppler measurements, such as those due to the low gain antenna in the bistatic receiver. This will enable us to develop a methodology for minimizing the above-mentioned errors in the three-dimensional wind field recontruction. [Related entries appear in past Reviews: 1997, III.U.1; 1998, 3.12.1.]

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3.11.2 Retrieval of Pressure and Temperature Perturbations from Bistatic Networks

The three-dimensional wind field retrieval method described by Protat and Zawadzki (1999) has been extended to retrieve the thermodynamic perturbations as well. This has been accomplished by adding the three projections of the momentum equation under the anelastic approximation (following the work of Gal-Chen 1978, Hane et al 1981, and Hane and Ray 1985) to the basic constraining model of Protat and Zawadzki. The retrieved quantities are the deviations of pressure and "virtual cloud" potential temperature from their horizontal limited-area average at each retrieval level. However, contrary to previous work, the local time derivatives of the wind components are introduced in the momentum equations, since these time derivatives are also retrieved in a moving frame of reference using the constraining model, under the assumption that the wind components vary linearly between two consecutive radar scans (5 minutes in the case of the McGill/University of Oklahoma bistatic network).

Moreover, in our method, the three-dimensional fields of wind, the local time derivatives of wind velocities, as well as the pressure and temperature perturbations are retrieved simultaneously. This implies that the three wind components are also constrained by the three momentum equations. Another modification of the retrieval of thermodynamic perturbations used here is the addition of a constraint that forces the vorticity equation to be satisfied. This leads to a much better momentum checking as well as to smaller residuals in the momentum equations. The method was applied to bistatic network observations of a shallow supercell and the results favorably compared to numerical simulations described by Rotunno and Klemp (1985). [Related entry in past Review: 1998, 3.12.1.]

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3.11.3 Wind Retrievals Applied to the Prediction of Icing Conditions

Supercooled liquid water is produced in the updraft regions of subfreezing clouds if condensation of vapor exceeds depletion through the depositional growth of solid particles like snow, graupel, and ice crystals. If the vertical velocity of air and a sounding are available, it is possible to deduce whether or not supercooled liquid water is being generated in the cloud and at what rate.

Based on this idea, a technique was developed to diagnose the presence of supercooled water clouds during snow events. The data required are single (or multiple) Doppler observations of reflectivity and radial velocity and a nearby sounding. From these data, the three-dimensional wind field is retrieved by a variational method based on the procedure of Laroche and Zawadzki (1994). From the retrieved vertical motion, the supercooled water is derived using the steady-state balance relation between snow content and cloud liquid water. The method was tested with a kinematic model that includes the dominant microphysical processes expected to occur in stratiform subfreezing conditions. A comparison between in situ aircraft measurements of supercooled water content and the diagnosed and model generated values shows good agreement.

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3.11.4 An Update on Refractivity Measurements Using Ground Targets

The field of refractivity (or index of refraction) near the earth's surface has been measured routinely for the past two years using the technique described in Fabry et al. (1997). During the period, measurements of refractivity by radar compared well with values computed from surface observations. At McGill, refractivity is measured to a range of 45 km and data coverage remains fairly constant except in periods of rain and strong anomalous propagation.

The refractivity field shows the greatest variability in summer because moisture is most variable. Rapid changes in refractivity are often associated with sudden moistening of boundary-layer air by evaporating rain, storm outflows, and cold fronts with sharp moist-to-dry discontinuities. On occasion, we observe convection forming at moisture or air mass interfaces that were not detectable in reflectivity or velocity fields.

Refractivity is a function of pressure, temperature, and moisture. Because most of the variability in summer is caused by moisture, it is possible to use refractivity to derive moisture quite accurately. For example, we have shown that, in combination with a single surface observation of pressure and temperature, dew point temperatures for a whole field of 45 km radius centered on the radar can be obtained with an accuracy better than 0.5°C, a performance comparable to that of automated surface stations. We hope that the additional moisture information will be useful for predicting convection and for improving thermodynamic retrievals. [Related entries in past Reviews: 1997, III.U.2; 1998, 2.11.]

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3.11.5 UPDATES TO THE MCGILL RAPID (RADAR DATA ANALYSIS, PROCESSING AND INTERACTIVE DISPLAY) SYSTEM

Recent additions to our RAPID system (Kilambi et al., 1997) include the following:

1) Rainfall accumulation corrections using vertical reflectivity profiles,

2) Ground echo identification with Doppler and reflectivity data, and

3) Generation of composite radar maps overlaid with satellite images.

3.11.5.1 Computing Vertical Profiles of Reflectivity

During each volumetric scan of our radar, (5 minutes, composed of 24 elevation angles between 0.5 and 32°), instantaneous vertical profiles of reflectivity from 1.0 to 8.0 km in height are computed for 5 range intervals 20 km wide from 10 to 110 km in range. Each profile is composed of 35 height slices 0.2 km thick. The 5 vertical profiles are displayed with every CAPPI map in order that forecasters may assess the suitability of particular low-level CAPPI maps that serve as input for rainfall accumulation. If a bright band is present, the intensity, height, depth of influence, and range variability are clearly revealed as would be the characteristics of any other precipitation type like low-level growth, virga, convection, or snow. If the bright band is centered close to the height of the low-level CAPPI, the forecaster should lower it, (or raise it if lowering is not possible), in order to reduce the contamination on the resulting accumulation product.

A correction can be performed after the generation of the surface rainfall accumulation map. This module also integrates all the 5 min profiles in order to derive a time-averaged vertical profile of reflectivity valid for the requested time interval. The forecaster can then choose to correct the rainfall estimation accounting for the mean vertical variation between the height of the low-level CAPPI's and the lowest height of the profile (1.0 to 1.2 km). Correction factors are interpolated at every kilometer.

We realize that a vertical profile correction should be applied to each of the CAPPI maps used to derive the accumulation product, and not simply to the latter. The outlined procedure is a simple preliminary approach that nonetheless achieves an adequate result. Recent simulations have shown that because of the limited number of elevation angles in a volume scan, bright band artifacts vary rapidly in range depending on whether the center of the radar beam is above, at, or just below the bright band at a given range. Averaging over 20 km intervals as done in our procedure and further averaging in time smooths these small-scale variations.

3.11.5.2 Ground Echo Identification

Until late 1997, ground echoes were avoided by simply interpolating horizontally across a pre-determined ground echo mask derived during non-precipitation conditions. Rainfall rate estimates over ground echoes were achieved using data from the first 2 pixels just outside the mask along the 4 cardinal directions in a distance-weighing scheme. However, the presence of highly variable anomalous propagation (AP) echoes renders all rainfall accumulation estimates practically useless in regions where these echoes occur. In an effort to identify AP regions and permanent ground echoes, we have devised a scheme that determines a ground echo mask every 5 minutes. The scheme consists of the following:

1) The absolute value of the measured Doppler velocity is locally averaged over a user-defined height typically between 1 and 3 km. This layer may include several Doppler elevation angles. The choice of an integration height is provided, rather than simply examining the elevation angle nearest to the selected height, so that precipitation echoes in a vertically sheared environment will be more easily recognized as such, while any fluctuations in the velocity signal from ground echoes will be reduced. Pixels where the average absolute Doppler velocity is less than a user-defined threshold (1 to 2 m s^{-1}) are considered potential ground echoes.

2) The vertical gradient of reflectivity is then computed between two user-selectable heights that usually correspond to the limits of the integration procedure in (1). Any pixel declared as a potential ground echo is NOT considered as such if the reflectivity difference is less than a user-specified threshold (usually 10 to 15 dB between the two heights).

3) A local horizontal reflectivity gradient is computed in a 3° by 3 km neighborhood centered on each polar pixel. No correction for the relative size of the polar neighborhood appears to be necessary since the gradients inside the larger neighborhood at farther ranges are smoothed by the wider beam width. Any pixel declared as a potential ground echo on the basis of previous tests is NOT considered as such if the horizontal gradient is less than a user-specified threshold (~5 dB).

A map of regions that are normally affected by AP has been derived for the Montreal area. It is used to prevent the identification of ground echoes over pixels with a very low probability of terrain-induced ground echoes. This precaution may be ignored by the user.

Horizontal interpolation of rainfall rates is then performed across the final ground echo mask on CAPPI maps used as input to the rainfall accumulation product. However, we believe that when the ground echo mask is extensive, a vertical extrapolation of precipitation aloft would be more advantageous. Thus, we are currently implementing a procedure that uses the "instantaneous" vertical profile to extrapolate reflectivity to the ground in clutter regions.

3.11.5.3 Composite Radar Maps and GOES Images

Since the fall of 1997, GOES visible and IR maps are routinely ingested into our RAPID system every 15 minutes. The visible data are normalized for sun angle and the IR data are converted into temperature. Each field is remapped at 2 km resolution on a Polar Stereographic projection covering an area of (960 km by 960 km) that includes southern Quebec, northeastern Ontario, and part of the northeastern United States.

Recently, low-level CAPPI's from 3 neighboring radars have been received by the RAPID software every 5 minutes and used to generate composite maps. The radars (and locations relative to the McGill radar) are:

1) Villeroy, near Quebec City (200 km to the northeast),
2) Carp, near Ottawa (130 km to the west), and
3) Britt, on the shore of Georgian Bay, (500 km to the west).

Radar pixels are remapped on the same Polar Stereographic projection to permit the overlaying of composite radar maps and GOES images. The user has the choice of selecting the "nearest" or "maximum" intensity for pixels with overlapping radar coverage. The former is usually preferred since the latter may enhance the contamination by the bright band and especially by AP echoes. In fact, we intend to use the information from neighboring radars to further refine the AP detection algorithm described above. In the meantime, we eliminate ground echoes from composite radar maps where the maximum visible brightness in the neighborhood is below a user-defined threshold or where the coldest temperature is warmer than another user-defined threshold. [Related entry in past Reviews: 1996, III.O.2.]

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7. Protat, A., and I. Zawadzki, 1999: On the retrieval of dynamic perturbations from bistatic multiple-Doppler radar network data. *J. Atmos. and Oceanic Technol.* (In press)

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For further information regarding the McGill radar system and research activities see the web site "http://www.radar.mcgill.ca/".

3.12 Princeton University/Department of Civil Engineering and Operations Research

3.12.1 Research Related to WSR-88D Meteorological Algorithms

A major focus of the research group is the hydrometeorological assessment of WSR-88D rainfall estimates. The work includes detailed case studies of heavy rainfall and/or hail storm events across the United States, particularly east of the Rocky Mountains. The purpose of these studies is two-fold: 1) to identify issues relevant to WSR-88D rainfall algorithm performance and 2) to provide training material for hydrometeorological forecasters. Also, systematic and statistical analyses are performed to document and study problems related to the radar measurement of precipitation and algorithm-based estimation of rainfall at ground. These analyses focus on range effects, bright band contamination, issues related to Z-R relationships, testing of different elements of the NEXRAD Precipitation Processing System, and application of hail thresholds. The quality control of recorded radar data, especially the automated identification of anomalous propagation echoes, is emphasized. Climatological studies are conducted to investigate regional characteristics of the rainfall and hydrometeorological environment.

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2. Baeck, M.L., J.A. Smith, and M. Steiner, 1998: Radar measurement of heavy rainfall over mountainous terrain. *Abstracts, 6th International Conf. on Precipitation: Predictability of Rainfall at the Various Scales*, Mauna Lani Bay, Hawaii, 1-9.

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6. Smith, J.A., M. Steiner, M.L. Baeck, and F.L. Ogden, 1998: Multi-parameter rainfall estimation coupled with distributed hydrologic modeling of the Fort Collins flash flood of 28-29 July 1997. Part I: Synopsis and radar analyses. *Abstracts, 4th International Symposium on Hydrologic Applications of Wea. Radar*, San Diego, California, Hydrologic Research Center, 75.

7. Smith, J.A., M. Steiner, G. Lander, and M.L. Baeck, 1998: Orographic rainfall in the GCIP region. *Abstracts, GCIP Mississippi River Climate Conf.*, St. Louis, Missouri, GCIP Project Office, 120.

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9. Steiner, M., and J.A. Smith, 1998: Convective versus stratiform rainfall: An ice-microphysical and kinematic conceptual model. *Atmos. Res.*, **47-48**, 317-326.

10. Steiner, M., J.A. Smith, S.J. Burges, and C.V. Alonso, 1998: Rainfall estimation using radar, gauge and drop spectra information -- The Goodwin Creek experience, Mississippi. *Abstracts, 4th International Symposium on Hydrologic Applications of Wea. Radar*, San Diego, California, Hydrologic Research Center, 20-21.

11. Steiner, M., J.A. Smith, S.J. Burges, C.V. Alonso, and R.W. Darden, 1998: Rainfall measuring issues -- The Goodwin Creek squalline of 27 May 1997. Amer. Geophys. Union, 1998 Spring Meeting, Boston, Massachusetts, EOS, Transactions, **79**, No. 17, April 28 / Supplement, p. 115.

12. Steiner, M., J.A. Smith, S.J. Burges, C.V. Alonso, and R.W. Darden, 1998: Extremes of spatial gradients in rainfall accumulations. *Abstracts, 6th International Conf. on Precipitation: Predictability of Rainfall at the Various Scales*, Mauna Lani Bay, Hawaii, 2-2.

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3.13.1 VERTICAL PROFILE REFLECTIVITY CORRECTIONS

A study was undertaken to address the problem of correcting rainfall estimates for the vertical profile of reflectivity. It was determined that a radar reflectivity threshold value of 30 dBZ at a height of 1.5 km above the freezing level can distinguish between areas of convection and regions of stratiform rain with bright band. For lower values of Z it is assumed that there is a standard bright band profile with a maximum reflectivity just below the height of the 0°C isotherm. When the Z threshold is exceeded, a "convective" vertical profile of reflectivity is assumed. This scheme is now used operationally with the United Kingdom national radar network (see also Sections 2.6 and 4).

Reference

1. Smyth, T.J., and A.J. Illingworth, 1998: Radar estimates of rainfall at the ground in bright-band and non bright band events. *Quart. J. Royal Meteor. Soc.*, **124**, 2417-2434.

3.13.2 ATTENUATION CORRECTION SCHEME

An evaluation was completed of attenuation correction methods. Findings indicate that the simple relationship which has been proposed between differential phase shift and attenuation only applies to rainfall with small raindrops and is not applicable to severe attenuation events. It is proposed that the total attenuation be derived directly from the differential attenuation between reflectivity measured with horizontally and vertically polarized radiation and estimated from (negative) values of differential reflectivity behind attenuating storm cores (see also Section 4).

Reference

1. Smyth, T.J., and A.J. Illingworth, 1998: Correction for attenuation of radar reflectivity using polarisation data. *Quart. J. Royal Meteor. Soc.*, **124**, 2393-2415.

3.13.3 HAIL DETECTION

In rainfall, measurements of differential reflectivity (Z_{DR}), reflectivity (Z), and differential phase shift (ϕ_{DP}) are not independent. The total phase shift calculated from values of Z and Z_{DR} should agree with the observed phase shift along the path. For rain this consistency can be used to calibrate the reflectivity (Z) of the radar to within 0.5 dB, providing the correct rain drop shape model is used. When the consistency check fails and the computed phase shift from Z and Z_{DR} does not agree with the observed value, one can infer that there is hail along the path.

Reference

1. Smyth, T,J., T.M. Blackman, and A.J. Illingworth, 1998: Observations of oblate hail using dual polarisation radar and implications for hail detection schemes. *Quart. J. Royal Meteor. Soc.* (accepted).

3.13.4 RAINFALL ESTIMATION WITH POLARIMETRIC RADAR

An invited review was presented to the American Meteorological Society's 1998 Annual Meeting that discusses the pros and cons of installing polarization capability on operational systems for improving estimates of rainfall rate (Illingworth 1998).

Reference

1. Illingworth, A.J., 1998: The contribution of polarimetric radar observations to precipitation estimation. Invited Review, 2nd Symp. on Integrated Observing Systems, Phoenix, Arizona, Amer. Meteor. Soc.

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4 BIBLIOGRAPHY OF RELATED RESEARCH ACTIVITY

This section presents a search of the formal journals, bulletins, popular magazines, technical reports, and conference proceedings for articles that relate to NEXRAD algorithms. The scope of the included papers is broad. Some involve the performance of algorithms; others provide supplemental information that when used in conjunction with existing algorithms may enhance their utility. Papers specifically mentioned are thought to be of general interest, to represent technology that could become important (e.g., if polarization capability were added to the WSR-88D), or to relate to particular problems (e.g., AP and bright band detection).

Each reviewed article is given a subjective rating as to its perceived importance to the NEXRAD program. In general, a "low impact" rating refers to articles of general interest. Case studies representing successful applications of WSR-88D data and products also fall into this category. "Moderate impact" usually refers to research that is related to current NEXRAD applications and technical needs or is likely to be important in the future. Polarimetric radar measurements and some potential applications fall into this category. "High impact" articles are thought to represent closely related research. Importantly, ratings are not an indication of research quality.

Journals selected for review were determined primarily by the likelihood of finding articles of interest and the constraints of time. The following is a list of journals and conference proceedings from which articles were taken:

Bulletin of the American Meteorological Society
IEEE Transactions on Geoscience and Remote Sensing
Journal of Atmospheric and Oceanic Technology
Journal of Applied Meteorology
Journal of the American Water Resources Association
Meteorological Applications
Monthly Weather Review
National Weather Digest
Quarterly Journal of the Royal Meteorological Society
Radio Science
Weather and Forecasting
Preprints, 28th Conference on Radar Meteorology

Papers Reviewed

Anagnostou, E.N., and W.F. Krajewski, 1998: Calibration of the WSR-88D precipitation processing system. *Wea. and Forecasting*, **13**, 396-406.
[Moderate impact, PPS parameter optimization. A method of globally optimizing the selection of parameters within the WSR-88D Precipitation Processing System at the product level is described. Optimization was judged by computing the root-mean-square difference between gauge observations and radar estimates. A probabilistic approach, dubbed the shuffled complex evolution method, was selected for error minimization because of its ability to handle complex multicomponent problems. The method was applied to two months of radar and raingauge

observations. Optimized parameters generally differed from default values. An overall reduction in RMSE of ~10% was achieved.]

Aydin, K., S.H. Park, and T.M. Walsh, 1998: Bistatic dual-polarization scattering from rain and hail at S- and C-band frequencies. *J. Atmos. and Oceanic Technol.*, **15**, 1110-1121.
[Low impact, possible alternative to modifying the WSR-88D for polarization capability. Simulations are made for bistatic passive receivers with dual-polarization capability. It is shown that combinations of cross-polarized and copolarized measurements can discriminate between rain and hail for most incident and scattering angle configurations. Although median particle volume diameters can be computed, solutions are not always unique. Other limitations occur at low signal strengths and low elevation angles for horizontally polarized transmissions.]

Baeck, M.L., and J.A. Smith, 1998: Rainfall estimation by the WSR-88D for heavy rainfall events. *Wea. and Forecasting*, **13**, 416-436.
[Moderate impact, concerns WSR-88D PPS performance with extreme rainfalls. Rainfall estimates for 5 flash flood situations in various geographical regions are examined. Significant underestimates of rainfall occurred in each case. Depending on the storm, the bias was attributed to such factors as the growth of precipitation toward ground, inappropriate Z-R relationships, and the imposition of hail thresholds that were too low.]

Barjenburch, K.M., and R.E. LaPlante, 1998: A preliminary assessment of the WSR-88D hail detection algorithm's performance over northern Ohio and northwest Pennsylvania. *National Wea. Digest*, **22**, 8-15.
[High impact, hail detection product evaluation. The paper summarizes a local study of the Build 9 Hail Detection Algorithm. The paper begins with a nice description of algorithm mechanics. The dataset consists of 46 storms on 16 storm days. A tendency to overestimate the frequency of severe hail and to underestimate maximum hail size was found. At a Probability of Severe Hail (POSH) threshold of $\geq$50%, the observed frequency of severe hail was 37%. A hail frequency $\geq$53% occurred for a POSH $\geq$70%. At this POSH threshold, the algorithm had a POD of 52%, a FAR of 69%, and a CSI of 24%. The authors conclude that radar operators need to be cautious when using algorithm output.]

Bauer-Messmer, B., J.A. Smith, M.L. Baeck, and W. Zhao, 1997: Heavy rainfall: Contrasting two concurrent Great Plains thunderstorms. *Wea. and Forecasting*, **12**, 785-798.
[Moderate impact, PPS evaluation. The paper discusses measurement errors in WSR-88D precipitation products for coexisting storms. Light rainfall from a fast moving squall line was overestimated (by 19%), and heavy rainfall from a slow-moving multicellular storm was underestimated (16%). Emphasis is placed on environmental conditions that led to the different storm structures and the role of storm-scale processes on the accuracy of the WSR-88D rainfall estimates. Although not shown in the paper, the authors state that the rainfall estimates were influenced by the presence of hail.]

Bolen, S., V.N. Bringi, and V. Chandrasekar, 1998: An optimal area approach to intercomparing polarimetric radar rain-rate algorithms with gauge data. *J. Atmos. and Oceanic Technol.*, **15**, 605-623.

[Low impact, radar-gauge comparison technique. An objective approach for locating elliptically-shaped optimal areas for radar-gauge comparisons is described. The procedure minimizes the RMSE (differences) between rainfall rates computed from K_{DP} and time averaged gauge observations. The shape and orientation of the ellipse is determined from distance decorrelation functions. For examples, the major axes of the ellipses were close to 1 km and the aspect ratios were 0.78 to 0.96. A caveat mentioned by the authors, which may preclude application, is that the radar estimates must be unbiased.]

Bringi, V.N., V. Chandrasekar, and R. Xiao, 1998: Raindrop axis ratios and size distributions in Florida rainshafts: An assessment of multiparameter radar algorithms. *IEEE Transactions on Geosci. and Remote Sensing*, **36**, 703-715.
[Moderate impact, application of polarimetric radar. The mass-weighted median diameter of raindrops (D_o) and rain rate are estimated from radar reflectivity and differential reflectivity and compared to in situ aircraft measurements. Surprisingly good results suggest that D_o can be estimated with a mean bias of 0.07 mm and a standard error of 0.35 mm. Light to moderate rain rates (10 to 60 mm h^{-1}) derived from Z_H and Z_{DR} had a bias of $\leq$4% and a fractional standard error of 30-40%. Rainfall rates derived from Z_H alone had larger bias errors.]

Capsoni, C., and M. D'Amico, 1998: A physically based radar simulator. *J. Atmos. and Oceanic Technol.*, **15**, 593-598.
[Low impact, information only. The paper describes a radar simulator for determining the influence of hydrometeors on radar signals. Precipitation is modeled by selecting populations of hydrometeors and accounting for polarization, propagation effects, and hardware characteristics. Key features are definition of the environment, generation of phase (I) and quadrature (Q) signals, and updating particle positions and characteristics (assumed to be random and filling the radar volume).]

Chang, M., and L.A. Flannery, 1998: Evaluating the accuracy of rainfall catch by three different gages. *J. Amer. Water Resources Asso.*, **34**, 559-564.
[Low impact, information only. Rainfall totals for a NWS standard gauge, a weighing gauge, and a standard gauge fitted with an Alter shield are compared to a reference pit gauge. On average all test gauges caught 10% less rain than the pit gauge. The recording gauge caught 2.7% less and the shielded gauge caught 1% more than the standard gauge. The magnitude of the biases increased with storm total rainfall (a 1 cm bias was determined for storms with 8 cm of rainfall). A catchment adjustment scheme, based on wind speed measurements and an estimated median drop size (derived from rain rate), reduced the biases by roughly 50%.]

Chapman, D., and K.A. Browning, 1998: Use of wind-shear displays for Doppler radar data. *Bull. Amer. Meteor. Soc.*, **79**, 2685-2691.
[Low impact, application. The authors assert that vertical cross-sections of Doppler radar data are useful for describing the flow patterns in two-dimensional features such as fronts and for detecting Kelvin-Helmholtz billows and shear zones in boundary layers. They contend that for fronts the shear zones are indicative of the streamline pattern. The measurements are made with the Chilbolton radar (0.28° beamwidth) at ranges of ~40 km. Some features (e.g., billows) might be difficult to see in reconstructed vertical cross-sections made with WSR-88D VCP's.]

Crum, T.D., R.E. Saffle, and J.W. Wilson, 1998: An update on the NEXRAD program and future WSR-88D support to operations. *Wea. and Forecasting*, **13**, 253-262.
[Low impact, information only. The paper gives a status report on NEXRAD activities, details a program to improve algorithms, and presents a look to the future. Among accomplishments are improved severe weather warning performance, greater detectability of severe weather and "clear air" phenomena, and longer lead times for warnings. The article describes efforts to upgrade the processing capacity of the radar product generator and data acquisition system. Possible future enhancements are polarimetric capability, bistatic receivers, and increased temporal and spatial resolution.]

Davies-Jones, R., and G.J. Stumpf, 1997: On the detection and measurement of circulation and areal expansion rate with WSR-88D radars. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 313-314.
[Moderate impact, potential upgrade or addition to vortex detection algorithms. Circulation and areal expansion rate are computed as measures of vortex intensity and indicators of trends in vortex strength. Circulation is a conserved quantity which should be less sensitive to range effects than other measures of vortex intensity such as the difference between positive and negative radial velocity extremes. In an example with a tornado at a range of 51 km, the circulation for radii of 0.5 to 3 km were relatively constant and close to that for the tornado itself. The coupling of significant circulations and contracting wind fields could be a predictor of possible further intensification and tornadogenesis.]

Durden, S.L., Z.S. Haddad, A Kitiyakara, and F.K. Li, 1998: Effects of nonuniform beam filling on rainfall retrieval for the TRMM precipitation radar. *J. Atmos. and Oceanic Technol.*, **15**, 635-646.
[Low impact, a theoretical and observational study of beam filling effects. Rainfall estimation with the TRMM radar is complicated by the large radar footprint (4.3 km) and attenuation losses. A theoretical model shows that under or overestimation of radar reflectivity and rainfall can result at ground depending upon the particular distribution of rainfall, attenuation, and rainfall intensity. At storm top, more relevant to the WSR-88D, attenuation is negligible and rainfall rates are overestimated by up to 10% in gradient regions.]

Eastment, J.D., T.M. Blackman, I.N. Moore, and G.D. Aulich, 1997: A bistatic radar system using an incoherent transmitter. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 288-291.
[Moderate impact, new technology. The components of a bistatic radar system being developed in the United Kingdom are described. The passive component is slaved to the Chilbolton S-band polarimetric radar. Details of system timing are given. Collocation of the two receivers revealed that the bistatic system is susceptible to sidelobe problems and to low signal-to-noise ratios, but tests are encouraging enough that the bistatic receiver will be deployed remotely in the future.]

Edwards, R., and R.L. Thompson, 1998: Nationwide comparisons of hail size with WSR-88D vertically integrated liquid water and derived thermodynamic sounding data. *Wea. and Forecasting*, **13**, 277-285.
[High impact, evaluation of VIL for estimating hail size. VIL and thermodynamically-normalized VIL parameters were compared to maximum reported hail sizes. Correlation coefficients between

the various parameters, including VIL, and hail size were ≤0.17 indicating essentially no "predictive" skill.]

Fabry, F., 1997: Rethinking radar data collection for the computing era. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc, 176-177.
[High impact, relates to system performance assessment. The author maintains that the collection and display of radar data has not kept pace with our ability to process data. Traditional data collection procedures and operational practice regarding displays often dictate the spatial resolution of data collected (e.g., the WSR-88D reflectivity resolution of 1° by 1 km). Examples are presented for reflectivity and velocity patterns determined from a single pulse-pair measurement. The information content in such fields can be very high and satisfactory for many operational functions. The argument is also made that for precipitation estimation many lower quality measurements may be better than infrequent high quality measurements. By tailoring some data collections according to the necessary accuracy, more frequent temporal samples at low antenna elevations may be possible in severe storm situations.]

Fulton, R.A., J.P. Breidenbach, D.-J. Seo, and D.A. Miller, 1998: The WSR-88D rainfall algorithm. *Wea. and Forecasting*, **13**, 377-395.
[Low impact, description of current algorithm. The article presents a detailed description of the various components of the realtime Precipitation Processing System (PPS) implemented on the WSR-88D. The product serves as guidance for flash flood warnings and as input into hydrological models. Optimization of adaptable parameters, bright band mitigation, range degradation, clutter suppression, and bias correction are seen as the primary future challenges.]

Gall, R., J. Tuttle, and P. Hildebrand, 1998: Small-scale spiral bands observed in hurricanes Andrew, Hugo, and Erin. *Mon. Wea. Rev.*, **126**, 1749-1766.
[Moderate impact, tropical cyclone analysis technique. Perturbation reflectivity fields from tropical storms are subjected to statistical analysis by application of cosine waves. The result yields fields of correlation coefficients which depict spiral rope-like features that have widths of ~10 km and lengths to 100 km and more. The features, which are not necessarily connected with rainbands and are far greater in number, move outward in time while rotating counterclockwise about the storms. The bands resemble boundary-layer rolls but extend to much greater heights. Their significance and source has not been determined.]

Gauthreaux, S.A., Jr., and C.G. Belser, 1998: Displays of bird movements on the WSR-88D: Patterns and quantification. *Wea. and Forecasting*, **13**, 453-464.
[Low impact, interesting biological application and data quality issue. The birds appear as point targets often with reflectivities of 20 dBZ or more. Maximum reflectivities are seen to the west and east of the radar where northward or southward flying birds present maximum cross-sections. (Most birds are well within the Mie scattering range at S-band and reflectivity/bird-size relationships can be complicated.) The effect of migrating birds on VAD wind profiles can be dramatic. Apparent increases in wind speed of >15 m s^{-1} may be observed during nighttime migrations. The large increase distinguishes birds from insects which normally exceed wind speeds by 2 to 6 m s^{-1}.]

Gauthreaux, S.A., Jr., D.S. Mizrahi, and C.G. Belser, 1998: Bird migration and bias of WSR-88D wind estimates. *Wea. and Forecasting*, **13**, 465-481.
[Low impact, user awareness issue. This paper is companion to Gauthreaux and Belser (1998) and gives further documentation of bird migration effects on WSR-88D products. Mean absolute differences up to 7 m s^{-1} are shown between WSR-88D VAD winds and radiosondes for high bird densities. Extreme differences are on the order of 15 m s^{-1}. Significant errors in VAD wind directions can also occur. An example from Lake Charles, Louisiana is presented where a radiosonde measured wind was 319° at 6.3 m s^{-1}, and a bird contaminated VAD wind was 191° at 10.3 m s^{-1}. The difference stems from a northerly velocity component of the birds. Bird (and insect) echoes are generally distinguished from precipitation echoes by their disk-like patterns (centered on the radar) and the manner and time of evolution.]

Gerard, A.E., 1998: Operational observations of extreme reflectivity values in convective cells. *National Wea. Digest*, **22**, 3-8.
[Low impact, not likely to serve as a basis for an algorithm. Thunderstorms with maximum radar reflectivity values ≥65 DBZ were stratified according to whether the height of echo exceeding this reflectivity threshold extended above or below the freezing level. Of classifiable storms with echo ≥65 dBZ above the freezing level, 96% produced severe weather. Of storms in which the threshold echo did not extend to the freezing level, only 30% (3) were severe.]

Golding, B.W., 1998: Nimrod: A system for generating automated very short range forecasts. *Meteor. Applications*, **5**, 1-16.
[Moderate impact, emerging technology. The Meteorological Office in the United Kingdom has been developing a forecast system that bridges the gap between nowcasting (observational-based) techniques and numerical prediction models. The emphasis is on the short term where observations, persistence, and extrapolation play key forecasting roles and where resolution and imperfect data assimilation hampers numerical models. The two techniques are integrated to produce forecasts out to 6 hours. Radar data are preprocessed at individual sites to remove ground clutter, correct for range biases, and mitigate bright band contamination. Gridded data are then sent to a central site for compositing. The observations are linearly extrapolated from recent values or trends and combined with forecasts from a numerical model using a variational scheme. Results show significant improvement over an earlier prediction scheme (FRONTIERS).]

Gorgucci, E., G. Scarchilli, V. Chandrasekar, P.F. Meischner, and M. Hagen, 1998: Intercomparison of techniques to correct for attenuation of C-band weather radar echoes. *J. Appl. Meteor.*, **37**, 845-853.
[Low impact, could be important if the WSR-88D is modified for polarimetric capability. Techniques that correct for attenuation at C-band with radar reflectivity, reflectivity and differential reflectivity, and specific differential propagation phase are reviewed and compared. Simulations indicated that the fractional standard errors for the various correction schemes were roughly 10% for the Z_{DR},Z_H pair, 20% for K_{DP}, and 30% for Z_H. When the methodologies were applied to radar measurements, the attenuation corrections for the combination Z_H and Z_{DR} and for K_{DP} were similar. An operational advantage with K_{DP} is an insensitivity to system calibration error.]

Gysi, H., R. Hannesen, and K.D. Beheng, 1997: A method for bright-band correction in horizontal rain intensity distributions. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 214-215.
[Moderate impact, potential method for improving precipitation products. A ray-by-ray method for identifying bright bands from low elevation scans is presented. The vertical profile of reflectivity is inferred from its range distribution at low antenna elevations. A search is made for maxima at likely heights for bright bands (0.75 to 3.5 km in the study). If a maximum is found, several tests are applied with such parameters as the maximum reflectivity, amplitude, thickness, variation in reflectivity below the band, the reflectivity decrease above the band, ... etc. If more than a prescribed number of radials test positively, a bright band adjustment is subtracted from the measurements. Adjustments are also made for the change in dielectric factor for ice. Adjusted rain patterns exhibit fewer concentric ring features and a reduction in radar overestimates at the range of the bright band. There is also a reduction in the rainfall underestimation at distant ranges where the beam rises above the melting layer.]

Haneda, T., and H. Uyeda, 1997: A technique for detecting a vortex using gradient of Doppler velocity. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 345-346.
[Moderate impact, possible addition to vortex detection algorithms. Vortex designations combine shears found in both the radial and azimuthal directions. Generally, the radial shears yield the vortex diameter; and the azimuthal shear helps place the vortex center. The technique worked well for two symmetric vortices but seemed to have trouble with an elliptically shaped vortex with its major axis at a large angle to the radar beam so that the two shear signatures nearly coincided.]

Hubbert, J., V.N. Bringi, L.D. Carey, and S. Bolen, 1998: CSU-CHILL polarimetric radar measurements from a severe hail storm in eastern Colorado. *J. Appl. Meteor.*, **37**, 749-775.
[Moderate impact, case study of storm hydrometeors with polarimetric measurements. This is a nice demonstration of how polarimetric variables permit diagnosis of hydrometeor evolution in thunderstorms. In particular, golfball-sized hail coincided with high LDR ($\geq$-18 dB), negative Z_{DR} ($\leq$-0.5 dB), and relatively low ρ_{HV} ($\leq$0.93). Morphological features identified include a positive Z_{DR} column associated with liquid drops transported above the freezing level, a cap of large LDR atop the Z_{DR} column thought to represent a region of mixed-phase precipitation that included large drops, and a column of positive K_{DP} interpreted as caused by drops shed from melting hail.]

Hufford, G.L., H.L. Kelley, and W. Sparkman, 1998: Use of real-time multisatellite and radar data to support forest fire management. *Wea. and Forecasting*, **13**, 592-605.
[Low impact, interesting application. The high sensitivity of the WSR-88D is exploited to remotely monitor the progress of a forest fire. Maximum reflectivities near the fire's location were 20 to 25 dBZ and decreased rapidly in the downstream direction. The authors suppose that the high reflectivities were dominated by fire-generated particles.]

Hunter, S.M., 1996: WSR-88D radar rainfall estimation: Capabilities, limitations and potential improvements. *National Wea. Digest*, **20**, 26-38.
[High impact, evaluation of the WSR-88D PPS and recommendations. The paper begins with a review of problems which impact radar-estimated rainfalls. Several recommendations and requests are made. In particular, the author calls for tilt test modification to prevent rejection of lowest

elevation meteorological echoes. Other requests are for additional research on bright band corrections and for gauge-radar adjustment techniques.]

Johnson, J.T., P.L. MacKeen, A. Witt, E.D. Mitchell, G.J. Stumpf, M.D. Eilts, and K.W. Thomas, 1998: The storm cell identification and tracking algorithm: An enhanced WSR-88D algorithm. *Wea. and Forecasting*, **13**, 263-276.
[Low impact, description of current algorithm. The paper outlines procedures for finding storm centroids, constructing 3D storm cells, and computing storm motion. Verification shows POD's as high as 96% for cells with maximum reflectivities >50 dBZ. Typical errors in forecast locations vary from 2 km for 5 min forecasts to 23 km for 60 min forecasts.]

Keenan, T., K. Glasson, F. Cummings, T.S. Bird, J. Keeler, and J. Lutz, 1998: The BMRC/NCAR C-band polarimetric (C-POL) radar system. *J. Atmos. and Oceanic Technol.*, **15**, 871-886.
[Low impact, information only. The paper describes characteristics of a C-band polarimetric radar developed jointly by the Australian Bureau of Meteorology Research Centre and the National Center for Atmospheric Research. The project was undertaken to determine the vertical distribution of hydrometeors in the tropics and to evaluate the use of polarimetric measurements in rainfall estimation. The radar transmits and receives linearly polarized horizontal and vertical signals. Parameters evaluated were reflectivity at horizontal polarization (Z_H), differential reflectivity (Z_{DR}), differential phase shift (ϕ_{DP}), and zero lag correlation coefficient (ρ_{HV}). The linear depolarization ratio will be added in the future. The radar operates in either traditional single or dual-polarization modes. Up to 1000 range gates are possible with a 2 μs pulse width and a PRT of 1 ms. Examples are presented of a tropical heavy rain event that caused a differential attenuation of -2 dB in Z_{DR} and 5 dB attenuation in Z_H. An attenuation correction scheme based on ϕ_{DP} showed some promise but resulted in a number of spurious hail signals. Preliminary results indicate that the K_{DP} parameter is a robust estimator of high rainfall rates.]

Kim, K.-E., G.-W. Lee, C. Campistron, and D.-I. Lee, 1997: Kinematic properties of wind fields and turbulence in tropical stratiform clouds. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 372-373.
[Moderate impact, radar measurements are used to estimate the turbulent kinetic energy (TKE). An increase in TKE coincided with the development of heavy stratiform rain and concentrated in the layer at and just below the melting layer. Richardson's numbers were slightly stable prompting the conclusion that TKE production by shear was largely dissipated by negative buoyancy.]

Kummerow, C., W. Barnes, T. Kozu, J. Shiue, and J. Simpson, 1998: The Tropical Rainfall Measuring Mission (TRMM) sensor package. *J. Atmos. and Oceanic Technol.*, **15**, 809-817.
[Low impact, information only. The paper describes rainfall measurement platforms on the TRMM earth satellite. The precipitation radar is designed to provide the three-dimensional structures of precipitation systems and quantitative precipitation estimates. The radar operates at 13.8 GHz (~2 cm wavelength) and has a gate spacing of 0.25 km. The beam width is 0.71° giving a foot print of 4.3 km at nadir.]

Lakshmanan, V., and A. Witt, 1997: Automatic detection of bounded weak echo regions. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 366-367.

[Low impact, potential algorithm. The work is based on the notion that weak echo regions (WER's) are signs of strong updrafts and that the presence of a WER is important information that a forecaster can use in deciding whether or not a severe storm warning should be issued. Reflectivity minima topped by maxima are found by a fuzzy-logic weighing of 25 storm attributes. The procedure provides detections in regions where range folded echoes might preclude detections by other algorithms (e.g., the Mesocyclone Detection Algorithm). Tests with an independent dataset produced a POD of 82%, a CSI of 33%, and a FAR of 41%. Although weak echo regions are indeed features of many severe thunderstorms, it's not clear what added value the WER information provides.]

Lee, J.E., and G.A. Field, 1997: Evaluation of terminal Doppler weather radar used in conjunction with the WSR-88D in a National Weather Service forecast office. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 410-411.
[Low impact, potential auxiliary information in severe weather situations. The Terminal Doppler Weather Radar (TDWR) operated by the FAA at most major airports features interlaced scanning with frequent updates of low-level information (a minimum elevation angle of 0.3° and a 1 min update cycle) which could be an important data resource during severe weather outbreaks. The TDWR system includes algorithms for gust front and microburst detection not available with the WSR-88D. The paper describes an experiment in which TDWR information was displayed at a NWSFO. The TDWR detected events not seen with the local WSR-88D and was considered to be an important complement to forecast operations.]

Lemon, L.R., 1998: The radar "three-body scatter spike": An operational large-hail signature. *Wea. and Forecasting,* **13**, 327-340.
[Moderate impact, an additional tool for designating hail storms. The paper reviews the "three-body scattering" explanation for "hail spikes" or "hail flares" and presents several examples as seen with WSR-88D's. The hail signature extends radially from the far side of thunderstorm cores and is commonly observed at elevation angles of 2 to 6°. Hail flares are a positive indicator of hail, but the conclusion is that they are not a sufficient condition for large hail (>2.5 cm) at the surface because significant melting may take place.]

Lenning, E., H.E. Fuelberg, and A.I. Watson, 1998: An evaluation of WSR-88D severe hail algorithms along the northeastern Gulf coast. *Wea. and Forecasting*, **13**, 1029-1044.
[Moderate impact, algorithm assessment and potential upgrade. The paper begins with a detailed description of the Probability of Severe Hail (POSH) component of the current Hail Detection Algorithm. Stringent verification criteria were imposed for a small dataset obtained in the Tallahassee region of Florida. Algorithm performance generally exceeded that in previous studies for other geographical regions. The POD was 72%, the FAR was 25%, and the CSI was 58% at a POSH threshold of 50%. Further investigation revealed that the low-level wet-bulb temperature may provide slightly better estimates of the Severe Hail Index (SHI) warning threshold than that determined from freezing level heights. The best daily SHI had a correlation coefficient of 0.55 with the freezing level and a correlation coefficient of 0.59 with the low-level wet-bulb temperature. An experiment with an optimized "VIL of the day", also based on the low-level wet-bulb temperature, out performed all other tested methods; the correlation coefficient was 0.68. The

advantage here is that a threshold VIL of the day can be determined in advance (from the sounding) rather than after the first hail reports are received.]

Liu, L., and L. Liu, 1997: A new adaptive filter for recovering 2nd trip echoes from random-phase-coded Doppler radar signals. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 188-189.
[Moderate impact, stated priority need. A new whitening filter for retrieving overlaid second trip echoes is described which makes use of a predictive error filter and frequency spectrum analysis. A simulation indicates that second trip echoes with a power ratio of -30 dB can be retrieved.]

Marzban, C., and G.J. Stumpf, 1998: A neural network for damaging wind prediction. *Wea. and Forecasting*, **13**, 151-163.
[High impact, potential algorithm. A neural network has been developed to determine which circulations detected by NSSL's Mesocyclone Detection Algorithm are likely to produce damaging surface winds. The paper begins with a pedagogical description of how neural networks operate. Input to the algorithm consists of 23 radar-determined circulation attributes. Experiments revealed that by most measures a neural network with two hidden nodes was optimal. CSI and Heidke's skill scores were ~50 and 60%, respectively.]

Matrosov, S.Y., 1998: A dual-wavelength radar method to measure snowfall rate. *J. Appl. Meteor.*, **37**, 1510-1521.
[Low impact, application of dual-wavelength radar system. The paper describes how snowfall rate can be determined from dual-wavelength radar measurements as long as the snowflakes are within the Rayleigh range at the longer wavelength and substantially outside this range at a shorter wavelength such as K_a-band. (The author argues that polarimetric techniques for snowfall estimation are limited because larger, low-density, irregularly shaped aggregates have only weak polarization signatures.) Attenuation at the shorter wavelength (i.e., the difference in reflectivities or dual-wavelength ratio) provides an estimate of particle median volume diameter (D_o) that is relatively insensitive to particle density and the details of the size distribution. Snowfall rate (S) and radar reflectivity are dependent on the number concentration N_o. Hence, the ratio of these variables is taken; and snowfall rates are computed from $Z/S=AD_o^B$. As with Z-S relations, A and B depend on hydrometeor density, fall velocity, size distribution, and shape; but in this case the sensitivity is thought to be less because of the D_o term. The technique can be fine tuned by matching snowfall estimates with gauge measurements and thereby accounting for density variations. Dual-wavelength estimates for specified densities were compared to snowfall estimates derived from several fixed Z-S relations. The dual-wavelength estimates were close to observed values. The fixed relations significantly underestimated the precipitation and differed from each other by factors as large as of 4.]

Matson, D., 1998: WSR-88D Doppler radar adaptable parameter optimization of the MESO/TVS algorithm. *National Wea. Digest*, **22**, 31-38.
[Moderate impact, application and product evaluation. A well-written study of the Build 9 Mesocyclone/Tornadic Vortex Signature (MESO/TVS) algorithm and the Build 10 Tornado Detection Algorithm (TDA) is presented. A short description of each algorithm is given. As a benchmark, the MESO/TVS algorithm was run at default Threshold Pattern Vector (TPV=10) and

Threshold TVS Shear (TTS=72 h^{-1}) values. These parameters were then reduced to detect smaller circulations. Optimum performance, as indicated by a CSI of 37%, occurred with a TPV of 7 and a TTS of 45 h^{-1}. At these thresholds, the POD was 38% and the FAR was 50%. Results for the Build 10 TDA at default values were a CSI of 37% and a POD of 41%. There was a substantial drop in the FAR to 14%.]

May, P.T., and R.G. Strauch, 1998: Reducing the effect of ground clutter on wind profiler velocity measurements. *J. Atmos. and Oceanic Technol.*, **15**, 579-586.
[Low impact. A simple technique whereby clutter echoes are removed from velocity spectra is described. The method consists of applying least squares fits to the clutter signal. The technique proved to be roughly equivalent to finite impulse response (FIR) filtering methods when several fitted points are used to characterize the clutter signal.]

Miller, M.A., J. Verlinde, C.V. Gilbert, G.J. Lehenbauer, J.S. Tongue, and E.E. Clothiaux, 1998: Detection of nonprecipitating clouds with the WSR-88D: A theoretical and experimental survey of capabilities and limitations. *Wea. and Forecasting*, **13**, 1046-1062.
[Low impact, system evaluation at weak signal strengths. The capability of the WSR-88D for detecting nonprecipitating clouds is determined via comparison with a nearby vertically pointing 94-GHz cloud radar. A cloud detecting capability has import for nowcasting activities and climatological studies. Echoes were detected by both radar systems 82% of the time in March and 39% of the time in October. At times, low-level echoes were detected with the WSR-88D but not with the cloud radar. Anomalous echoes late in the afternoon were attributed to Bragg scattering and insects; those in evening times often lacked height continuity and were thought to be caused by residual ground clutter.]

Pamment, J.A., and B.J. Conway, 1998: Objective identification of echoes due to anomalous propagation in weather radar data. *J. Atmos. and Oceanic Technol.*, **15**, 98-113.
[High impact, relates directly to an expressed technical need. A procedure for detecting anomalous propagation with supplemental information such as surface synoptic reports, infrared satellite observations, a climatology for AP, and lightning strike locations is presented. The independent observations are combined statistically to compute the probability that a radar echo is in fact "dry". Comparison with an interactive clutter rejection scheme disclosed that ~90% of AP and precipitation echoes were identified correctly. Possibilities for further improvement include the addition of visual cloud images and a radar echo pattern recognition scheme.]

Pereira Fo, A.J., and K.C. Crawford, 1997: Very short-term quantitative precipitation forecast with the WSR-88D. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 412-413.
[Moderate impact, developing technology. The paper describes preliminary attempts to make quantitative precipitation forecasts with extrapolated radar data and wind information. The radar data are adjusted with gauge observations. Although CSI scores are low, early findings suggest that the scheme can be applied to flash floods and that for short time periods the radar-derived forecasts are better than those produced with numerical models.]

Pereira Fo, A.J., K.C. Crawford, and C.L. Hartzell, 1998: Improving WSR-88D hourly rainfall estimates. *Wea. and Forecasting*, **13**, 1016-1028.
[Moderate impact, potential algorithm upgrade. The stage III precipitation product of the Arkansas-Red River Basin River Forecast Center (ABRFC) was improved with a statistical analysis scheme that minimizes errors in rainfall estimates by combining WSR-88D and gauge measurements. The resulting analysis errors (variances) are less than the observation error variance. An advantage with the scheme is that the expected error in the system is known. The ABRFC analysis was found to underestimate longterm rainfalls by as much as 40%. Also, spurious rainfall estimates in the ABRFC product are documented in regions where rainfall estimates are made from simple averages of non-zero amounts from more than one radar.]

Richter, C., and M. Hagen, 1998: Drop-size distributions of raindrops by polarization radar and simultaneous measurements with disdrometer, windprofiler and PMS probes. *Quart. J. Royal Meteor. Soc.*, **123**, 2277-2296.
[Moderate impact, results suggest that changes in DSD's can be monitored with polarimetric radar. The paper begins with a review of polarimetric measurements and the calculation of parameters describing an exponential DSD. Specifically, the authors calculate the median volume diameter (D_o) from the differential reflectivity (Z_{DR}) and the distribution intercept N_o from Z_H and Z_{DR}. The required accuracy for the two measurements was asserted to be $\pm$ 1 dB and $\mp$ 0.2 dB, respectively. Quantitative agreement is found with DSD information garnered from wind profilers, aircraft-based particle measurements, and raindrop disdrometers. For the experiment, a tendency was noted for the radar to overestimate N_o but to make reasonable estimates of D_o. This was attributed to the fact that D_o is dependent only on Z_{DR} (a ratio of power measurements); whereas N_o has a dependency on Z_H and hence is relatively sensitive to system calibration.]

Rosenfeld, D., and E. Amitai, 1998: Comparison of WPMM versus regression for evaluating Z-R relationships. *J. Appl. Meteor.*, **37**, 1241-1249.
[Moderate impact, possible adjustment procedure for rainfall estimates. One minute disdrometer observations are used to compare the accuracy of Z-R relationships determined by the window probability matching method (WPMM) and by regression. Sampling volume differences are simulated by averaging reflectivity values in time, and differences in sampling height are included by introducing time lags between Z and R. The authors conclude that both methods give similar results for rainfall accumulations, but WPMM outperforms the regression method for rain intensities.]

Ryzhkov, A.V., and D.S. Zrnić, 1998a: Discrimination between rain and snow with a polarimetric radar. *J. Appl. Meteor.*, **37**, 1228-1240.
[Moderate impact. Polarimetric parameters (radar reflectivity, differential reflectivity, specific differential propagation phase, and the correlation coefficient between reflectivity measurements at horizontal and vertical polarization) in 6 Oklahoma snow storms are examined for signatures that distinguish snow from rain and for delineating regions of snow and rain. Cold snow (temperatures $<-5^\circ$C) exhibits lower Z_H values and larger K_{DP} and Z_{DR} than warm snow. The reason seems to be that cold snows are characterized by small crystals with a preferred alignment. For both warm and cold events the dominance of ice crystals caused Z_{DR} and K_{DP} to increase with height. Rain was

characterized by large Z_{DR}; snow was represented by relatively low Z_{DR}. Transition regions had large K_{DP} and a minimum in ρ_{HV}.]

Ryzhkov, A., and D. Zrnić, 1998b: Beamwidth effects on the differential phase measurements of rain. *J. Atmos. and Oceanic Technol.*, **15**, 624-634.
[Moderate impact, potential problems with K_{DP} rain estimates are discussed. Simulations are performed to examine the effect of radar volume nonuniformities on differential phase. Regions of negative K_{DP} are found at the periphery of small, isolated storm cells and in association with radar reflectivity gradients characteristic of squall lines and bright bands. The artifacts cause spurious rain rate estimates with K_{DP} and limit the spatial resolution in the derived-rainfall patterns. The authors content that averages of rainfall should be essentially unbiased as long as storms are well contained within watersheds. Further, they believe that in contaminated regions the integral of $R(K_{DP})$ can act as a constraint for rainfall estimates obtained from Z_H.]

Ryzhkov, A.V., and D.S. Zrnić, 1998c: Polarimetric rainfall estimation in the presence of anomalous propagation. *J. Atmos. and Oceanic Technol.*, **15**, 1320-1230.
[Moderate impact, an advantage of polarimetric measurements is demonstrated. Rainfall events with mixtures of precipitation and AP echoes are investigated. A simple scheme, based on the cross-correlation coefficient (ρ_{HV}), is presented for discriminating between echo types when AP and precipitation are separated. AP and precipitation are characterized by cross-correlation coefficients of <0.7 and >0.95, respectively. The scheme may not be effective when hail is present or the radar beam passes through the melting layer, and ρ_{HV} falls below the 0.7 threshold. The scheme will also create "holes" in precipitation patterns if AP and precipitation echoes are overlaid. In this case, the ϕ_{DP} measurement becomes noisy but retains enough signal that the AP regions can be bridged with the trend in ϕ_{DP}.]

Sachidananda, M., and D.S. Zrnić, 1997: Phase coding for the resolution of range ambiguities in Doppler weather radar. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 246-247.
[Moderate impact, stated priority need. The method utilizes transmitted pulses that are phased shifted with a systematic code sequence and received echo samples are multiplied by a factor for recovery of phase information. The first trip echo is made coherent and the second trip echo is phase modulated. (The second trip echo can be made coherent by application of another factor.) A series of processing steps are executed depending on the relative strengths of the echoes. Simulations indicate that second trip velocities can be recovered for power ratios of 60 dB and first trip echo spectrum widths of 4 m s^{-1}.]

Smith, P.L., 1998: On the minimum useful elevation angle for weather surveillance radar scans. *J. Atmos. and Oceanic Technol.*, **15**, 841-843.
[Moderate impact, radar data quality issue for low elevation angles. The paper examines the effect of a reduced VCP base elevation on the detection of low-level meteorological phenomena. In theory a reduction from the current 0.5° to 0° would improve the detectability of boundary-layer features by 6 dB but would degrade reflectivity measurements overall by 3 dB because one half of the beam would intercept the ground. (In practice the power reduction is much less.) A compromise might be a base angle of 0.33° which would result in enhancement of boundary-layer

echoes by 3 dB and an overall power degradation of ~0.8 dB. Existing ground targets would increase by ~3.8 dB. The net benefit for such a change might be small and vary from site-to-site.]

Smith, P.L., and J. Joss, 1997: Use of a fixed exponent in "adjustable" Z-R relationships. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 254-255.
[Low impact, could be important if verified by observations. The authors make two important observations: (1) in empirical drop-size distribution studies the exponent generally varies by <10% and (2) for typical events most of the rain falls at rates within a factor of 10 of the median rate. Thus, they argue that a reasonable approach to rainfall estimation with Z-R relationships is to tune the coefficient to match the median rain rate and to fix the exponent at a typical value (e.g., 1.5). Maximum rainfall rate errors for departures ≤0.2 from the selected exponent will be <30%. Moreover, if the fluctuations are random, they will tend to cancel out.]

Smyth, T.J., and A.J. Illingworth, 1998a: Correction for attenuation of radar reflectivity using polarization data. *Quart. J. Royal Meteor. Soc.*, **124**, 2393-2415.
[Low impact, polarimetric radar application. The paper begins with a balanced review of previously proposed attenuation correction techniques that employ radar reflectivity and polarimetric parameters. A procedure for correcting radar reflectivity and differential reflectivity, based on the distribution of specific differential phase and the total differential attenuation at horizontal and vertical polarization, is then outlined. The differential attenuation, manifest as negative Z_{DR} at the far side of storms, effectively constrains the magnitude of the corrections thereby avoiding problems that plague radar reflectivity schemes. The total differential attenuation is distributed over the intense rain region and used with K_{DP} to find the parameters N_o and D_o. The attenuation at horizontal polarization is then calculated. Finally, adjusted Z_H and Z_{DR} values are computed from the attenuation at horizontal polarization and the differential attenuation.]

Smyth, T.J., and A.J. Illingworth, 1998b: Radar estimates of rainfall rates at the ground in bright band and non-bright band events. *Quart. J. Royal Meteor. Soc.*, **124**, 2417-2434.
[High impact, a promising methodology for predicting surface reflectivity from tilt measurements. The paper first describes a polarimetric method for discriminating between stratiform and convective rain types and then presents new methods for correcting vertical profiles of radar reflectivity. The linear depolarization ratio (LDR) is shown to have characteristic signatures for graupel and snow (thought to dominate convective and stratiform rain types, respectively). The separation of hydrometeor types corresponded to a reflectivity of roughly 30 dBZ. Data presented also show good correlation between the reflectivity value at the bright band and at the surface. Three techniques for obtaining reflectivity estimates at ground were evaluated. As a benchmark, profiles were first computed with the technique of Kitchen et al. (1994, Quarterly J. Royal Meteor. Soc.) which models the profile according to the height of the freezing level, the height of the precipitation, and the low-level reflectivity measurements. The authors modify the Kitchen et al. method by imposing a 30 dBZ reflectivity threshold 1.5 km above the bright band to discriminate between precipitation types and then making adjustments according to median lapse rates for stratiform and convective events. A third method used the 30 dBZ/1.5 km thresholds to find median reflectivity profiles for convective and stratiform rainfalls. The two new techniques show correlations between "predicted" and "observed" reflectivities at ground of ~0.95.]

Smythe, G.R., W.E. Benner, and T.M. Weiss, 1997: Evaluation of the Integrated Terminal Weather System (ITWS) microburst detection and prediction algorithms. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 268-269.
[High impact, independent evaluation of the Lincoln Laboratory microburst algorithm. Results for 512 microbursts and 2195 windshear events at three test sites revealed that >98% of the events were detected. An evaluation of a related "prediction" algorithm determined that roughly 30% of the microbursts were correctly predicted with an average lead time of 215 s.]

Strauch, R.G., and R. Frehlich, 1998: Doppler weather radar velocity measurements using a single pulse. *J. Atmos. and Oceanic Technol.*, **15**, 804-808.
[Low impact, concept deemed incompatible with WSR-88D spatial and temporal sampling requirements. The paper addresses the issue as to whether or not single-pulse velocity estimates with a weather radar provide sufficient accuracy to unravel the velocity ambiguities that are inherent with pulsed Doppler weather radars. Single-pulse estimation uses a broadband receiver and acquires increased numbers of range samples rather than a time series at a particular range location to make velocity estimates. For pulse lengths as long as 8 µs the number of independent estimates needed to produce useful velocities was thought to be unrealistic (several hundred samples would be required).]

Stuart, N.A., H.D. Cobb, and G.J. Stumpf, 1997: A comparison of the storm-scale vortex detection capability, between the WSR-88D mesocyclone detection algorithm and the National Severe Storms Laboratory mesocyclone detection algorithm during Tropical Storm Bertha. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 361-363.
[Moderate impact, assessment of a possible upgrade to the current MDA. The data were collected from hurricane Bertha which spawned 10 confirmed tornadoes in the Chesapeake Bay area. Post analysis was conducted with the current algorithm and a proposed upgrade developed by NSSL. The NSSL algorithm detected a greater number of mesocyclones to greater distances. Not all mesocyclones produced severe weather reports. The proposed algorithm gave tornado probabilities ≥90% for 2 of the 10 tornadoes and gave significant warnings for 3 other events.]

Stumpf, G.J., A. Witt, E.D. Mitchell, P.L. Spencer, J.T. Johnson, M.D. Eilts, K.W. Thomas, and D.W. Burgess, 1998: The National Severe Storms Laboratory mesocyclone detection algorithm for the WSR-88D. *Wea. and Forecasting*, **13**, 304-326.
[High impact, potential replacement for current WSR-88D algorithm. Primary improvements with the proposed algorithm are thought to be lowered thresholds which result in more mesocyclone detections, range dependent thresholds, and diagnosis in time as well as space. Comparison with the current WSR-88D algorithm shows considerable improvement in skill. POD's are ~50% and FAR's are roughly 70% (see Stumpf et al., 1998, Table 14). Heidke skill scores, which measure the improvement above chance, are significant (~30%).]

Tapia, A., J.A. Smith, and M. Dixon, 1998: Estimation of convective rainfall from lightning observations. *J. Appl. Meteor.*, **37**, 1497-1509.
[Low impact. The paper proposes to correct radar-estimated rainfalls for range bias with lightning information. The operating hypothesis is that relationships between radar-estimated rainfall and lightning can be established at short ranges and the results extended to far distances or to regions

where radar data is of poor quality or lacking altogether. Parameters investigated were the rainfall mass (as determined from radar) divided by the total number of cloud-to-ground flashes, the spatial distribution of rainfall relative to the flashes, and the temporal distribution of the parameters. Rainfall-lightning ratios were quite variable from storm-to-storm and within storms. A simple model is presented that incorporates the number of flashes, time of the flash, its location, and a representative rainfall-lightning ratio. Although details are not examined, the model appears to capture the essential features of the large-scale rainfall pattern.]

Tong, H., V. Chandrasekar, K.R. Knupp, and J. Stalker, 1998: Multiparameter radar observations of time evolution of convective storms: Evaluation of water budgets and latent heating rates. *J. Atmos. and Oceanic Technol.*, **15**, 1097-1109.
[Low impact, polarimetric radar application. The ice contribution to measured radar reflectivity is computed with the difference reflectivity parameter (Z_{DP}) defined as $Z_{DP}=Z_H-Z_V$. The parameter is sensitive only to rain as long as ice particles tumble and have no preferred orientation. Departures from a linear relationship between Z_{DP} and measured Z_H signify the presence of ice and are a measure of the ice contribution to reflectivity. The liquid water contents of rain and ice are then determined with empirical relationships. Once the rain rate is estimated, heating rates can be found assuming that deposition and sublimation rates are small. Results look plausible. The storm glaciates as it matures, and net latent heating early on gives way to net cooling. Heating dominates because the efficiency of rainfall is less than 100%.]

Torlashi, E., and A.R. Holt, 1998: A comparison of different polarization schemes for the radar sensing of precipitation. *Radio Sci.*, **33**, 1335-1352.
[Moderate impact, compares measurements for several polarimetric bases. Radar signals from linear and horizontal, slant linear ±45° (a possible WSR-88D configuration), and left-hand and right-hand circular polarization states are simulated. Theory is compared to observations made with the Deutsches Zentrum für Luft- und Raumfahrt (DLR) radar. Particularly in ice regions, slant linear depolarization measurements reveal considerably more signal than linear horizontal/vertical depolarization measurements. Circular polarization measurements show variations in canting angles for liquid and ice particles. Slantwise measurements within the melting layer suggest that as particles melt they undergo changes that affect their canting angles. Although melting layers are depicted by all parameters, this feature was lost in reflectivity measurements beyond 16 km.]

Turner, R.J., and D.M. Gonsowski, 1997: A review of VIL density performance at NWSO Goodland, Kansas. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 370-371.
[Moderate impact, possible modification to VIL product. A study of VIL density (VIL divided by the storm height) as an indicator of severe hail (≥19 mm) was conducted for western Kansas. Thunderstorms that did not produce large hail were included only if they moved over populated areas between 8 a.m. and 10 p.m. The dataset is skewed in that it contained 183 hail storms and 27 storms which produced small or no hail. A VIL density of 3.25 g m^{-3} correctly identified 91% of the severe hail cases and falsely identified 43% of the non-severe storms as severe. Hail size increased with VIL density but the relation is noisy. The authors suppose that low population densities in western Kansas may have contributed to the uncertainty.]

Vaillancourt, P., A. Bellon, and I. Zawadzki, 1997: Results from a mesocyclone detection algorithm over southwestern Quebec, Canada. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 349-350.
[Low impact, an evaluation of the "pattern vector" technique in Canada. One-dimensional vectors at each elevation are assembled into two-dimensional features. The latter are checked for vertical continuity and to designate mesocyclones. Non-symmetrical features are ignored. An evaluation was made with different sets of thresholds (representing weak, moderate, and strong filtering) for storms producing tornadoes and winds >90 km h^{-1}. (Such storms are relatively rare in Canada.) Weak filtering (low thresholds) expectedly resulted in many detections (13 of 14 tornadoes) but gave a high FAR. No misses were recorded for damaging winds.]

Vieux, B.E., and P.B. Bedient, 1998: Estimation of rainfall for flood prediction from WSR-88D reflectivity: A case study, 17-18 October 1994. *Wea. and Forecasting*, **13**, 407-415.
[Moderate impact, concerns performance of the WSR-88D PPS for rainfall estimation. PPS rainfall estimates were made for a flash flood by computing rain rates from 0.5° data for the WSR-88D default relationship ($Z=300R^{1.4}$) and for $Z=250R^{1.2}$. The latter gave relatively small bias errors (6 to 15%) compared to the default relationship (31%).]

Witt, A., M.D. Eilts, G.J. Stumpf, J.T. Johnson, E.D. Mitchell, and K.W. Thomas, 1998a: An enhanced hail detection algorithm for the WSR-88D. *Wea. and Forecasting*, **13**, 286-303.
[Low impact, description of current WSR-88D algorithm. The principal algorithm components are the Probability of Hail (any size), the Probability of Severe Hail (diameters $\geq$19 mm), and an estimate of the maximum size hail. The probability of any-size hail is determined from the height of the 45 dBZ echo above the freezing level. The potential of severe hail is found by computing a "hail kinetic energy" from radar reflectivity and making adjustments for temperature lapse rate. An evaluation of the hail-of-any-size parameter is difficult due to the lack of reports for smaller hail sizes, but field experiments in Colorado suggest the CSI is ~90%. Verification criteria for the Severe Hail Index were not very constraining (a 30 km radius and time windows of 20 and 60 min). Performance varies from one storm day to another and from location to location. CSI's for different geographical areas ranged from 16 to 55% depending on the verification criteria. Predicted hail sizes show considerable scatter but an overall increase in size with the Severe Hail Index. A nice discussion of problems in verification and regional differences in algorithm performance is given.]

Witt, A., M.D. Eilts, G.J. Stumpf, E.D. Mitchell, J.T. Johnson, and K.W. Thomas, 1998b: Evaluating the performance of WSR-88D severe storm detection algorithms. *Wea. and Forecasting*, **13**, 513-518.
[Low impact. The paper describes problems encountered with algorithm verification. For example, a single report is usually sufficient to verify a warning at a forecast office; hence, the full scope of the event is not generally known. Multiple tornadic events from a single storm are often treated as a single event. Recorded reports tend to focus on the most severe weather observed, and null events are seldom recorded. Several ways to score algorithms, each with their own strengths and weaknesses, are discussed.]

Wood, V.T., and R.A. Brown, 1998: Effects of radar sampling on single-Doppler velocity signatures of mesocyclones and tornadoes. *Wea. and Forecasting*, **12**, 928-938.

[Moderate impact, user awareness issue. Simulations with a combined Rankine vortex are used to study the effect of random sampling on radar-estimated vortex intensities. Significant underestimation of mesocyclone rotational wind speeds stem from beam broadening with range. In addition, there are relatively small variations in intensity that arise from angular differences between the vortex core and the radar beam. Angular differences have pronounced effects on the radar-observed radius of maximum wind, which can be over or underestimated. Consequently, it is difficult to establish whether observed intensity changes are due to evolution or sampling. Because of their small size, tornado intensities are greatly underestimated and their diameters overestimated.]

Xiao, R., V. Chandrasekar, and H. Liu, 1998: Development of a neural network based algorithm for radar snowfall estimation. *IEEE Transactions on Geosci. and Remote Sensing*, **36**, 716-724.
[Moderate impact, possible snowfall estimation algorithm. A multilayer feed forward neural network consisting of one hidden layer is applied to vertical profiles of radar reflectivity for estimating snowfall liquid equivalent. No particular Z-S relationship is assumed, rather a relationship is derived from a training set of radar and gauge data. Results for a small sample (two storms and three snowgauges) show consider improvement over a fixed Z-S relationship. The improvement comes largely from bias reduction.]

Xin, L., and G.W. Reuther, 1998: VVP technique applied to an Alberta storm. *J. Atmos. and Oceanic Technol.*, **15**, 587-592.
[Moderate impact, technique evaluation. Simulations indicate that the volume velocity processing (VVP) method is reliable when the wind field is determined from seven parameters consisting of u, v, deformation, and shear terms. For sectors of 30 to 40° by 20 to 40 km, the mean wind components were estimated within 10% and other terms within 25%. Divergence estimate errors were 10^{-5} s^{-1}, roughly a tenth of that typically observed with convective storms for the above scales. Derived fields agreed qualitatively with observed trends in echo intensity and shapes.]

Yang, D., B.E. Goodison, J.R. Metcalfe, V.S. Golubev, R. Bates, T. Bangburn, and C.L. Hanson, 1998: Accuracy of NWS 8" standard nonrecording precipitation gauge: Results and application of WMO intercomparison. *J. Atmos. and Oceanic Technol.*, **15**, 54-68.
[Low impact, information only. Rain, snow, and mixed precipitation were measured with a variety of gauge configurations and compared to a double fence reference gauge designated by the World Meteorological Organization. Of interest, particularly for gauge-radar comparisons, are the results of tests with unshielded and with Alter wind shields. Snowfall measurements, expressed as percentages of the reference gauge amounts, were 69.9% for shielded gauges and 43.8% for unshielded gauges. For rain, catchments were 92.2% for shielded gauges and 88.8% for unshielded gauges. Errors increased with wind speed becoming as large as 80% for snowfall and 20% for rain with an unshielded gauge and mean wind speeds >6 m s^{-1}.]

Zerr, R.J., 1997: Freezing rain: An observational and theoretical study. *J. Appl. Meteor.*, **36**, 1647-1661.
[Low impact, a precipitation modeling study with implications for discrimination between frozen and liquid precipitation. Factors which determine whether freezing rain or ice pellets occur at ground are examined. Environmental conditions for freezing rain typically involve an upper layer

where frozen precipitation is generated, a surface layer of subfreezing temperatures, and an intermediate layer of above freezing temperatures. The depth of the layer necessary to melt ice particles depends on several factors (e.g., particle mass, the temperature distribution in the melting layer, and humidity). Model results suggest that the thickness of the melting layer necessary to melt 99% of the ice particle can be as large as 1300 m. The distance for particles to refreeze is also large, typically >500 m. Potentially, the model could be used with radar observations of the bright band and temperature information to determine the likelihood that precipitation particles melt in sandwiched warm layers and refreeze in surface-based sub-freezing layers.]

Zhang, X., H. Deng, and L. Liu, 1997: An applicable scheme of unambiguous range-velocity extension for Doppler radar. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 180-181.
[Moderate impact, addresses prioritized need. A method utilizing random phase coding to suppress range folded echoes and a staggered pulse repetition time (PRT) to unfold radial velocities simultaneously is proposed. With phase coding, echoes within the selected trip are coherent and those outside the trip are not. A whitening filter is employed to remove the unwanted signal. With staggered PRT's the composite unambiguous velocity is increased.]

Zrnić, D.S., and A.V. Ryzhkov, 1998: Observations of insects and birds with a polarimetric radar. *IEEE Transactions on Geosci. and Remote Sensing*, **36**, 661-668.
[Low impact, application of polarimetric measurements. The sensitivity of polarimetric radar measurements to particle size, shape, and orientation is exploited for identifying insects and birds. Insects are characterized by large differential reflectivity that can exceed 10 dB and relatively small differential propagation phase (except for large insects which can have a backscatter component). Bird dimensions greatly exceed the Rayleigh scattering range. Differential reflectivity signatures are usually <4 dB and can even be negative. The backscatter component of the differential phase can be large (100° or more). Biotic targets are readily distinguished from meteorological echoes by relatively low cross-correlation coefficients (<0.8 versus >0.90 for liquid precipitation).]

APPENDICES:

APPENDIX A: LIST OF ACRONYMS AND SYMBOLS

ACARS	Aircraft Communications Addressing and Reporting System
AP	anomalous propagation
AWIPS	Automated Weather Interactive Processing System
BWER	bounded weak echo region
CSI	critical success index
D_o	median drop-size diameter
DSD	drop-size distribution
FAA	Federal Aviation Administration
FAR	false alarm ratio (or rate)
GEWEX	Gobal Energy and Water Cycle Experiment
GOES	Geostationary Operational Environmental Satellite
ITWS	Integrated Terminal Weather System
K_{DP}	specific differential propagation phase
MDA	Mesocyclone Detection Algorithm
MEHS	Maximum Expected Hail Size
MIGFA	Machine Intelligent Gust Front Algorithm
MIT	Massachusetts Institute of Technology
N_o	drop-size distribution intercept
NASA	National Atmospheric and Space Administration
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NN	Neural network
NWS	National Weather Service
NSSL	National Severe Storms Laboratory
NWSFO	National Weather Service Forecast Office
NWSO	National Weather Service Office
ORDA	Open System Radar Data Acquisition
ORPG	Open System Radar Product Generator
POD	Probability of detection
POH	Probability of Hail
POSH	Probability of Severe Hail
PPS	Precipitation Processing System
PRF	Pulse repetition frequency
PRT	Pulse repetition time
PUP	Principal User Processor
R	Rainfall rate
RDA	Radar data acquisition
RIDDS	Radar Ingest and Data Distribution System
RMSE	Root mean square error
RUC	Rapid update cycle
S	Snowfall rate
SCIT	Storm Cell Identification and Tracking
TDA	Tornado Detection Algorithm

TRMM	Tropical Rainfall Measuring Mission
TTS	Threshold TVS Shear
TPV	Threshold Pattern Vector
TVS	Tornado Vortex Signature
UCP	Unit Control Position
UTC	Universal Time Constant
VAD	Velocity azimuth display
VCP	Volume Coverage Pattern
VDA	Velocity Dealiasing Algorithm
VIL	Vertically integrated liquid water
WARP	Weather and Radar Processor
WATADS	WSR-88D Algorithm Testing and Display System
WDSS	Warning Decision Support System
WER	weak echo region
WPMM	window probability matching method
WSR-88D	Weather Surveillance Radar)1988 Doppler
Z	radar reflectivity
Z_{DR}	differential reflectivity
Z_H	radar reflectivity at horizontal polarization
Z_V	radar reflectivity at vertical polarization
μ	gamma drop-size distribution shape parameter
ρ_{HV}	cross-correlation coefficient
ϕ_{DP}	differential propagation phase

APPENDIX B: SURVEY ANNOUNCEMENT

A Survey of Research Related to WSR-88D Meteorological Algorithms

Request for Information

The Next Generation Weather Radar (NEXRAD) program continually seeks to improve its suite of meteorological algorithms and to assess unfulfilled or new operational requirements. As in recent years, a survey is being taken of all organizations involved in related research in order to keep abreast of new developments.

An overview of the NEXRAD program and the WSR-88D system is given by Crum and Alberty (1993). A review of the current algorithm-generated WSR-88D products can be found in the article by Klazura and Imy (1993). A comprehensive algorithm description is given in Federal Meteorological Handbook No. 11, Part C (1991).

Current WSR-88D algorithm-generated products and displays include:

1) Radar reflectivity, radial velocity, and spectrum width fields
2) Echo tops
3) Precipitation accumulation
4) Vertical wind profile
5) Reflectivity and velocity cross sections
6) Vertically integrated liquid water
7) Severe weather probability
8) Hail index
9) Mesocyclone detection
10) Tornado detection
11) Storm tracking information
12) Combined shear
13) Combined moment.

Specific prioritized technical needs that have been identified are:

1) Evolution of WSR-88D hardware and software to implement advances in technology and science
2) Data quality improvements
3) System performance assessment
4) WSR-88D Level II (see Crum et al. 1993) data archive of storm phenomena
5) Data acquisition rate needs and strategies (including VCP issues)
6) Severe weather detection and prediction
7) Precipitation analysis techniques
8) Feature detection, tracking, and forecasting techniques
9) Wind analysis techniques
10) Turbulence analysis techniques
11) Tropical cyclone analysis techniques

12) Icing analysis techniques
13) Data compaction and transmission techniques
14) Interpretive techniques/human interface techniques.

A short synopsis (1-2 pages) is requested from individuals and organizations conducting work directly or indirectly related to WSR-88D algorithms, products, and/or technical needs. Interest extends not only to radar meteorological research, but to related activity such as feature detection and tracking. Submitted information should include the name of the organization, a short description of the current or recent work, the names of contact persons (including telephone numbers and E-mail addresses), individual and organizational Home Page addresses, and either references to or reprints of relevant publications, conference papers, and other reports. The information will be compiled in a summary report and made available to all respondents at the OSF's Applications Branch Web site (http://www.osf.noaa.gov/app/sta/algorithm.htm). Those without access to the Web or specifically wanting a hard copy should so indicate with their submissions. [A limited number of reports from last year's survey are still available.] The deadline for submissions is December 1, 1998. For further information contact:

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Crum, T.D., and R.L. Alberty, 1993: The WSR-88D and the WSR-88D Operational Support Facility. *Bull. Amer. Meteor. Soc.*, **74**, 1669-1687.

Crum, T.D., and R.L. Alberty, and D.W. Burgess, 1993: Recording, archiving, and using WSR-88D data. *Bull. Amer. Meteor. Soc.*, **74**, 645-653.

Federal Meteorological Handbook, No. 11, 1991: *Doppler Radar Meteorological Observations*. Part C, WSR-88D products and algorithms. FCM-H11C-1991, Office of the Federal Coordinator for Meteorological Services and Supporting Research, Rockville, Maryland, 210 pp.

Klazura, G.E., and D.A. Imy, 1993: A description of the initial set of analysis products available from the NEXRAD WSR-88D system. *Bull. Amer. Meteor. Soc.*, **74**, 1293-1311.

APPENDIX C: LIST OF RESPONDING ORGANIZATIONS AND INDIVIDUAL CONTRIBUTORS

Organizations

Bureau of Reclamation
Colorado State University
Forecast Systems Laboratory
Lincoln Laboratory
McGill University
National Severe Storms Laboratory
NEXRAD Operational Support Facility
NWSFO, Charleston, West Virginia
NWSFO, Salt Lake City, Utah
NWSO, Goodland, Kansas
NWSO, Wakefield, Virginia
Princeton University
Techniques Development Laboratory
University of Iowa
University of Reading
U.S. Naval Research Laboratory

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