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 115 survey announcements were mailed to individuals and organizations who had responded in the past and to organizations engaged in radar-based research. Responses from 25 organizations (including research laboratories, universities, and operational groups) in 4 countries were received. Many respondents are actively developing and implementing operational algorithms. The reported research addresses nearly all technical needs expressed in the survey announcement.

As in previous years, there is considerable on-going effort to evaluate and enhance the existing suite of NEXRAD algorithms and to develop new algorithms. Particularly in geographical regions where severe weather events usually are not associated with archetypal mid-western supercells, there is much interest in improving the detection of thunderstorm mesocyclones and tornadoes by adjusting adaptable parameters. Algorithm developers are looking for new parameters and new detection techniques.

The single most active area of research continues to be precipitation measurement. Efforts include product evaluation, the determination of bias errors, and the improvement of rainfall estimation techniques. Several groups have successfully applied area-time-integral methods for estimating precipitation. Attempts to improve rainfall estimation by classifying storms as stratiform and convective have been unsuccessful.

Applications of polarimetric radars continues to be a large and growing area of research. The measurements are being used to characterize winter precipitation by type, for precipitation estimation, for hail detection, and to study thunderstorm electrical properties. Other applications include the detection of clutter, insects, and birds.

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 (see Appendix A). A description of on going research at responding organizations is presented in Section 3. Brief reviews of recent published papers and conference presentations relevant to algorithm development can be found in Section 4.

2 TOPICAL ACTIVITIES SUMMARY

2.1 Archive of Storm Phenomena

The archive of WSR-88D Level II data for severe weather events being assembled by the National Severe Storms Laboratory continues to grow. A total of 6135 hail, 1504 tornado, and 4345 severe wind events are now available for study. Ground truth information is on file for storms in 1995 and earlier (Section 3.4.31).

2.2 Velocity Dealiasing and Range Unfolding

From the lack of responses to the research survey and perusal of the literature, it is apparent that little is being done to improve current velocity dealiasing and range unfolding algorithms. Rather, efforts are directed toward the development of new techniques. NSSL has been experimenting with a multiple-pulse repetition frequency (PRF) dealiasing algorithm (Section 3.4.2.11). By varying the PRF, velocity data are collected for different Nyquist intervals and compared to identify velocity folds.

An application of compressed wave forms for reducing range ambiguities is described by Bucci et al (1997). The paper extends previous results with simulated data to observations. Close agreement is found for radar reflectivity, velocity, and spectrum width estimates made from simple pulses and Barker coded pulses. An advantage of the compressed form seems to be in regions of strong reflectivity gradient at the edges of storms.

2.3 Anomalous Propagation and Clutter Removal

Lincoln Laboratory has developed a procedure for editing anomalous propagation (AP) from NEXRAD composite and layer reflectivity products (Section 3.9.1). Editing is based on tilt reflectivity, velocity, and spectrum width information. The procedure features site adaptable range-height criteria.

A radar hardware processing technique for clutter cancellation, proposed by Farina (1997), employs a set of linear filters weighted according to target Doppler frequency. A non-linear processing scheme is designed that has the low sidelobe level of the Chebyshev filter and the mainlobe retention of a uniform weight filter. This is achieved by replacing the uniform filter by two additional filters that remove the first and second sidelobes. The non-linear filter out performs the Chebyshev filter and approaches the optimum linear filter in performance but without the computational impact.

Polarimetric radar signals are sensitive to the geometry of the illuminated scatterers and, hence, have properties which make them ideal for ground clutter detection. Anomalous propagation and ground echoes exhibit low cross-correlation coefficient ($_{HV}$) between reflectivity measurements at horizontal and vertical polarization and high spatial variance in both differential reflectivity (Z_{DR}) and differential propagation phase ($_{DP}$). Zrni and Ryzhkov (1997) show that for AP, $_{HV}$ is typically < 0.7 and for precipitation, $_{HV}$ is usually > 0.9.

da Silveira and Holt (1997) describe a neural network technique that utilizes circular polarimetric measurements to identify clutter. Parameters that best discriminate between weather and ground echoes are the circular depolarization ratio and the degree of polarization. The radar data are processed by a neural network for classification. The anisotropic behavior of ground clutter causes significant depolarization of signals. In fact, the depolarization can be as large as the copolar signal (LDR 0 dB). Because raindrops are oriented with their major axis close to the horizontal, rain typically has a LDR value of less than -27 dB. Tumbling hail may have a LDR signature as large as -10 dB. Hagen (1997) proposes to use these properties of the linear depolarization measurement to detect clutter. A simple test with a LDR threshold of -15 dB removed 86% of clutter echoes from "clear day" samples.

2.4 Severe Weather Detection

2.4.1 Mesocyclones

The detection of tornado bearing mesocyclones in tropical storms is made difficult by their small reflectivity cores, weak circulations, and relatively shallow depths (Spratt et al. 1997). At far ranges, the current volume coverage patterns (VCP's) may see the mesocyclone only at a single elevation angle, and the rotational velocity of the circulation is underestimated due to beam broadening. Manual detection of mesocyclones is often necessary, employing shear thresholds that differ from Midwestern values to account for the smaller and weaker circulations. Spratt et al. present several tornadic storm cases and look for trends in such radar parameters as echo top, VIL, maximum reflectivity, shear, mesocyclone diameter, and spectrum width. Mesocyclones shrank in diameter and shears increased during tornadogenesis.

Although prominent hook echoes were not produced, appendages and notches were evident. High spectrum widths coincided with the tornadoes. To aid forecasters tasked with providing tornado warning with tropical storms the authors recommend that a new VCP be developed in which high elevation sampling be relaxed to permit a faster update cycle at the lower levels.

Desrochers and Harris (1996) present a new model for approximating mesocyclone kinematics. The flow is assumed to have an inner core where the velocity increases with radius and an outer core with an inverse relationship. A departure from the traditional mesocyclone model is that the inner core is modeled as an ellipse with prescribed vorticity and divergence. Mesocyclone properties determined from the elliptical model can differ significantly from the simpler (circular flow) model. An analysis of a single storm sampled by dual-Doppler shows that the circular model can significantly underestimate the peak vorticity and divergence when the mesocyclone is elliptically shaped. For the illustrative example, the orientation angle between out and inbound radial velocity maxima suggested that the mesocyclone flow was slightly convergent. However, analysis of the zero isodop from one radar indicated a moderately divergent flow, while the other radar indicated a strongly convergent flow. The paper shows this result is consistent with an elliptical representation of the mesocyclone. Because mesocyclones often undergo radical changes in their flow structure as they evolve, it is not clear how important the details of mesocyclone flows are to the warning function.

Several organizations have been seeking to optimize the adaptable parameters in the Mesocyclone Detection and TVS Algorithms for locations other than the Great Plains. Case studies show that the lowering of default values for the Threshold Pattern Vector, Threshold TVS Shear, and Threshold High Shear increases the number of detections (Sections 3.5.1.1, 3.5.4.3, and 3.6.1,2). Activities at NSSL for improving the mesocyclone algorithm are detailed in Section 3.4.2.2. Recent work on an expanded database has focused on neural network detection techniques, consideration of additional diagnostic parameters, and on more rapid algorithm updates.

2.4.2 Tornadoes

Operational tests are being conducted at the NEXRAD/Operational Support Facility and at individual National Weather Service forecast offices to improve the detection of tornadoes at locations other than the central U.S. The NEXRAD/OSF has been conducting tests to fine tune the adaptable parameters for both the mesocyclone and TVS algorithms (Section 3.6.1). Case studies with lowered default values for the Threshold Pattern Vector and the Threshold TVS (Sections 3.5.1.1 and 3.5.4.3) resulted in greater numbers of tornadoes being detected and an increase in lead time. The improvement was offset somewhat by an increase in false alarms.

A study to improve tornado detection with the combined shear, radial velocity shear, and spectrum width products is being conducted at the North Little Rock, Arkansas National Weather Service office (Section 3.5.4.1). NSSL has modified its tornado detection algorithm to incorporate new information as it becomes available rather than at the end of a volume scan (Section 3.4.2.3).

2.4.3 Waterspouts

No reviewed papers or reported research specifically addressed waterspouts. Efforts to improve the detection of tornadoes associated with tropical cyclones are described in Sections 3.5.3.1 and 3.16.1.

2.4.4 Microbursts

Takayama et al. (1997) present an analysis of a hail storm which produced several microbursts. The descent of the radar reflectivity core and widening of the high reflectivity area at ground heralded an increase in hail. Surface wind observations and temperature drops attested to a cold divergent outflow. The axis of minimum temperature roughly matched the region of hail reports. Hail apparently increased the precipitation loading and augmented evaporative cooling and consequently enhanced the strength of the microburst.

A study to detect microbursts is progressing at the National Weather Service office in Salt Lake City (Section 3.5.5.1). As in other investigations, microburst precursors were found to be the descent of a reflectivity core and the appearance of an elevated convergence zone. Detection is hampered by relatively weak reflectivity which is often below that for storm cell detection. NSSL has been developing a damaging wind prediction and detection algorithm that addresses these problems (Section 3.4.2.5).

2.4.5 Hail

The vertically integrated liquid water (VIL) product has long been used by forecasters for estimating severe thunderstorm potential and hail threat. But the utility of VIL varies day to day depending on airmass characteristics. At times tall thunderstorms with large VIL do not produce large hail, while on other days short thunderstorms with small VIL may produce large hail. Forecasters are faced with determining a "threshold value" or a "VIL of the day". Amburn and Wolf (1997) avoid the problem with a parameter that is thought to be independent of airmass. They compute a "VIL density" which is the WSR-88D VIL value divided by the storm's height. A scatter plot of echo top versus VIL shows fairly good separation between severe hail and nonsevere hail cases. The number of severe hail events increased dramatically for VIL density values 3.5 g m^{-3}.

Billet et al. (1997) performed regression analysis with the VIL parameter and environmental variables to predict hail size and the probability of severe hail (> 19 mm). The dataset consisted of 145 events (131 with hail) at radar ranges of 23 to 167 km. A preliminary analysis had winnowed an original list of 18 variables to the VIL parameter, the 850-hPa temperature, the freezing level height, and the mean storm-relative wind in the layer from the surface to 2 km. The natural logarithm of the hail diameter was the dependent parameter. Because a test with an independent dataset revealed that only 25% of the variance in hail size was explained, the relationship was considered to be of questionable value. The probability of large hail was then investigated with the same independent variables. The derived relationship showed fair correspondence between the forecast and observed probability of severe hail. Critical success scores were 0.56 to 0.59, POD's were 0.64 to 0.80, and FAR's varied from 0.11 to 0.35 for threshold probabilities of 40 to 60%. Other studies attempting to "forecast" large hail are in progress at the National Weather Service offices in North Little Rock (Section 3.5.4.2) and Salt Lake City (Section 3.5.5.3).

In response to user complaints that the current hail detection algorithm "over warned", NSSL reexamined algorithm performance at four diverse locations (Section 3.4.2.4). Results did not uncover a significant over warning problem but have led to a slight modification of the POSH equation to compensate for radar site elevation differences..

Bauer-Messmer and Waldvogel (1997) argue that radar echoes signify that precipitation particles are already present in storms and hence provide lead times for hail occurrence which are at best 20 min or so. To improve lead times these authors incorporate visual and infrared observations from earth satellites. Visual images provided an estimate of the cloud's optical thickness, and infrared images were used to estimate storm tops. Radar data provided ground truth. [Previous studies with hail pads in Switzerland indicated that reflectivity > 55 dBZ correlated well with hailfalls.] Hail storm severity was determined by integrating the areal coverage of > 55 dBZ echo over time. Severe hail storms associated with storm clusters having integrated areas > 40 km^2. The assumption that each cloud cluster in the visible images produced hail gave a probability of detection (POD) of 100% but a false alarm rate (FAR) of 81%. Hence ~20% of designated clusters produced hail. Subsequent experiments sought to reduce the FAR by adding other parameters to the decision process. An experiment in which time continuity over three successive satellite images was required yielded a POD of 84% and a FAR of 66%. Still other experiments examined the predictive potential of the convective available potential energy, the bulk Richardson number, and wind shear. POD's for severe hail were usually 100%, but FAR's remained high.

Takayama et al. (1997) discuss a close association between hail and the generation of downbursts. The weight of the hail, evaporation, and melting were thought to increase the negative buoyancy and enhance the strength of the downbursts. Techniques for detecting hail with polarimetric radar are described in Section 2.10.

2.4.6 Turbulence

Issues related to turbulence estimation with radar were reviewed in a report by Archibald and Hardaker (1997). References to a number of studies based on spectrum width and radial velocity gradients are given. The authors suggest that radar-based estimates of turbulent dissipation may also be useful for detecting gust fronts aligned along radar rays and for determining storm stability.

An example of Kelvin-Helmholtz waves that developed in a shear layer along a warm frontal boundary is presented by Chapman and Browning (1997). The waves, possible indicators of clear air turbulence, were aligned with the mean wind and concentrated in a layer where the wind veered strongly with height. RHI's perpendicular to the axes of the waves show a spectacular braided pattern.

2.4.7 Flash Floods

Smith and Baeck (1997) examined five flash flood situations sampled with WSR-88D's with hopes of finding common features. Rainfall estimates were adjusted with gauge observations for bias. Three storms exhibited relatively low reflectivity centroid heights. Two storms which did not have low centroids produced large hail. Maximum reflectivities for these storms were reported to be 72 and 76 dBZ. Radar-derived rainfall flux and runoff were related to the mean slope of the respective watersheds. Interestingly, runoffs for three of the storms either exceeded or were very close to the radar-estimated rainfalls.

2.4.8 Tropical Cyclones

Tropical cyclones often produce tornadoes upon landfall. Typically tornadoes form in the sector 0 to 120 from north. The distribution may be bimodal, i.e., some form near the eyewall or along inner rainbands while others form in the outer rainbands. Compared to Midwestern supercells, mesocirculations in thunderstorms associated with tropical cyclones tend to be more subtle and may not be detected by the WSR-88D at large distances due to beam broadening and overshooting (Spratt et al. 1997). For one storm, only five mesocyclone detections were made with the current WSR-88D algorithm during a time stretch in which 13 detections were made manually. The VIL parameter was generally very low (15-29 kg m^{-2}) for tornadic storms in tropical cyclones but higher than that of neighboring non-tornadic storms. No universal relationship existed between tornadogenesis and the lowering of echo tops. Most tornadic storms exhibited weak reflectivity notches that often persisted well beyond the lifetime of the tornado. Large spectrum widths often coincided with the tornadoes; trends appeared to be correlated with the intensity of the parental mesocirculation.

Issues relating to tornado detection in tropical storms are also being investigated by the Global Hydrology and Climate Center (Section 3.16). To find common properties, time series of various radar-derived parameters and lightning activity have been constructed. As in other studies, radar signatures for tornadic storms associated with tropical cyclones were weak compared to mid-western storms. Tornado occurrences are almost always marked by an increase in mesocyclone rotation rate but not all increases cause tornadoes.

Experiments in rainfall estimation in tropical storms have been conducted by Glitto and Choy (1997). Using the center bin and "best" bin as bases for comparison with rain gauges, the Precipitation Processing System (PPS) underestimated rainfall totals in Tropical Storm Gordon by ~40%. The bias was determined by computing (1) the sum of the gauge amounts divided by the sum of the radar amounts [G/R] and (2) the average ratio between gauge and radar amounts [(1/N)(G/R)]. [Note that latter term when multiplied by the total of the radar estimates usually does not return the sum of the gauge amounts. Also, the use of the best bin for gauge/radar comparisons will generally underestimate the radar bias.] The PPS bias parameter (RESBI) was then set to 1.4 and the hail threshold (MXRFL) reset to 55 dBZ. Application of the adjusted PPS algorithm to Tropical Storm Jerry resulted in a significant improvement in the rainfall estimates--the radar overestimated the rainfall by ~15%.

2.4.9 Boundary-Layer Phenomena

No reviewed papers or reported research specifically targeted the recovery of boundary-layer wind fields. An investigation of insect populations in the boundary layer is reported by Russell and Wilson (1997). The detection and discrimination of insects and birds with polarimetric radar is discussed by Ryzhkov and Zrni (1997).

2.4.10 Snowfall

The Bureau of Reclamation has been developing an accumulation algorithm for dry snowfalls not attended by brightbands. Snow water equivalents (SWE's) are estimated with simple power law relationships of the form Z=SWE. Typical values are 100 to 300 for and 2.0 for . Considerable underestimation occurs at radar ranges greater than 70 km (see Section 3.2.1 for details). The utility of the WSR-88D to estimate snowfall is also under investigation at the National Weather Service office in Salt Lake City (Section 3.5.5.2).

Ryzhkov and Zrni (1997) present a case study in which dual-polarization measurements are used to distinguish between snow and rain echoes. Compared to rain, low values of Z_{DR} and K_{DP} (on the order of hundredths of 1 km^{-1}) are measured for snow. The latter measurements were made by averaging the differential phase data over 48 range locations.

Polarimetric observations from rain and snow are also described in the paper of Chandra et al. (1997). They found K_{DP} values of ~0.25 km^{-1} in stratiform rain, 1.1 km^{-1} in the melting layer, and 0.01 km^{-1} in an overlaying snow layer. Plots of co-to-cross polar phases revealed small but measurable differences for snow that will be explored in further studies.

Colorado State University is conducting polarimetric studies to classify frozen precipitation as aggregates, crystals, and snow pellets (Section 3.10.1). Particle observations from a video disdrometer provide ground truth. Ultimately it is hoped that the measurements will lead to improved snowfall estimates.

2.5 Feature Detection, Tracking, and Forecasting

Several organizations are involved with the development of algorithms for detecting, tracking, and forecasting future locations of individual storms and particular storm features. The National Severe Storms Laboratory (NSSL) has been perfecting an algorithm for identifying and tracking individual storm cells (Section 3.4.2.1). Plans call for the inclusion of a cross-correlation tracking component for multi-cellular storms.

A cross-correlation tracker has been under development at Lincoln Laboratory for the past several years. Recent improvements (Section 3.9.3) have focused on the handling of cell mergers and splits. The algorithm shows considerable skill at predicting storm locations out to 1 h (Section 3.9.4). Algorithm development at Lincoln Laboratory also includes the Machine Intelligent Gust Front Algorithm (MIGFA) (Section 3.9.2).

Recent activity at the Air Force Research Laboratory (AFRL) has been in the detection of mesocyclones with wavelets (Section 3.1.2). The technique may have advantages because of its filtering qualities and capability to search for particular image characteristics. Other AFRL algorithms are designed to detect and monitor trends in bounded weak echo regions within severe thunderstorms (Section 3.13). An algorithm to detect synoptic fronts and gust fronts with fuzzy logic is also under development.

The Atmospheric Environment Service/Environment Canada has algorithms for detecting descending reflectivity cores, determining the likelihood of severe weather, and for BWER detection (Section3.17.1-3).

2.6 Precipitation Analysis Techniques

Area-time-integral (ATI) and probability matching methods (PMM) for estimating precipitation have shown considerable popularity in recent years. Both methods depend on the existence of a representative probability density function of rain rates in a particular region. The ATI method capitalizes on the observation that the spatially averaged rainrate is correlated with the fraction area of rainrate above a specified threshold. The proportionality factor can be determined with disdrometers, radar reflectivity, or by separate regression between the average rainrate and the fractional area greater than some threshold.

For climatological models, where the mean watershed rainfall for a specific time interval may be desired, the ATI method may be ideal. The technique was applied by Buarque and Sauvageot (1997) to squall lines with trailing stratiform rain areas. High correlations (0.85 to 0.99) were found between averaged rainfall determined from gauge data and the fraction of precipitation area above various rainrate thresholds. The parameters for the probability density functions for the convective and stratiform areas differed. The optimum rainrate thresholds were 11 mm h^{-1} for the convective line and 2.6 mm h^{-1} for the stratiform rain. The proportionality constant between the averaged rainrate and the fractional area above the threshold was 40 and 7 mm h^{-1}, respectively.

Oki et al. (1997) propose to apply the area-time-integral technique to rainrate measurements from the TRMM satellite. The stability of the method is examined in several tests using a combination of radar and gauge information to determine the rain rate. A proportionality factor of 3.5 mm h^{-1} gave the highest correlation between average rainrate and the fractional area. A simulated application is detailed.

A similar paper is presented by Li and Sénési (1997) who apply the thresholding (ATI) technique to single storms having areal coverage < 1000 km^2 rather than the more common application to large areas with a large number of storms at different stages of development. The paper contains a nice review of previous work. The authors perform the usual regression between observations of average rainfall and fractional areal coverage above a specified rainrate threshold. The proportionality factor between average rainfall rain and fractional area shows strong seasonal variation. For example, a threshold of 1.3 mm h^{-1} was applicable for winter storms; while a threshold of 6.5 mm h^{-1} was found for summer events. Correlations were 0.91 and 0.92 respectively. Tests indicate that areas as small as 200 to 500 km^2 give stable relationships.

The probability matching method and window probability matching method (WPMM) were applied to a random set of paired values in the simulation study of Ciach et al. (1997). The authors caution that the transformation relating the probability density function of one variable to the other will yield a correlation of a statistical origin between the variables even when they are not correlated. Rosenfeld responds that this is true for the PMM but not the WPMM. As evidence he shows the result of tests with Z and R measurements made with a disdrometer. The standard deviation of the rainrate was estimated from the probability density function of Z. Large errors occurred when the PMM was fed with randomly distributed points. The WPMM seems to work well as long as the reflectivities are > 20 dBZ.

A method for short-term prediction of point rainfalls by combining radar and raingauge information has been developed by Burlando et al. (1997). Radar provides an estimate of storm motion and isolates gauges that have the highest cross-correlation functions for rainfalls at nearby gauges. [Rainfall amounts derived from the radar alone are regarded as providing unreliable estimates of rainrate.] The parameters of a multivariate model are then estimated assuming time stationarity and that rainfalls at selected locations are correlated. The motion of precipitation echoes is determined by centroid tracking or is computed from a lag-correlation method. A first-order autoregressive model weighs the gauge observations and predicts the rainfall at specific locations. One hour forecasts are based on the current observation and past history of hourly observations at a particular site and at an upwind "leader" station. Results show that the technique performs better than models using only the correlation between gauge sites, a univariate gauge analysis, or methods with radar data alone. The utility of the technique would seem dependent upon the spacing of the rain gauges (~15 km in this study) and the precipitation type.

A proposed rainfall estimation algorithm for TRMM is described by Ciach et al. (1997). In a first step, storms are classified as stratiform or convective by applying a "peakedness" test. Rainfall estimation is made with vertically integrated reflectivity in an attempt to increase the signal-to-noise ratio of the measurements. Corrections are applied for system and range biases. Storm motion is computed by the cross-correlation method and time interpolated data points are created at 1 min intervals between data samples. Parameters which control the algorithm are determined by minimizing rmse's in radar-raingauge comparisons. Optimization of the parameters is done collectively rather than one parameter at a time. Differences between the statistics of stratiform and convective rainfalls were insignificant.

Delrieu et al. (1997) describe a French experiment in which X-band radars are evaluated as a possible addition to an existing dense network of rain gauges and S-band radars. The X-band radar is seen as a cost effective gap filler in mountainous areas and as a complementary system in hydrologically sensitive urban regions. The paper is concerned primarily with correcting the X-band signals for rain attenuation by monitoring echoes from fixed ground targets. Three attenuation correction algorithms are examined. The radar scanned at two elevation angles, a high angle (5) free of clutter and a low angle (1) with strong mountain echoes for determining the path integrated attenuation (PIA). The latter is determined from the measured reflectivity profile, the coefficient and exponent of an assumed reflectivity-attenuation relationship, the range r_o at which clutter ends, the attenuation factor at that range, and the radar calibration error. Three algorithms for correcting for attenuation (one based on reflectivity measurements and a reflectivity-attenuation relationship and two algorithms that use the mountain PIA) are explored. A procedure incorporating r_o, a refined mountain PIA, and an optimal radar error parameter worked best.

Cerro et al. (1997) examined a dataset of thirty-second drop-size measurements obtained with an optical disdrometer. The measurements were stratified by rainfall intensity, fit to exponential, gamma, and log normal models, and used to calculate various moments of the distributions. Particle diameters and fall velocities were calculated from the duration and amplitude of attenuated signals from an infrared light source. A least squares approach produced the power law relationship $Z=262R^{1.55}$ for all rain types. The correlation coefficient was 0.90. Drop-size distributions were also computed via the moments method for exponential, gamma, and log normal models. From these relationships the parameters that define the DSD were found. Calculated parameters (e.g., the intercept N_o and the slope of the exponential distribution) were expressed in terms of rainrate. Two parameter distributions show some improvement over one parameter (Marshall-Palmer) distributions but tend to overestimate the number of very small and very large drops. This deficiency has led to the use of three parameter functions which include a DSD shape factor. Modeled rainrates were then compared to rates determined with the disdrometer. The exponential distribution underestimated the low moment DSD parameters (e.g., N, the number of drops) but was accurate for high moment parameters (e.g., Z) because it was insensitive to DSD extremes. The gamma function performed well at low moments but not as well as the exponential and log normal models for the high moments. The moments method revealed that an appropriate relationship for all rain intensities was $Z=376R^{1.46}$.

Yuter and Houze (1997) analyzed raindrop distributions obtained by aircraft in the Pacific. Storm-type classifications (convective versus stratiform) were based on the statistical properties of the radar echoes. Surprisingly, drop-size distributions for stratiform rainfalls often exhibited large drops characteristic of convection. In fact, the DSD's for both rain types showed considerable overlap. Another interesting finding was that the reflectivity varied by ~9 dB for a particular stratiform rain rate. More than 7% of the samples had rainfall rates in excess of 10 mm h^{-1}. Variability in the stratiform DSD's was attributed to the presence of fallstreaks lowering from the melting level. The fallstreaks were thought to be caused either by remnant convective elements or by overturning within the melting layer. The authors conclude that Z-R distributions for stratiform and convective rainfalls are not distinct; and therefore, separation of precipitation into stratiform and convection types is not justified.

Steiner and Houze (1997) address the issue of estimating the proportion of convective and stratiform rains by investigating the sensitivity of the estimates to the exponent and coefficient of the Z-R relationship. For Darwin, Australia the parameters were critical; the convective rain fraction varied from 30 to 80%. In Florida, convective rain fractions were less variable (80 to 100%). Clearly, an inappropriate Z-R relationship could have a disastrous effect on the estimated rain. Much higher correlations between radar and gauge observations were computed for Australia than for Florida. The reason seems to be the greater fraction of convective rain in Florida. Correlations, unlike the precipitation totals, showed little sensitivity to parameter changes. Arbitrary selections of Z-R relationships leads to an error of ±20% when the convective rain fraction is roughly 50%. Errors are about 10% if one type dominates. An attempt to find the optimum A and b for the Z-R relationship based on monthly totals was unsuccessful. The authors speculate that the time scale was too long.

There is considerable interest in estimating surface rainfall at distances where the radar beam rises above the melting level. Suggested techniques generally involve the extrapolation of the vertical distribution of radar reflectivity to ground. Kitchen (1997) describes a correction scheme based on multiple elevation angles to improve the diagnosis of the reflectivity profile. Previous attempts have often assumed that the profile was spatially homogeneous. The proposed method employed measurements from a discrete number of elevation angles to estimate the profile. The difference between an idealized profile and the measurements is expressed as a penalty function which is minimized by iteration. The model considers brightband effects and orographic growth below the brightband. The reflectivity profile is modeled according to the reflectivity magnitude at the base of the melting layer and two decay constants. Calculated reflectivities are found by weighing the idealized profile by the observed values. A simulated multiple scan method reduced the bias by 64%, while a single scan method reduced the bias by 35%. Tests with real data showed less benefit.

Xiao and Chandrasekar (1997) have estimated rainfall with a neural network and compared results to estimates derived from radar reflectivity and a combination of reflectivity and differential reflectivity (see Section 2.9). Results suggest that the neural network approach can improve rainfall estimates.

An evaluation of rainfall totals made with the WSR-88D that services the Louisville, Kentucky metropolitan area is given by Wilson et al. (1997). Radar-derived accumulations for a single storm were a factor of two less than gauge observations. The bias increased with time. A similar study was conducted with the Bismark, North Dakota WSR-88D (Section 3.18.1). The radar overestimated rainfall in 5 convective storms by 11%; largest discrepancies occurred at far ranges. Other studies seeking to improve the utility of the WSR-88D for estimating rainfall are being conducted by the NWSO at Greenville-Spartanburg, South Carolina (Section 3.5.2.1). Researchers have been comparing WSR-88D rainfall estimates with a raindrop disdrometer and determined that the radar is 4 dB low.

Baeck et al. (1997) evaluate range dependent biases in WSR-88D precipitation estimates. An assemblage of extreme rainfall events shows an increase in storm underestimation with range. For select radars, warm-season mean hourly accumulations are shown to peak at ~100 km, while cold season rains peak at 60-70 km. The cause is attributed to brightband effects and to biscan maximization.

Range dependent biases, systematic differences between radars, and comparisons between radar and gauges in hourly WSR-88D precipitation products are described in the report of Smith et al. (1996). Severe rainfall underestimates at short radar ranges are attributed to anomalously low reflectivity measurements at the higher elevation angles used by the PPS algorithms. Rainfall underestimates at far ranges were thought to be a detection problem. The report also documents significant rainfall estimate differences in the overlap area between neighboring radars.

The University of Iowa/Institute of Hydraulic Research (Section 3.11.1) has a comprehensive program in precipitation estimation with the WSR-88D. Emphasis is on bias adjustment, parameter optimization, and gauge-radar comparisons. Princeton University/Department of Civil Engineering and Operations Research (Section 3.14) is also actively engaged in improving radar rainfall estimates. Current study topics are algorithm performance during heavy rainfall and hail events.

2.7 G.Wind Analysis Techniques

Wind retrieval from single-Doppler radar data continues to be an active area of research. McGill University has been attempting to construct three-dimensional wind fields in an operational environment. Techniques being evaluated include a network of bistatic receivers (Section 3.12.1) and the use of variational analyses for deriving wind fields from single-Doppler observations (Section 3.12.2).

An ongoing task at the University of Oklahoma/Center for Analysis and Prediction of Storms has been the development of techniques for inserting radar reflectivity and radial velocity measurements into numerical forecast models (Section 3.13.2). Other efforts are directed toward the retrieval of three-dimensional wind and temperature fields from single-Doppler radar data (Section 3.13.4).

Recent work at the U.S. Naval Research Laboratory (Section 3.8.1) has combined VAD analyses with simple adjoint and least squares wind retrieval methods. The VAD divergence profile serves as a constraint for the retrievals.

2.8 Data Acquisition Strategies

Howard et al. (1997) investigate the impact of VCP-11 and VCP-21 scanning strategies on estimated storm tops and trends. The discrete scanning strategy of the WSR-88D can lead to erroneous information. For example, the authors note that a 30 dBZ echo top of 10 km at 55 km when scanned by a WSR-88D operating in a VCP-21 pattern will register a height of 10 km. If the echo top remains constant and the storm moves outward slightly in range, the next indicated height will be 6 km, suggesting a rapid decline in storm intensity. This and other sampling problems are investigated with a simple thunderstorm model.

2.9 Interpretive Techniques/Human Interface Techniques

NSSL is continuing its efforts to merge the mesocyclone and tornado detection algorithms into a single generalized algorithm for detection and diagnosis of vortices (Section 3.4.2.8). A tornado warning guidance product is also under development (Section 3.4.2.9). This product is intended to aid forecasters by providing tornado probabilities for various radar-determined parameters. A Warning Decision and Support System (WDSS) has also been under development that integrates output from old and enhanced radar algorithms as well as other datastreams such as lightning data, surface data, and numerical models to help forecasters weigh the potential threat of severe weather (Section 3.4.3.2). Other products such as the WSR-88D Algorithm Testing and Display System (WATADS) enable forecasters to perform adaptable parameter studies on WSR-88D and NSSL algorithms (Section 3.4.3.3).

2.10 Data Analysis Techniques

Wavelets are a new family of basis functions that are finding favor for the analysis of multi-scale features, for detecting singularities and transient phenomena, and for data compression. Kumar and Foufoula-Georgiou (1997) give a nice review of the history of wavelets, discuss their basic properties, and describe several applications. Numerous references to introductory articles are provided. The paper begins with a discussion of the differences between Fourier and wavelet analysis and shows that the choice of wavelet has only a small effect on the result. One example of interest is a scale analysis of a mesoscale convective system with a trailing stratiform rain region which indicates that wavelets may be an objective method for discriminating between convective and stratiform rains.

Briggs and Levine (1997) use wavelets to remove noise from forecast and observed 500-hPa heights prior to computing verification statistics for determining the "closeness" of the forecast and observed fields. The paper begins with a nice introduction that summarizes previous applications and lists several pedagogical references. Other more traditional methods of comparison, which produce a single comparative number, e.g., the root-mean-square-error, are reviewed. In contrast, the wavelet approach provides a multivariate measure of closeness. The discussion includes sections on the theory of discrete wavelet transforms, the selection of the transform, thresholding to remove unwanted information, and the use of wavelets to derive statistical properties of images. In an example, 2-D forecast and analyzed fields are compared at various scales to reveal spatial differences.

The Air Force Research Laboratory as been developing a mesocyclone detection algorithm based on wavelets (Section 3.1.2). Wavelets are thought to have certain advantages for feature detection and data preprocessing.

Andreas and Treviño (1997) use wavelets to detect trends in time series data. Wavelets are used to determine first and second-order terms in a trend polynomial. A comparison reveals that the least squares method gives better trend estimates. However, the wavelet method is more computationally efficient, i.e., fewer operations are required to determine a trend. Techniques are also described for recognizing significant trends and for removing them. The criteria are based on the resolution of the measuring instrument. The authors assert that, if the variance of the original datastream and the detrended data differ by more than the square of the measurement resolution, the trend should be removed.

A study in which ice edges and ice floes were tracked by wavelets is presented by Liu et al. (1997). The scheme was developed to track features not detected by correlation methods. The wavelet studied, a second derivative of a Gaussian function, was applied to Langmuir streaks (linear ice features that are roughly parallel to the wind and where heat transfer takes place), edges, and floes. The technique involves multiscale wavelet transforms where large-scale wavelets detect an approximate boundary which is then refined with small-scale transforms.

Several applications of wavelets are described by Tawfik et al. (1997). A brightband is detected by an edge detection method applied to the derivative of a smoothed radar image. A pyramidal scheme is used to remove extraneous information from the radar images and to reduce the information required for reconstruction. In another study, the power of the technique to determine the dominant wavelength in convective and stratiform rain events is demonstrated. The lengths were 4.5 and 18 km, respectively.

The use of adaptive Kalman filters in determining sea state are described by Blancet et al. (1997). A linear filter combines model forecasts and observations, weighted according to accuracy, for improved predictions of the sea state. [The Kalman filter is the optimal assimilation scheme when the error statistics of the observations and model are known.] In the paper the authors examine the ability of three adaptive filters to estimate unbiased, stationary system noise. The filters readjust the model noise matrix as new information becomes available. Simulated data are used to define a "true" ocean state and "observations" are constructed by adding a known noise factor to the sea state. The noise component was then retrieved with the adaptive filters. An empirical noise estimator on a reduced grid worked well and efficiently. [A theoretical discussion of data assimilation applications with the Kalman filter can be found in Cohn (1997).]

An application of a Kalman filter to derive water vapor profiles from Raman lidar, a microwave radiometer, an acoustic sounding system, and surface observations, is presented by Han et al. (1997). Microwave radiometers provide integrated water contents that lack structural information; Raman lidars give detailed profiles but are limited in range. Hence, the approach is to combine the measurements based on the relative strengths of the sensors. As a first step, a Kalman filter is applied to a time history of the lidar data. Then a statistical analysis is done to combine the lidar and microwave data as constrained by climatological information. The merit of the scheme is in the historical measurements (z) with which the atmospheric state (s) is determined. The s and z vectors are related by $z_i=H_is_i + {}_i$ where H is the observation matrix and ${}_i$ is an error term. In the second step, the profile of estimated water vapor from the filter is mapped with the integrated water vapor and cloud liquid. The profile structure is largely determined from the lidar data and the climatological information. Limited verification accomplished by withholding a portion of the lidar data shows considerable skill.

Data analyses with neural networks has also become popular in recent years. Neural networks are able to model complicated nonlinear problems through training processes. The network consists of a layer of input (data) nodes, one or more intermediate or hidden layers, and an output layer. Transformations map the information from one layer to the next. In the application of Hsu et al. (1997) a neural network combines measurements from rain gauges, radar, and earth satellites to estimate rainfall. A variation, the Modified Counter Propagation Network (MCPN), trains each transformation independently. The input-hidden layer transformation forms a self-organizing feature map (SOFM) that performs automatic discretization of the input. The advantage of the scheme is an efficient hidden-output transformation that maps the discrete SOFM clusters to the output. The result is a marked reduction in the required training. The input-output data and the number of nodes in each layer are specified. Importantly, the input data must provide sufficient information to ensure proper discrimination of the output (rainfall in this case). Six variables were used. The model was trained with data collected near Japan. In some tests model weights were updated recursively as new information became available. In other tests the model weights were not updated. Case studies were run to determine monthly rainfalls and transferability between seasons and climatological regions. Comparison was made with the GOES precipitation index (GPI), a method whereby rainfalls are estimated with cloud top temperatures. The recursive neural network was credited with significant increase in the correlation between observed and estimated rainfalls.

Xiao and Chandrasekar (1997) applied a neural network to rainfall estimation with radar. The network ingested three-dimensional measurements (Z_H and Z_{DR} singularly and in combination) and compared them to raingauge observations. [The nonlinear mapping capability of the network relaxes the need for specifying a particular relationship for rainfall rate.] Two hidden layers were used for extracting local and global features. A recursive least squares learning algorithm was implemented to reduce the training period. The input data consisted of radar measurements on a 3 by 3 km horizontal grid with 1 km vertical spacing and a mean vertical profile. The output consisted of the average rainrate for one observation time. Results for 4 storms and 17 gauge sites show improvement over rainfall estimates derived directly from R (Z) and R(Z, Z_{DR}) relationships. The bulk of the improvement was in bias removal, but there is a small increase in the correlation between the radar estimates and the gauge observations as well. Rainfall estimates with the Z-Z_{DR} pair where better than that with Z alone.

Matsoukas et al. (1997) have used a neural network for estimating rainfall from both raingauge and radar measurements. An error function is computed by comparing the estimated rainfall to the radar and gauge observations. The network is trained by back propagation and attempts to minimize differences. In the paper the loss of information due to sparse gauge sampling is examined. Raingauges were simulated by selecting random points on the radar grid. Rainfall estimates at specific locations were determined by distance weighing and by the neural network. Root mean square errors were higher with the neural network than with the distance weighing scheme. However, when a noise component was added to the data, the generalization capability of the neural network gave better results.

Miller and Emery (1997) have developed a cloud classification system based on a neural network. The planned application, for the TRMM satellite, seeks to classify clouds according to their visible and infrared images and then to calculate rainfall rate with a passive microwave technique. Data from the TRMM radar would verify the estimates at nadir. The neural network approach was selected to take advantage of the method to handle within class variability and non-normal cluster distributions. The model has three layers. The input layer comprises eleven observed variables such as albedo, thermal brightness temperatures, etc. Output are designations in 9 cloud categories. The number of cloud pixels correctly determined varied from 73 to 90%. Heidke skill scores were > 0.66.

An application of a neural network to detect ground clutter has been proposed by da Silveira and Holt (1997). The use of neural networks to detect tornadoes and mesocyclones is under investigation at the National Severe Storms Laboratory (Section 3.4.2.7). [For additional studies with neural networks regarding signal extraction and pattern recognition see the special issue of the IEEE Transactions on

Signal Processing, November 1997.]

Lin et al. (1997) describe methods of approximating images with polygons when a multitude of scales are present. With one technique, smoothing of image boundaries is achieved by an iterative method. Shapes are reduced to curvature extrema which serve as vertices of reconstruction polygons. The ratio of the arc length along the boundary to the total length of the segments measures the goodness of fit. A Gaussian filter is applied and a curvature function is defined by the first and second derivatives of points along the feature boundary. The width of the filter is proportional to the square root of the distance between vertices. Iterations continue until the number of extrema stabilizes. A second proposed method represents features according to specified compression ratios. Iterations continue until a desired compression ratio (the number of peaks) is attained. If the number of vertices exceeds the specified number more smoothing is done to obtain a more compact representation.

2.11 Radar Analysis Techniques

The index of refraction is determined by the distribution of temperature and moisture in the atmosphere. Fluctuations in these parameters alter the speed at which radar waves propagate and consequently the time for signals to reach a target and return. For ground targets the range is fixed; and the time delay varies with the average index of refraction over the path traveled by the radar wave. Fabry et al. (1997) have measured changes in the phase of returned signals from ground targets and their temporal evolution to deduce changes in the refractive index. The phase change is analogous to the differential propagation phase used in rainfall measurement. Under normal conditions the refractive index measured represents conditions within 10's of meters of the ground. Fabry et al. present a long time series of radar-derived index of refraction and values computed independently from temperature, humidity, and pressure that shows excellent correspondence. Examples include a front and a region of high moisture associated with rain. The authors assert that the technique may depict the structure of temperature and moisture fields associated with fronts, microbursts, and outflows from convective storms. Implementation requires only software additions and a very stable transmit frequency over long periods (months or more).

A simulation model for brightband detection is described in the paper by Borga et al. (1997). The model is applied to simulated stratiform precipitation fields which are generated by a stochastic two-dimensional space-time model and a one-dimensional cloud model. Model parameters were set according to observations collected with a vertically pointing radar. A simple representation of the melting layer is made. A gamma distribution of particle size is assumed from which radar reflectivity is calculated. Simulated brightband reflectivities were 6 to 9 dB when associated surface reflectivity values were in the 20 to 30 dBZ range. The brightband correction algorithm of Andrieu and Creutin was then applied to the simulated three-dimension radar reflectivity fields. Experiments were performed for moderate and heavy rain cases, variable freezing levels, and variable melting layer thicknesses. Simulated radar scans at 3 elevation were used to correct scans at 1.5. Correlation coefficients and rmse statistics revealed significant improvement in the corrected reflectivity profiles.

A study illustrating that receiver noise can cause an increase in spectrum widths with range is presented by Gordon (1997). The problem is alleviated by a thresholding technique that keys on the peak spectral value.

Tian and Srivastava (1997) present a technique for determining the attenuation of radar signals at C-band that incorporates two radars. Observations from a S-band polarimetric radar provided verification. Retrieved attenuations are thought to have standard errors on the order of 0.5 dB km^{-1}. Application to a moderate thunderstorm uncovered specific attenuations as large as 2 dB km^{-1}. Locations of maximum attenuation and reflectivity factor did not always coincide as would be expected when attenuation is estimated directly from reflectivity. Attenuation-corrected reflectivities did not agree well with S-band reflectivities. Possible reasons were clutter contamination at close ranges, wet radome losses, blockage, and short integration paths. Although quite noisy, plots of differential reflectivity and the ratio of attenuation and reflectivity follow theory and were thought to show the "plausibility" of the retrieval method. Departures in various regions of the storm could represent concentrations of dry ice particles, high water content, and very small droplets. Although attenuation at S-band is generally small and usually ignored, there are situations such as radially oriented squall lines where the attenuation can be 2 dB or more. Losses of that magnitude can cause significant underestimation of precipitation. Application of the technique at S-band may be difficult because of the small losses that normally occur at S-band and the uncertainty introduced in radar comparisons by mismatched radar antenna patterns, ground clutter, sidelobes, and sampling differences.

2.12 Polarimetric Radars

López and Aubagnac (1997) present a nice diagnostic study of thunderstorm microphysics based on polarimetric observations. They use reflectivity, differential reflectivity, and specific differential propagation phase to discriminate particle types within the storm, to compute mixing ratios of ice and rain, and to correlate changes in the storm's microphysical properties with lightning activity. Under the assumption that graupel and hail particles tumble as they fall, K_{DP} was used to estimate the fraction of rain when mixed with ice particles. The proportion of radar reflectivity due to water (Z_w) and ice (Z_i) was then computed. Ice particles are categorized with Z_i and by weighing Z_{DR} and K_{DP} measurements. A surge in lightning activity followed a rapid depletion of the supercooled water. The liquid water was converted to graupel. Small hail accounts for roughly 20% of the ice content. The hail is thought to have accumulated a positive charge from collisions with ice crystals as it fell. This charge is hypothesized to induce cloud-to-ground flashes from the negatively charged graupel residing at higher levels.

Electrical fields in thunderstorms can alter the orientation of small ice crystals and create a differential phase shift. Metcalf (1997) studied this effect by transmitting radar signals with a right-circular polarization and receiving signals at right and left-circular polarization. The differential phase shift was computed from the cross-covariance amplitude ratio (CCAR); particle canting angles were derived from the phase shift. Changes in the vertical structure of signal propagation within storms appeared to be tied to the evolution of the storm's electrical properties and the apparent canting angle of particles illuminated by the radar beam. At elevations greater than 7 km, lightning strokes were marked by a strong propagative component a few seconds before a stroke, a reduced propagation immediately afterwards, and a return to a strong propagative component within a few more seconds. An opposite effect occurred at lower levels. Particle canting angles were also affected. Metcalf's results suggest that the magnitude of the differential phase is related to the strength of the electrical field. By monitoring the differential phase it may be possible to characterize hydrometeors and anticipate lightning activity.

An X-band dual-polarization Doppler radar was the primary observing platform for a study of an extratropical cyclone (Asuma et al. 1997). The radar provided differential reflectivity (Z_{DR}) measurements over a distance of 30 km. Field mills monitored electrical activity. The radar detected reflectivity brightbands intermittently, while the Z_{DR} parameter showed the melting layer at all times. Z_{DR} measurements also indicated that snowflakes with a preferred horizontal orientation existed well above the melting layer and that graupel particles existed in other regions of the storm. Some hypothesize that charging in electrical storms is due largely to collisions between graupel and ice particles at temperatures of roughly -10C (the non-inductive process). The finding that periods of large electric fields coincided with low Z_{DR} above the freezing level supports this notion.

In a similar paper Bringi et al. (1997) describe the evolution of the kinematic, microphysical, and electric fields in a thunderstorm complex in Florida. Each cell produced a Z_{DR} column, i.e., a region of positive Z_{DR} that extended well above the freezing level. The columns, which represent supercooled droplets being lifted in updrafts, extended to altitudes where temperatures were < -8C. Once the Z_{DR} column achieved its maximum height a region of enhanced linear depolarization ratio (LDR) formed at the top of the column. This signaled the onset of droplet freezing within the column. In the one cell to produce lightning, incloud lightning began within 5 min of the development of mixed phase precipitation within the Z_{DR} column.

Observations of supercooled raindrops in cumulus clouds probed with a dual-polarization radar are also presented by Blyth et al. (1997). Columns of enhanced Z_{DR} were found to extend well above the freezing level. Z_{DR} values between 1 and 2 dBZ extended up to 4.5 km AGL where temperatures were approximately -10C. Radar reflectivity was ~25 dBZ. A subsequent cell that developed within the cloud and did not have a Z_{DR} column was thought to have depleted the liquid water from the first cell.

Below the melting layer, hail is readily detected with the Z_{DR} parameter. Tumbling hail has no preferred orientation and is characterized by a Z_{DR} value near 0 dB; rain falls as oblate spheroids and has a Z_{DR} of > 1.5 dB. Above the melting layer, the presence of graupel and frozen debris and the absence of raindrops precludes hail detection with the Z_{DR} parameter. However, detection is possible by the LDR parameter (Kennedy et al. 1997). A LDR signature arises whenever the major or minor axes of illuminated particles are not aligned with the electric field vector. Tumbling hail creates a strong LDR signal. Hail at ground was preceded by the development of an elevated region with LDR > -25 dB where temperatures were -13C. In two storms the enhancement occurred 6 to 8 min before the arrival of large hail at ground.

Radar signals are also depolarized by ground clutter. The depolarization may be as large as the copolar signal (LDR 0 dB). The LDR signature for rain is usually < -27 dB, while for hail LDR may be > -13 dB. These properties of LDR facilitates the detection of clutter (e.g., Hagen 1997). A neural network technique for detecting clutter with circular polarization measurements is proposed by da Silveira and Holt (1997). The parameters examined were the circular depolarization ratio and the degree of polarization.

Polarimetric measurements are also being examined in snowfalls. Ryzhkov and Zrni (1997) found that with considerable smoothing (over 48 radar bins) they are able to estimate values of K_{DP} in snow as small as a few hundredths of 1 km^{-1}. The implication is that K_{DP} may be useful for discrimination of dry (cold) and wet (relatively warm) snowfalls. A Z_{DR} threshold of 0.2 dB appears to discriminate between pure rain and wet snow. The transition zone between rain and snow showed a sharp increase in Z_{DR} and a decrease in $_{HV}$. Chandra et al. (1997) investigated the change from snow to rain in vertical cross-sections of stratiform precipitation. For snow, the melting layer, and rain they found characteristic K_{DP} values of 0.01, 1.1, and 0.25 km^{-1}, respectively.

Rainfall estimates made with radar reflectivity, specific differential propagation phase, a reflectivity relationship tuned to match K_{DP}, and the area-time-integral method were compared in the study of Ryzhkov et al. (1997). In order to implement the ATI method it was assumed that the sample distribution of rainrate mirrored the population probability density function. The distribution for rain was determined from a tuned Z-R relationship. For the Z-K_{DP} combination, an empirical relationship was used to compute K_{DP} from Z_H, and then rainrate was computed from K_{DP}. Although K_{DP} rainfall estimates were more than a factor of 2 low in one stratiform rain case, overall, the optimum rainfall estimates were made with K_{DP} by itself. Estimates from Z improved when the relationship was tuned with K_{DP}. Rainfall estimates from tuned Z-R relationships may recover more range detail than estimates derived from K_{DP} alone.

Three parameters, the intercept N_o, the median drop size D_o, and the shape factor μ are needed to model a drop-size distribution with a gamma function. N_o and D_o can be computed from Z and Z_{DR}. To find μ, a third measurement is required. Wilson et al. (1997) propose to close the system with the difference in the mean radial velocity at horizontal and vertical polarization--the differential Doppler velocity (DDV). [Other possible parameters are the specific differential phase and the spectrum width.] The enabling hypothesis is that larger droplets have greater terminal velocities and are more oblate (larger Z_{DR}). The larger drops contribute more to the mean Doppler velocity at horizontal polarization than at vertical polarization. Theoretical relationships between DDV and differential reflectivity allows estimation of μ. The procedure was applied at elevation angles from 10 to 40. Normalization by the elevation angle yields DVV signals on the order of 0.15 $m\ s^{-1}$. The procedure gives spatially coherent values of μ. The spread in DVV vales for a specified Z_{DR} suggests that two parameter drop-size distributions do not depict the total natural variation in rainfall rate.

>Simulated measurements of radar reflectivity and differential reflectivity show that for simultaneous measurements the scatter between Z_H and Z_V pairs is much reduced from that for alternate sampling. Hence, fewer samples are needed with simultaneous sampling to determine Z_{DR} with specified accuracy. Ohsaki and Nakamura (1997) test a rainrate estimator proposed for satellite implementation that is based almost entirely on Z_{DR}. The slope of the drop-size distribution is calculated from Z_{DR}. and Z_H are combined to find N_o. The number density of the drops is then determined from $N(D)=N_o\exp(-D)$; and finally the rainrate is computed. A test of the procedure reveals that, although Z_{DR} can be measured more accurately with simultaneous measurements, the sensitivity of the proposed rainrate estimator creates errors in rainrate that are larger than those from the Z_H and Z_{DR} pair. The problem is exacerbated at antenna pointing angles near nadir.

Galloway et al. (1997) present a study of cloud properties at W-band. Signatures for the melting layer were found in linear depolarization ratios (relatively large values between -22 and -12 dB) and in the correlation coefficient between radar reflectivity at horizontal and vertical polarization (a minimum). A radar reflectivity brightband was not detected. Differential reflectivity measurements of ice needles (2.5 to 5 dB) revealed that the particles were predominantly aligned with their major axes in the horizontal. Measurements of ice needles at vertical incidence revealed a LDR signal caused by a random distribution of orientations and a Z_{DR} signal of 0.3 dB. The latter was described as being within the standard measurement error.

Aydin and Tang (1997) calculated polarimetric radar signatures (radar reflectivity, differential reflectivity, linear depolarization ratio, dual-frequency ratio, and specific differential phase) at millimeter wavelengths for hexagonal columns, hexagonal plates, and stellar crystals. While plates and crystals had similar scattering properties, the calculations suggest that columns can be discriminated from plates or stellar crystals by pointing a radar vertically or by evaluating trends in the measurements as the antenna elevation increases.

Rainfall estimates derived from a combination of reflectivity and differential reflectivity with a neural network were compared by Xiao and Chandrasekar (1997) to rainfall estimates from a relationship that computed rainfall directly from these two parameters (see Section 2.9). The neural network had lower bias errors and higher correlations between the estimates and the gauge observations.

Non-meteorological radar returns from ground clutter, anomalous propagation, and birds can impact algorithm performance. Birds can cause significant bias in VAD wind analyses; ground returns can contaminate precipitation products. An article by Zrni and Ryzhkov (1997) shows that the magnitude of the cross-correlation coefficient $_{HV}$ is a robust parameter for discriminating between meteorological and ground echoes. Insects can be distinguished from precipitation by large differential reflectivity values (up to 10 dB). Birds have a Z_{DR} signature of -1 to 3 dB. Characteristic signatures also exist for the backscatter differential phase (less than 50 for insects and up to 150 for birds).

In rain, radar signals at horizontal polarization are attenuated more than vertically polarized signals. Rainfall estimates using differential radar reflectivity are sensitive to the differential attenuation. A correction scheme outlined by Smyth and Illingworth (1997) incorporates the K_{DP} parameter and the biased Z_{DR} measurements. The differential attenuation ($A_{H-V)}$) is estimated from biased (negative) Z_{DR} measurements behind intense rain cores. The loss is then distributed at range gates where K_{DP} >1 km^{-1} (implied intense rain rates). The DSD parameters N_o and D_o are determined from A_{H-V} and K_{DP}. The attenuation at horizontal polarization (A_H) is computed; and finally, corrections are applied to Z_H and Z_{DR}. The methodology was tested on a storm in which rain rates exceeding 250 mm h^{-1} caused severe attenuation at S-band and introduced a bias in Z_{DR} of -1.75 dB. Ali-Mehenni and Testud (1997) present an iterative attenuation correction scheme for Z_{DR} that also yields the parameter N_o. Knowing N_o could improve rainrate estimates.

Yet another attenuation correction scheme is proposed by Carey et al. (1997). Reflectivity attenuation and differential attenuation are derived from observed relationships between Z_H and $_{DP}$ and between Z_{DR} and $_{DP}$ respectively. The procedure assumes that the attenuations are linearly related to K_{DP}. An important assumption is that the data are homogeneous. Restricting the analyses to particular classes of hydrometeors (through imposition of constraints on K_{DP}, $_{HV}$, LDR, and the backscatter differential phase) yields improved estimates of Z_{DR} as indicated by a reduction in scatter between Z_{DR} and $_{DP}$.

2.13 Data Compaction and Transmission Techniques

Active research in WSR-88D data compression for more efficient storage and transmission is reported by the University of Iowa/Institute of Hydraulic Research (Section 3.11.1) who have implemented a run length encoding method.

The University of Oklahoma/Center for Analysis and Prediction of Storm has also developed a data compression technique (Section 3.13.3). Compression ratios of five-to-one have been found for "worst case" scenarios.

3 ACTIVITIES ACCORDING TO ORGANIZATION

3.1 Air Force Research Laboratory and Hughes STX

3.1.1 Overview

During the past year there were five research projects at the Air Force Research Laboratory (formerly Phillips Laboratory): (1) wavelet-based mesocyclone detection, (2) storm structure algorithm, (3) precursors to lightning, (4) frontal structure algorithm, and (5) Doppler spectrum width analysis. The wavelet work is an in-house effort. The remaining tasks were performed under contract with Hughes STX Corporation. A mandated reduction in U.S. Air Force funding for NEXRAD algorithm development resulted in the termination of the Hughes STX research effort as of June 1997. The Hughes STX final reports contain the source code for the algorithms and are available to U.S. Government agencies.

3.1.2 Wavelet-Based Mesocyclone Detection

A major obstacle to automated mesocyclone detection is that the observational data are often corrupted by noise and contain complex flow features. Wavelets can be applied as band-pass filters to quickly and efficiently extract features with a predetermined shape and size (e.g., to separate a TVS from its parental mesocyclone). A wavelet with a profile similar to a Rankine-combined vortex has been applied for mesocyclone signature extraction. Results indicate that preprocessing the radar data with wavelets greatly improves the performance of conventional mesocyclone detection algorithms by eliminating noise and extraneous information. Examples of how the technique is applied are given in the reports listed below. During the coming year, efforts will be directed towards implementing the technique for operational use in a collaborative program with Canada's Atmospheric Environment Service.

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3.1.3 Storm Structure Algorithm

The Storm Structure algorithm automatically analyzes the high reflectivity factor core of thunderstorms for evidence of Weak Echo Regions (WER's) or Bounded Weak Echo Regions (BWER's). This is done by using image processing and pattern recognition techniques to represent salient components of two-dimensional WER's and/or BWER's. Detections are combined to produce three-dimensional features. Physical characteristics of the 3-D (B)WER are quantified and monitored with time. Characteristics such as volume, area, centroid locations, and deficit analyses are automatically computed for each volume scan.

The algorithm has been tested on a small set of severe storms (about 100 Archive II volumes) with encouraging results. The algorithm successfully identifies and quantifies supercell (B)WER's. Best results occur with high precipitation supercells within 100 km of the radar. The algorithm has difficulty with low precipitation supercells. The algorithm requires further testing on a broad set of thunderstorms to better evaluate its overall performance.

From a limited number of test cases, it has been documented that the algorithm predicts the initial onset of hail and tornadoes in supercells. Severe weather follows the formation of BWER's and is predicted by monitoring the reflectivity factor deficit of the (B)WER.

Early indications are that the incorporation of spectrum width information could be a valuable asset for earlier and more reliable detection of the initial 2-D WER at low levels. These findings and a more thorough discussion of the test results and analyses are included in the final technical report. [The algorithm designer (formerly at Hughes STX) is now with SenCom.]

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3.1.4 Precursors to Lightning Initiation

The purpose of this work was to examine storm structure for precursors to lightning. The analysis focused on the structure of reflectivity factor and was limited to altitudes above the 0C isotherm. Storm volume and layer statistics were generated and correlated with cloud-to-ground lightning data from the National Lightning Detection Network. Typical parameters computed include storm mass, volume, echo top, centroids, and maximum reflectivity factor. Layer statistics include precipitation intensity, centroid location, and areal coverage.

Lightning activity over the lifetime of 4 Kansas storms was investigated. The onset of lightning associates with a rapid increase in storm top, precipitation mass, layer areal extent, and maximum reflectivity factor. Subsequent lightning bursts correlate with increases in storm mass and volume. A more thorough discussion of the test results and analyses are included in the final technical report.

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3.1.5 Frontal Structure Algorithm

An automated algorithm has been developed by Hughes STX for the Air Force Research Laboratory to detect fronts and forecast their motion. Fields of gradient magnitude and direction are extracted from radar reflectivity factor and Doppler velocity. Through fuzzy logic, these fields are combined to portray a front or thin-line. Often, because of radar viewing angle, a front is not completely represented in one field. By using reflectivity and Doppler velocity information, fronts can be more completely defined. It was considered that spectrum width might provide additional information for frontal delineation; but for the cases examined, spectrum width provided scant additional information. Another feature of the algorithm is that derived 2-D winds along the front, determined from a sectorized wind retrieval technique, can be used to predict frontal motion. The technique appears most effective for time periods up to 30 minutes and can account for differential front movement.

The algorithm was applied to 100 volume scans containing cold front and gust front cases. It works best on cold fronts where the leading edge is delineated in both radar reflectivity and Doppler velocity fields. However, in several of the gust front cases examined, the thin-line was extracted from the Doppler velocity information alone. Details of the algorithm are provided in the reports listed below.

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3.1.6 Doppler Spectrum Width Analysis

The purpose of the work was to explore the utility of Doppler spectrum width (SW) for storm structure and severity assessment. It was found that high spectrum widths (> 8 m s^{-1}) are observed consistently in certain locations within storms, e.g., in the inflow region and at the storm's rear. High SW in the inflow region appears to outline the updraft boundary. This is especially evident at low levels in the weak echo region of the storm. High SW at the storm's rear presumably associates with 3-body scattering from large hail. The SW hail flare is better delineated than that with reflectivity factor or Doppler velocity because there is no other general source of high SW in that region of the storm. A hail flare algorithm is outlined in the final Hughes STX report.

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3.2 Bureau of Reclamation

3.2.1 Snow Accumulation Algorithm (SAA)

The Bureau of Reclamation is continuing development of a Snow Accumulation Algorithm (SAA) for use by the WSR-88D (NEXRAD) radar network. This development receives primary support from the WSR-88D Operational Support Facility and secondary support from the Bureau of Reclamation.

The current version of the SAA is intended for dry snowfall without bright band contamination. Special hourly observations of snow water equivalent (SWE) were obtained during the 1995-96 and 1996-97 winters from several areas scanned by WSR-88D radars. These include Albany, New York; Cleveland, Ohio; Denver, Colorado; Minneapolis, Minnesota; the Grand Mesa of western Colorado; the Sierra Nevada of California; the Cascades of Washington; and Anchorage, Alaska. Observations are limited from some sites because of Level II data recording problems and/or sparsity of storms. However, most locations within 60 km of the radar, where underestimation is minimal, provided hundreds of hours of measurable SWE from gauges or snow boards.

Observations of SWE are being related to reflectivity factor measurements from the radars to determine "best fit" and coefficients for the commonly-used equation Z=SWE. An optimization scheme is used to empirically determine the parameters and assuming that average hourly radar-estimated and surface-observed SWE accumulations should be equal. This scheme is providing values near 2.0 and corresponding values in the 100 to 300 range with the usual metric units. These are only preliminary estimates.

Underestimation of SAA-estimated SWE occurs beyond approximately 70 km range because of earth's curvature, beam widening, and possible reduced beam filling at greater ranges. The underestimation problem is severe with shallow lake-effect storms but less apparent with larger scale 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 the lack of a range correction scheme is a shortcoming with the prototype algorithm. Reclamation hopes to develop a range correction scheme based on the vertical profile of Z if resources become available. In the meantime, a simple empirical scheme, based on 1995-96 radar-snow board comparisons, will be tested in real time at Albany during the 1997-98 winter.

Realtime tests at Cleveland and Minneapolis revealed the need to customize the "hybrid scan" file in order to use the lowest practical radar beam tilt at all locations. As with the NEXRAD precipitation algorithm, the SAA uses a hybrid scan file to direct which beam tilt should be used for each range bin location. Empirical tests support the use of higher tilt beams over regions with persistent ground clutter. But over terrain with limited relief, it is possible to use the lowest (0.5) tilt beam within 10-20 km of the radar, thereby scanning the region near the surface where Z tends to be highest. Anomalous propagation does not seem to be a problem with dry winter snowfalls.

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3.3 NASA/Goddard Space Flight Center

3.3.1 Origins of Variability of Rainfall Relations in the Tropics

This work is based upon measurements of drop-size distributions by airborne and surface disdrometers and a radar profiler obtained in the tropical Pacific during TOGA COARE. From airborne observations of DSD's and simultaneous vertical air motions below the melting level, we find differences in the Z-R relations (of form $Z=AR^b$) for stratiform and convective rains; the latter occurs when the draft magnitude is > 1 m s^{-1}. The convective relation is identical to that found at the surface by Tokay and Short (J. Appl. Meteor., 1996). Their stratiform relation has a larger coefficient (A) and smaller exponent (b), i.e., a decrease in the slope on a log-log plot. This may result from truncation at the small size end of the DSD in the presence of windshear sorting, but such a mechanism is ruled out in a large population of samples where truncation may occur randomly at either end of the DSD. The decrease in the number of small drops resulting from evaporation is found to be the dominant mechanism in stratiform rain. In some cases the variations are systematic and correspond to increases of the mass weighed drop size which is characteristic of evaporating rainfall. Hence, the stratiform Z-R relation is height dependent. Study of surface DSD's at Kapingamarangi Atoll along with Z and Doppler velocity measured by the radar profiler confirm the time and space variability of the Z-R relations in stratiform rain due to evaporation. Particularly noteworthy are the differences in the convective Z-R relations on the leading and trailing edges of convective rains. This renders the conventional method of assigning individual relationships to convective or stratiform rainfalls in serious doubt. There is a need for either a means to identify the conditions controlling this variability or for the use of polarimetric radar.

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3.4 NOAA/National Severe Storms Laboratory

3.4.1 Introduction

The National Severe Storms Laboratory (NSSL) conducts research to analyze Doppler radar data and to develop and enhance hazardous weather detection algorithms utilizing radar. Algorithm testing is accomplished both in a post-analysis research environment and in real time at National Weather Service forecast offices. 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 NWS for inclusion in the WSR-88D and AWIPS systems.

Datasets from the 1995 and 1996 Verification of the Origin of Rotation in Tornadoes Experiments (VORTEX) continue to be analyzed for determining the characteristics of tornadic storms and for improving present and future algorithms.

3.4.2 Algorithm Development and Enhancement

3.4.2.1 Storm Cell Identification and Tracking (SCIT) Algorithm

The Storm Cell Identification and Tracking (SCIT) algorithm is currently part of the Build 9 Radar Products Generator (RPG) of the WSR-88D system. This version of SCIT identifies cells using multiple reflectivity thresholds and is capable of identifying embedded cells in multi-cellular storms. The new version also provides time and time-height trends of storm features.

As a result of work being conducted on the Damaging Downburst Prediction and Detection Algorithm (DDPDA), the resolution of the output from the SCIT algorithm has been increased to improve the identification of downburst precursors. This change has also improved the tracking of reflectivity cores with the SCIT algorithm. The SCIT algorithm has also been modified to include continuous updating of storm cell locations. The process of "building" three-dimensional storms from two-dimensional components continues as each elevation is completed, providing updated locations of storm cells more often than at the end of each volume scan.

NSSL plans to integrate correlation-tracking software from 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 1998 convective season.

3.4.2.2 Mesocyclone Detection Algorithm (MDA)

The NSSL Mesocyclone Detection Algorithm (MDA) is expected to appear in the WSR-88D system in the 2nd or 3rd Builds of the Open System Radar Product Generator (ORPG). 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.

Testing continues with the Mesocyclone Detection Algorithm on an ever-expanding database of tornadic and non-tornadic supercells. The database now contains over 40 individual storm days (over 200 tornadoes and over 300 hours of radar data) from a variety of locations across the country. Entries in the database also serve as input to a neural network (NN) under development to determine the probability of tornadoes or severe weather.

Recent enhancements to the MDA include the addition of several diagnostic parameters (such as line-integrated divergence and rotation) and modifications to detection techniques. A number of new input parameters for the NN have been added, including trend information and near-storm environmental parameters. The NN also incorporates information from the Tornado Detection Algorithm (TDA) in its diagnosis of storm-scale vortices.

The MDA has been amended to include continuous update processing of 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 old position is updated. Future work will involve combining the detection capabilities of both the MDA and TDA into a storm-scale Vortex Detection and Diagnosis Algorithm (VDDA).

3.4.2.3 Tornado Detection Algorithm (TDA)

In cooperation with the OSF Applications Branch, the Tornado Detection Algorithm (TDA) has undergone extensive modification for inclusion in the WSR-88D Build 10 Radar Products Generator (RPG) to be released in the summer of 1998. NSSL continues to test the TDA in real time at select NWS forecast offices. Incorporation of the TDA into the WSR-88D Algorithm Testing and Display System (WATADS) is ongoing.

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 using both simulated and actual WSR-88D data show that this technique may complement current techniques used within the TDA and the Mesocyclone Detection Algorithm to identify potentially hazardous vortices.

The TDA has been amended to include continuous update processing of Tornadic Vortex Signature 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 location is updated. Ongoing work includes building three-dimensional TVS detections as each elevation is completed. Future work will combine the detection capabilities of both the MDA and TDA into a storm-scale Vortex Detection and Diagnosis Algorithm (VDDA).

3.4.2.4 Hail Detection Algorithm (HDA)

A performance evaluation of the Hail Detection Algorithm (HDA), part of Build 9, was conducted in response to users' perceptions that the algorithm was "over warning" 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 examined for algorithm bias. Analysis of the Warning

Threshold Selection Model for 51 days at Melbourne showed no apparent over or underforecasting 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 the over warning in some situations could be mitigated 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.

NSSL plans several future enhancements to the HDA. The first enhancement is based on results of cloud modeling studies which show that mid-altitude rotation in a storm plays a significant role in the growth of very large hail. Use of the MDA to provide a measure of mid-altitude rotation in storm cells should improve the accuracy of the maximum hail size estimates and reduce instances when very large hail (i.e., larger than two inches) is erroneously predicted for non-supercell storms. Second, the calculation of a volumetric (3-D) Severe Hail Index, versus the one-dimensional SHI that is now used, should allow better discrimination between large, severe hailstorms which have similar one-dimensional vertical reflectivity profiles and small cells that may be producing little, if any, severe hail. Third, NSSL plans to add a terrain model to the HDA, which should account for the differential melting that occurs where terrain height varies substantially.

3.4.2.5 Damaging Downburst Prediction and Detection Algorithm (DDPDA)

NSSL is developing an algorithm capable of detecting and predicting damaging wind events using radar reflectivity and velocity data. The Damaging Downburst Prediction and Detection Algorithm (DDPDA) attempts to locate downburst precursors -- events that can be detected in the middle and upper levels of a storm prior to the onset of strong surface winds. Early versions have 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 strengths.

The DDPDA has undergone a number of improvements, especially to the component routines and input routines that analyze downburst precursors. The resolution of the output from the Storm Cell Identification and Tracking (SCIT) algorithm, which is used as input to the DDPDA's core-tracking routine, was increased. This improved the number of correctly tracked reflectivity cores from 64 to 78%. Additionally, environmental data have been added to the DDPDA, and the radial velocity processing routines have been improved.

Future plans for the DDPDA include modifying it from an algorithm which predicts and detects "wet" downbursts into one which can also predict "dry", high-based downbursts. Early efforts will focus on tuning the SCIT algorithm so that it can detect the low-reflectivity cells that produce these events and on adding near-storm environment data to the procedure. NSSL also plans to investigate methods to unambiguously score downburst occurrence, using Low-Level Windshear Alert System (LLWAS) and (Terminal Doppler Weather Radar (TDWR) product data.

3.4.2.6 Near-Storm Environment (NSE) Algorithm

The goal of the Near-Storm Environment (NSE) algorithm is to provide the NSSL WSR-88D algorithms with environmental shear and stability information from the Rapid Update Cycle (RUC) model. Recently, the capability for incorporating surface observations has been added.

Long-term plans call for replacing the RUC information with output from the higher resolution RUC-II model and for investigating the use of the Local Analysis and Prediction System (LAPS) mesoscale model as input. In addition, new parameters will be derived as needed for further WSR-88D algorithm development. Tests will be completed for the incorporation of surface data into the NSE algorithm.

3.4.2.7 Neural Network (NN) and Statistical Analyses

The original pair of Neural Networks (NN's) developed for the diagnosis of tornadic and damaging wind circulations has been supplemented by additional NN's. Currently, two networks examine circulations detected by the NSSL Mesocyclone Detection Algorithm (MDA), two examine circulations detected by the Tornado Detection Algorithm (TDA), and another two diagnose circulations detected by both the MDA and TDA.

The NN's were designed to produce probabilities of occurrence for tornadic and damaging wind phenomena. Other statistical techniques have also been examined. An ongoing mathematical analysis of performance shows that most, if not all, commonly used measures of verification are unreliable for rare events. Two journal articles summarize this finding.

The NN's currently employ techniques for the selection of parameters that are unspecified a priori. Recently, supplementary techniques have been developed to aid in the determination of these parameters. Analogs of the present NN's using these techniques will be developed. Similar NN's may be developed for hail and lightning detection.

3.4.2.8 Vortex Detection and Diagnosis Algorithm (VDDA)

Groundwork is underway to merge the NSSL TDA and MDA into a single algorithm called the Vortex Detection and Diagnosis Algorithm (VDDA). The new algorithm will allow for detection of a variety of storm-scale vortices and for sharing analyses (such as vertical association and time association) between algorithms. The integration of data from other radar-based algorithms and sensors will provide a more thorough analysis of the vortices.

The VDDA will feature components from both the MDA and TDA, as well as some new techniques such as a least-squares method to compute radial and azimuthal convergence and an 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 has been assembled. The MDA and TDA will be tested on these data to determine the strengths and weaknesses of each algorithm and to develop new two-dimensional feature detection and diagnosis techniques.

Future plans include development of a dataset of gust fronts, mesocyclones with embedded TVS's, and mesocyclones with rear-flank downdrafts for testing. More robust vertical and time association techniques will be developed for the VDDA. NSSL also plans to investigate the use of wavelet analysis and the elliptical vortex model to enhance two-dimensional detection capabilities.

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

3.4.2.9 Tornado Warning Guidance

NSSL and the NEXRAD OSF worked together to generate supplemental tornado warning guidance for the National Weather Service (NWS) based on the latest ideas about tornado prediction. The new guidance comes from an extensive analysis of WSR-88D data using the NSSL Mesocyclone Detection Algorithm. Radar-based parameters which measure different aspects of thunderstorm vortices were evaluated to determine how well they discriminate between tornadic and non-tornadic storms. Tornado probability diagrams were then generated for several of the parameters (those which can be manually calculated from the base data) for different range intervals.

Statistical analysis was performed using a dataset of 29 cases with trend information. The preprocessing of the data necessary for a proper development of the neural networks allows for extraction of statistically sound information that can then be used in tornado warning guidance. The primary focus is to determine the best set of variables for predicting tornadic circulations, but the existence of correlations among the variables renders any multivariate analysis useless. As a result, univariate probabilities were computed for all relevant variables. These probabilities can aid in the selection of the best predictors. Additionally, linear correlation coefficients between all relevant variables and ground truth have been computed; these aid in the identification of the best linear predictors. The statistical analysis will continue in anticipation of a warning guidance document in 1999.

3.4.2.10 Multiple-Radar Algorithm Comparison Study

A study was conducted to determine the variation in severe storm detection algorithm output that occurs when storms are viewed simultaneously by more than one WSR-88D. The study was part of an initial effort to expand the Warning Decision Support System (WDSS) to include information from multiple WSR-88D's. Output from the Severe Storm Analysis Package (SSAP) for two supercell storms which occurred on 25 May 1996 between Lubbock and Midland, Texas was examined.

Large differences were found in the algorithm output from the two radars. At ranges less than 130 km, storm-top divergence observations were sensitive to the Volume Coverage Pattern (VCP) and can be highly degraded when the radar is scanning in VCP-21. In supercells, velocity dealiasing errors and consequently errors in the output of velocity-based algorithms occurred more frequently in VCP-11 than with VCP-21. Integration of algorithm output from multiple WSR-88Ds into the WDSS will require accurate error filtering to avoid propagating incorrect guidance information.

3.4.2.11 Multi-PRF Dealiasing Algorithm (MPDA)

The Multi-PRF Dealiasing Algorithm (MPDA) is a WSR-88D scanning strategy and data processing package designed to minimize the amount of overlaid echoes (range folding) in velocity data and the number of aliased velocity measurements. The premise of the MPDA scanning strategy is 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. The 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 WSFO and NSSL through the Warning Decision Support System (WDSS). Three significant convective events were captured using the realtime processing software.

A switch from floating point to integer calculations and the conversion of high computationally intensive calculations to lookup tables has 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 can be critical in determining the quality of 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 1996 versions of the MPDA.

Future plans for the MPDA will focus on a more robust two-dimensional dealiasing scheme and fault mitigation in areas where only single velocity estimates exist. Data acquisition strategies will also be examined to help reduce the time of collection and noise level in the velocity data.

3.4.3 Radar Data Processing Systems

3.4.3.1 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 for communicating with the WSR-88D Wideband User Port, to ingest the Level II data, and to distribute it over an Ethernet connection to other workstations for processing. The RIDDS system is also capable of archiving the Level II data. There are currently 25 NWS and DOD sites with the RIDDS software; eight more sites are planned for 1998.

3.4.3.2 Warning Decision Support System (WDSS)

A prototype Warning Decision Support System (WDSS) has been developed which combines enhanced or new WSR-88D severe weather algorithms and innovative display capabilities to support warning meteorologists in severe or hazardous weather situations. The WDSS processes realtime Level II data from the WSR-88D (via the RIDDS software) and executes the algorithms outlined in Section 3.4.2. The algorithm output and base data products are displayed using the Radar Analysis and Display System (RADS). In addition to WSR-88D data, the WDSS has the ability to integrate other datastreams such as surface observations, satellite imagery, ground strike locations from the National Lightning Detection Network (NLDN), and numerical model output. These data can be displayed in RADS 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 during the spring and summer convective seasons. In 1997, the WDSS was tested in Pleasant Hill, Missouri and Sterling, Virginia and is currently in use at Albany, New York for testing the Bureau of Reclamation's Snow Accumulation Algorithm. The realtime operational tests provide feedback from forecasters and enable continuous enhancement of both the algorithms and display concepts. Work is currently underway to begin integrating WDSS functionality into the Advanced Weather Interactive Processing System (AWIPS). Integration is targeted for Build 6.0 of the AWIPS (scheduled for release in summer of 1999). The upgrade 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. New algorithm processes, planned for integration into AWIPS, include County Warning Area-based tabular information and a satellite-based storm cell identification and tracking algorithm. 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 summer of 1998.

3.4.3.3 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 personnel to examine past weather events in detail. Users have the ability, through a graphical interface, to change adaptable parameters and input environmental data (such as soundings) before executing the software. The WATADS software also includes a version of RADS created specifically to display output from both the current WSR-88D algorithms and NSSL algorithms.

WATADS 9.0 was released in May of 1997. WATADS 10.0 will be released in the spring of 1998, and will include the Build 10.0 Tornado Detection Algorithm (TDA), a compressed file utility, and new versions of NSSL experimental algorithms. A WATADS 10.1 release is scheduled for late summer of 1998 and will include Build 10.0 Precipitation Algorithm changes, Year 2000 compliance, the capability to run the Areal Mean Basin-Estimated Rainfall (AMBER) algorithm, plus new versions of NSSL experimental algorithms.

3.4.3.4 Inventory of WSR-88D Level II Data

The NSSL-OSF Level II database has grown to a total of 1020 tapes. The tapes have been acquired in cooperation with the National Climatic Data Center (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, data 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.

3.4.3.5 Open System Radar Product Generator (ORPG) Development

A Memorandum of Understanding between the Environmental Research Laboratories (ERL) 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, 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 in early 1999.

The ORPG is expandable for accommodating future growth and resource demands. An ability to easily incorporate new meteorological algorithms, product generators, and functionality will be provided through encapsulation of services and modules as well as a loose coupling of system processes. The ORPG will accommodate future expansion as resource requirements (processing, memory, storage) increase. The software is portable across POSIX-compliant systems, making relatively inexpensive COTS hardware available for the ORPG and helping to avoid 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-Build 1 (MB1) was completed in December 1996. Mini-Builds 2 and 3 were completed during 1997. The primary development activities have been in product distribution, RDA monitoring and control, communications, and continued GUI UCP 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.

3.4.3.6 Open System Radar Data Acquisition (ORDA) Development

Significant accomplishments have been made in the upgrade of ERL's research and development WSR-88D. Conceptual hardware and software designs have been completed. Detailed design of the synchronizer board for timing and an interface board have been completed and fabrication has begun. Prototype signal processors and host computers have been acquired. Development of algorithms for generating base data on the new digital signal processor has started. Final design of the building to house the radar and provide work space has been completed.

Modifications of the microwave circuits include installation of a dual-polarization feed, waveguides, and an elevation rotary joint. A dual-azimuthal rotary joint and other microwave components have been procured . Pattern measurements were made on the antenna before and after the changes. This is a first measurement on a WSR-88D antenna in the field. The original patterns and patterns for vertically polarized and horizontally polarized waves conform to specifications. A good match exists down to 20 dB below the main lobe and the cross-polar pattern is more than 35 dB below the co-polar pattern.

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3.5 NOAA/National Weather Service Offices

3.5.1 Chanhassen, Minnesota

3.5.1.1 Optimizing the WSR-88D MESO/TVS Algorithm Using WATADS

A tornado outbreak occurred in east central Minnesota at approximately 0000 UTC on 22 July 1995. Storms formed within 80 km of the KMPX WSR-88D at the Minneapolis/Chanhassen Weather Service Forecast Office (WSFO). The WSR-88D MESO/TVS Algorithm (MTA) identified only two Tornado Vortex Signatures (TVS's) out of 14 confirmed tornadoes. A detailed examination of Doppler velocity products revealed operator-defined TVS's, intense gate-to-gate azimuthal shear, in 10 of the 14 storms. Because the algorithm performed poorly and the KMPX radar sampled many weak tornadoes at close range, an opportunity was presented to optimize MTA performance.

Numerous combinations of two adaptable parameters, the Threshold Pattern Vector (TPV) and Threshold TVS Shear (TTS), were systematically tested using the WSR-88D Algorithm Testing and Display System (WATADS) and Archive Level II data. MTA performance improved significantly when default values (TPV = 10 and TTS = 72) were set to TPV = 7 and TTS = 35. The number of tornadoes detected increased from two to seven, and the average TVS alert lead time, within 60 km of the radar, increased from 10 to 15 minutes. However, the number of TVS's falsely identified increased from zero to two.

In 1995 and 1996 the NEXRAD Operational Support Facility (OSF) authorized radar offices to lower TPV and TTS from their default values under the Unit Radar Committee Level of Change Authority (WSR-88D Handbook Vol. 1, 1996). Recommended values for TPV and TTS, based on research from data collected from many different sites across the United States (Lee 1995; Lee 1996), were provided for field office use. The values of TPV and TTS used to optimize MTA performance during the Minnesota tornado outbreak agreed with OSF recommended values of TPV and TTS.

References

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3.5.1.2 Doppler Radar Algorithm Performance During a Highly Sheared Tornado Outbreak

During the afternoon and evening of 26 October 1996, a strong low pressure system over Nebraska moved northeastward through eastern South Dakota and into central Minnesota. Synoptic scale conditions ahead of the low were unseasonably unstable. In addition, analysis of the vertical wind field structure suggested that the large-scale environment was extremely sheared (both in direction and speed), indicating that developing storms would be highly tilted and fast-moving. A total of 14 low-topped (mini supercell) tornado-bearing thunderstorms developed across central Minnesota. Eight storms, which developed within range of the National Weather Service (NWS) Minneapolis/Chanhassen WSR-88D, (KMPX) have been selected for study.

A detailed investigation of storm structure using both reflectivity and velocity data has been made. Storms exhibited very low-topped mesocyclones and storm echo tops that were located well downstream from the storm base. Performance of the WSR-88D Mesocyclone and Tornadic Vortex Signature algorithms are being compared to the NSSL Mesocyclone Detection Algorithm (MDA) and Tornado Detection Algorithm (TDA). Since the current WSR-88D and NSSL MDA algorithms did not detect the majority of these strongly tilted mesocyclones, algorithm development of more aggressive three-dimensional routines may be needed to compensate for high shear environments and resulting storm tilt. An envisioned algorithm would identify a high shear environment from the VAD Wind Profile (VWP) or nearby upper air sounding. The algorithm would compensate for the high shear by enlarging the search area to increase the likelihood of linking circulations at multiple elevation scans for mesocyclone detection.

The use of base spectrum width (SW) data in developing a modified mesocyclone detection algorithm has been examined. Data were gathered during an interval from approximately 15 minutes before tornado touchdown to 5 minutes after tornado dissipation. Preliminary results indicate trends in SW that vary by more than 9 kts, even at distances greater than 100 nm, and that correspond quite well with the life cycle of the tornado. This suggests that to detect circulations in highly sheared environments, the algorithm should look for the maximum SW value within a specified radius of that circulation for confirmation of greater rotation.

Reference

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3.5.2 Greenville-Spartanburg, South Carolina

3.5.2.1 Rainfall Estimation

The Greenville-Spartanburg NWSO has been collaborating with Dr. Carlton Ulbrich of the Department of Physics and Astronomy at Clemson University to improve rainfall estimates made by the WSR-88D radar (KGSP) at the Greenville-Spartanburg Airport in Greer, South Carolina. Radar reflectivity factor measurements at the lowest elevation angle have been compared with disdrometer measurements made at the Clemson University Atmospheric Research Laboratory. The laboratory is only 30 nm from the radar; hence, the radar pulse volume is only a few hundred meters above the disdrometer. In the study, corrections were made to account for the time required for raindrops to fall from the pulse volume to the surface. Adjustments were also made for droplet drift by the environmental winds. Results for four storms with prolonged rainfall indicate that the radar systematically underestimates the reflectivity factor relative to the disdrometer by about 4 dB. This offset explains the factor of 2 underestimation of rainfall measurements by the KGSP radar relative to raingauge measurements.

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3.5.3 Melbourne, Florida

3.5.3.1 Tropical Cyclone Tornadoes

Melbourne members have continued their study of WSR-88D archive data for operator defined signatures related to tropical cyclone outer rainband tornadoes. The shortcomings of the current mesocyclone and tornado vortex signature (TVS) algorithms for detecting rainband tornadoes have been investigated with detected rotation and shear parameters (reference 1). Based on this research, the authors recommend the development and implementation of a new radar scan strategy or Volume Coverage Pattern which would increase low-level vertical resolution and reduce the recycle time between data collections. Other aspects of severe weather signature detection using the WSR-88D during tropical cyclone events have also been studied (references 2,3 and 4). Improvements with the next generation of the mesocyclone and TVS algorithms will likely result, based in part upon the rotation/shear characteristics and reflectivity/velocity parameters collectively observed and documented during several events outlined in these papers.

References

1. Spratt, S. M., D. W. Sharp, P. Welsh, A. Sandrik, F. Alsheimer, and C. Paxton, 1997: A WSR-88D assessment of tropical cyclone outer rainband tornadoes. *Wea. and Forecasting*, **12**, 476-498. (see the web site http://www.nws.fit.edu/waf2.html)

2. Hodanish, S.J., S.M. Spratt, and D.W. Sharp, 1997: WSR-88D characteristics of tornado-producing convective cells associated with tropical cyclones. *Preprints, 22nd Conf. on Hurricanes and Tropical Meteorology*, Ft. Collins, Colorado, Amer. Meteor. Soc, 675-676. (see http://www.nws.fit.edu/)

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4. Spratt, S.M., and D.W. Sharp, 1997: Hurricane Operations at NWSO Melbourne: Applied Research and Real-time Forecasts/Warnings. *Preprints, 22nd Conf. on Hurricanes and Tropical Meteorology*, Ft. Collins, Colorado, Amer. Meteor. Soc., 659-660. (see http://www.nws.fit.edu/)

3.5.3.2 Rainfall Estimation

Studies have been conducted concerning the impact of adaptable parameter changes on the accuracy of WSR-88D rainfall accumulation estimates. A comparative analysis was performed using data from two tropical cyclone events and several recommendations are made to improve future radar-based rainfall sampling. (see also Sections 2.6 and 4)

Reference

1. Glitto, P. A., and B. K. Choy, 1997: A comparison of 72-hour storm total precipitation performance during Tropical Storm Gordon and Tropical Storm Jerry. *Wea. and Forecasting*, **12**, 459-471.

3.5.3.3 Testing with the Warning Decision Support System (WDSS)

A detailed evaluation of the "next generation" WSR-88D algorithms, currently available on a realtime Warning Decision Support Workstation (WDSS) developed at NSSL has been conducted at Melbourne. Specifically, the hail, mesocyclone, tornado, and microburst detection algorithms have been subjectively verified for accuracy during three spring (cool season) weather events.

Additionally, the NWSO Melbourne is poised to "test" tropical cyclone algorithms on the WDSS in the future. Informal discussions have been held among NWSO Melbourne personnel, the Hurricane Research Division's Tropical Cyclone Algorithm Working Group, and National Severe Storm Laboratory's WDSS developers.

Reference

1. Sharp, D.W., 1997: Operational Assessment of the Warning Decision Support System, AMU Tasking Report, 7/97.

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3.5.4 North Little Rock, Arkansas

3.5.4.1 Combined Shear (CS), V_r/Shear, and Alphanumeric Mesocyclone Shear Products

The use of various shear parameters observed during severe storm situations has been investigated. For the March 1, 1997 tornadic outbreak in Arkansas shear values computed from the alphanumeric product alerted forecasters to impending activity. In one case only this parameter detected a tornado. Trends in radial velocity shear agreed with tornado intensity in another storm. Experience suggests that mesocyclones having peak-to-peak wind diameters of 3 miles or less and shear values of $20\text{x}10^{-2}$ s^{-1} associate with tornadoes on the ground. The tornadic storms also exhibited concentrations of high spectrum width.

Performance of the Combined Shear (CS) product has been examined for a storm which produced a small-scale transient tornado and two bow echoes. The CS product depicted the "wrapping up" of the tornado-spawning mesocyclone. Shear threshold values of 80 to $100\text{x}10^{-4}$ s^{-1} associated with damage. A paper entitled "Using WSR-88D Shear Products During Severe Storm Events" is expected to appear in "Southern Region Topics".

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3.5.4.2 Forecasting Large Hail with the WSR-88D

A new VIL estimation diagram which combines the "VIL of the Day" and the "VIL Density" concepts was been developed. The combination of schemes seems to satisfy some of the problems in hail estimation, namely that echoes too close or distant from the radar are not adequately sampled. A "VIL Estimation Diagram" has been produced for realtime hail size estimation from the echo top, 500-hPa temperature, and VIL. A summary paper is in regional review.

A second study has examined the implications of freezing level and wet-bulb zero height on the production of large hail (.75 in). Findings indicate that the 500-hPa temperature is a good estimator of hail size when used with a scheme like "VIL of the Day" or the "VIL Estimation Diagram".

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3.5.4.3 Other Activities

Several other projects are in progress at the North Little Rock NEXRAD WSFO. One activity uses archived Level II data and involves the adjustment of the mesocyclone threshold pattern vector (TPV) and the threshold TVS shear (TTS) to optimize tornado detection. During the March 1 episode, the radar identified two TVS's within 35 mi of the radar. In post analysis with adjusted parameters a third TVS was identified at a range of 50 mi. Tests with three other events are being conducted. Yet another activity is the comparison of rainfall amounts estimated by the North Little Rock and Shreveport WSR-88D's.

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3.5.5 Salt Lake City, Utah

3.5.5.1 Microburst Prediction

Several microburst cases obtained with the KMTX WSR-88D have been analyzed. Precursor signatures that have been identified are (1) a descending reflectivity core and (2) radial velocity convergence near or above cloud base. Convergence values of 15 kt over 5 nm or less gave warning leadtimes of 10-12 min. More work needs to be done to evaluate the rate of false alarms with these weak values. Results point to the importance of choosing the right radar tilt for determining the convergence precursor as terrain elevations for different sites in the West are highly variable.

Many of the microburst storms studied had peak reflectivities below thresholds for the WSR-88D storm cell identification and tracking algorithm (SCIT). Thus, sensitivity studies with the SCIT parameters are recommended. The weak reflectivity values also make the manual identification of these storms difficult.

Several cases have been selected for more intensive study, for development of the NSSL damaging downburst prediction and detection algorithm, and for use as Western Region training material. A number of Western Region Technical Attachments have been published on microburst prediction.

3.5.5.2 Snow

The coefficient and exponent in the Z-S relation were determined for a 5 December 1996 snowfall event that seemed caused by symmetric instability. Two snow bands deposited more than 6 in each over a 6 h period. A time delay of ~45 min occurred between the arrival of reflectivity echo at a gauge site and the first measurement of surface snowfall. Observed snowfall rates were greater than that determined from Z-S relationships. Postulated sources for the discrepancies are blockage of the radar beam, an incorrect Z-S relationship, and gauge measurement errors. Three other snow events are also being studied.

Reference

1. Vasiloff, S., 1997: Interpretation of radar data during snow events in mountainous terrain. *Western Region Tech. Attach.*, **No. 97-35**.

3.5.5.3 Hail Studies

An evaluation of the WSR-88D Hail Detection Algorithm has been made with the Salt Lake City radar. For the most part the algorithm performed well. Results for distant storms were erratic. In particular, the probability of severe hail (POSH) for storms beyond 80 km seemed high. It was found that the probability of hail (POH) and the POSH were near 100% for most hail events. The maximum expected hail stone size was thought to be overestimated by 30 to 50%.

References

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3.6 NOAA/NEXRAD Operational Support Facility

3.6.1 Mesocyclone and TVS Parameter Survey

Work is now underway at the Operational Support Facility (OSF) and at many National Weather Service (NWS) field sites to fine-tune default adaptable parameters and to optimize Mesocyclone and TVS algorithm performance for diverse climatological and local environmental conditions. Because the algorithms originally were developed in the Great Plains, tuning and optimizing capabilities are requisite for sites in other geographical regions. The OSF and NWS provided recommendations to NWS field sites for modifying adaptable parameters in the Mesocyclone and Tornado Vortex Signature (TVS) Algorithms. Out of 136 possible surveys, 90 were returned which detailed field site optimization studies of the Mesocyclone Threshold Pattern Vector (TPV) Number and Threshold TVS Shear (TTS). Approximately 10% of the sites (mostly in the Southern and Great Plains) indicated they like the default parameters. Only 20% of the sites indicated that they intend to use WATADS to evaluate parameter performance. Approximately 20 sites had reduced the TPV and TTS parameters and felt that they had enough cases to comment on the algorithm's performance after making the changes. Only 2 or 3 sites indicated that the changes were for the worse.

Reference

1. Lee, R.R., 1997: Regional adaptation of NEXRAD Mesocyclone and TVS Algorithms. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 347-348.

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3.6.2 TVS Parameter Study in Minnesota

Algorithm performance during an upper Midwest tornado outbreak are in agreement with OSF recommendations previously distributed to WSR-88D field sites. The WSR-88D MESO/TVS Algorithm (MTA) adaptable parameters, TPV (Threshold Pattern Vector) and TTS (Threshold TVS Shear), were lowered from default values TPV = 10 and TTS = 72 h^{-1} (2.0×10^{-2} s^{-1}) to TPV = 7 and TTS = 35 h^{-1} (9.7×10^{-3} s^{-1}). The number of tornadoes detected by MTA increased from two to seven, but the number of storms falsely identified increased from zero to two. Average lead time, within 60 km of the radar, increased from 10 to 15 min.

Reference

1. Tipton, G.A., E.D. Howieson, J.M. Margraf, and R.R. Lee, 1998: Optimizing the WSR-88D MESO/TVS Algorithm using (WATADS) - A case study. *Wea. and Forecasting*. (In press)

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3.6.3 Algorithm Performance During the Jarrell, Texas Event

There are at least three lessons that forecasters can learn from this event. First, the performance of the current Mesocyclone and TVS Algorithms can be improved by lowering several adaptable parameter values. Second, algorithm detections labeled 3-D correlated shear are not necessarily less dangerous than mesocyclone detections. Third, when storm relative velocity products indicate rotation associated with convection having a history of tornadic development in a highly unstable environment, renewed tornadic activity may occur before algorithm confirmation of strong, deep rotation.

Reference

1. Lee R.R., M. Magsig, G. Stumpf, and D. Mitchell, 1998: Performance of Radar Circulation Detection Algorithms: Texas Tornadoes 27 May 1997, Preprints, 16th Conf. on Wea. Analysis and Forecasting, Phoenix, Arizona, Amer. Meteor. Soc.

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3.6.4 Optimizing Build 9 Mesocyclone Algorithm Performance

Tests show that to achieve the best possible performance with the Build 9 Mesocyclone Algorithm (B9MA), only two adaptable parameters need to be modified from their default values: (1) the Threshold Pattern Vector (TPV) adaptable parameter value should be lowered from 10 to 6 and (2) if the Integrated Rotational Strength (IRS) index is applied to reduce false alarms, the Threshold High Shear (THS) value should be lowered from 14.4 h^{-1} to 7.2 h^{-1} and the TPV value should be lowered from 10 to 6. Both of these actions improve B9MA performance over the default baseline configuration. Algorithm improvements using the IRS filter or some other equivalent can not be implemented until WSR-88D software is updated sometime in the future; however, forecasters can lower the TPV adaptable parameter value to improve B9MA performance now.

Forecasters at WSR-88D radar sites have been notified that lowering the TPV adaptable parameter value enables the B9MA to detect previously missed smaller-scale mesocyclones and have been cautioned to expect an increase in the number of false alarms. The algorithm already finds many nontornadic mesocyclones. Anecdotal evidence from forecasters at Minneapolis, Minnesota; Jackson, Mississippi; Sterling, Virginia; Melbourne, Florida; Portland, Oregon; and other sites confirms that reducing the TPV value increases the algorithm's overall performance at the expense of additional false alarms for low-topped convection.

Reference

Lee, R.R., and A. White, 1998: Improvement of the WSR-88D mesocyclone algorithm. Submitted to *Wea. and Forecasting*

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3.6.5 Status of the Terrain-Based Hybrid Scan

Terrain-based Precipitation Processing Subsystem (PPS) Hybrid Scan files have been installed for operational evaluation at five sites in the contiguous United States (KBHX - Eureka, California; KMTX - Salt Lake City, Utah; KCCX - State College, Pennsylvania; KGSP - Greer, South Carolina; and KFCX - Blacksburg, Virginia) and at six Alaskan sites (PAPD - Fairbanks, PAKC - King Salmon, PAHG - Anchorage/Kenai, PABC - Bethel, PAEC - Nome, and PAIH - Middleton Island). As expected, these files have significantly mitigated the concentric circular artifacts that had been caused by the original Hybrid Scan files, particularly during stratiform and orographic rain events. The terrain-based Hybrid Scan files have made the PPS products more representative of the actual precipitation field. Based on the positive results of the field evaluation, the OSF is planning to generate and distribute terrain-based Hybrid Scan files to all sites, hopefully by the end of the summer.

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Reference

1. O'Bannon, T., 1997: Using a "terrain-based" hybrid scan to improve WSR-88D precipitation estimates. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 506-507.

3.6.6 Test of an Anomalous Propagation Recognizer in an Off-Line PPS Algorithm

Investigation has begun of a new procedure to replace the internal PPS Tilt Test for removing clutter contamination caused by anomalous propagation (AP). The Tilt Test, which compares the decrease in rainfall area between the lowest tilt and the second tilt, can cause serious errors in the precipitation estimates. If the decrease exceeds a threshold (default value 75%), the lowest tilt is rejected by the algorithm. This procedure functions reasonably well with extensive AP under "clear air" conditions but can severely impact precipitation estimates when AP and precipitation are observed.

Under contract with the OSF, the National Center for Atmospheric Research (NCAR) is developing an AP Recognizer with the goal of assisting radar operators in making clutter filtering decisions. The technique uses a set of fuzzy logic relationships to determine the likelihood that individual radar data bins are contaminated with AP. The statistical information (reflectivity texture, mean velocity, velocity texture, and mean spectrum width) is derived from realtime radar data. Preliminary evaluation of the AP Recognizer shows good and consistent discrimination between clutter and meteorological targets. Plans call for inserting the AP Recognizer logic into an off-line version of the PPS software for comparison with the PPS Tilt Test clutter removal system.

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3.6.7 Sensitivity of the NSSL Tornado Detection Algorithm to Missing Data

The Operational Support Facility (OSF) plans to install a new tornado detection algorithm (TDA) developed by scientists at the National Severe Storms Laboratory (NSSL) in the Build 10 software release for the WSR-88D system. Before distribution to kinematic algorithms such as the TDA, velocity data are dealiased by a velocity dealiasing algorithm (VDA) in the WSR-88D Radar Product Generator. The VDA may, in regions of high azimuthal shear, remove up to four radially contiguous velocity bins that do not conform to the surrounding flow to prevent them from causing large-scale errors in the velocity field. This study compares the performance of the TDA using the "standard" VDA with a version used by NSSL that does not remove any velocity bins. Almost four hours of radar data from 1736 to 2130 UTC on May 11, 1992 from the KTLX WSR-88D were used. On this day, 22 tornadoes were confirmed by damage survey teams. When scored against ground truth, the results show that the NSSL TDA is somewhat insensitive to the version of the VDA used. Using the standard VDA, the TDA found slightly fewer tornado vortex signatures (TVS's) [45 versus 47], missed slightly more TVS's [17 versus 15], but had a lower false alarm rate [22 versus 24 TVS's]. The Critical Success Index, as an overall measure of performance, was only slightly lower [54 versus 55 percent].

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3.7 NOAA/Techniques Development Laboratory/Office of Systems Development

3.7.1 Summary of Recent Algorithm Research and Development

The Techniques Development Laboratory (TDL) Local Applications Branch develops automated techniques for evaluating radar and other data to determine the threat of thunderstorms, severe local storms, and flash flooding. Integration of several algorithms, related products, and procedures into the Advanced Weather Interactive Processing System (AWIPS) is currently being refined and tested.

Efforts during the period October 1996 - September 1997 focused on implementation and testing of realtime versions of the Thunderstorm Product and the 0-1 h quantitative precipitation forecast (QPF) algorithm.

Testing and operational implementation of the Thunderstorm Product is underway. Radar data and lightning strike observations are processed to identify thunderstorms and estimate the probability that thunderstorms will shortly produce severe weather (high surface winds and/or large hail). The thunderstorm identification procedure is based on a decision tree that considers the presence or absence of lightning, vertically-integrated liquid (VIL) in excess of 10 kg m^{-2}, and reflectivity of 40 dBZ or more. The severe weather probabilities are based on VIL, environmental wind velocity, and freezing level height.

The 0-1 h QPF algorithm yields probability forecasts of rainfall exceeding 0.1, 0.25, 0.5, and 0.75 inch at points within a 4 km grid, a categorical rainfall forecast on the same grid, and the probability of rainfall exceeding 1 in anywhere within a 28 km square region centered on convective cells. The forecasts are based on an extrapolative-statistical algorithm calibrated with WSR-88D Stage III gridded rainfall estimates.

Documentation on these algorithms is available on the TDL home page at "http://www.nws.noaa.gov/tdl/". Realtime output from the Sterling, Virginia WSR-88D is also available from this web site.

TDL has undertaken a coordination effort to integrate radar analysis and nowcasting products from the NWS, NSSL, and NCAR within a single platform, called the System for Convection Analysis and Nowcasting (SCAN). The first SCAN prototype was deployed at the Sterling, Virginia last summer. It consists of the NSSL WDSS, the NCAR Thunderstorm Autonowcaster package, and the AWIPS Thunderstorm Product. Forecasters at Sterling have made extensive use of these advanced interpretation systems. Further information is available at http://www.nws.noaa.gov/tdl/scan/scan2.html.

The 0-3 h QPF algorithm is now being refined and tested. This extrapolative-statistical algorithm yields the probability that rainfall will exceed 0.1, 0.5, 1 and 2 inches, at some point within each box of a 40 km grid covering the continental U.S. Input to the algorithm includes a 10 km national-scale radar reflectivity mosaic and upper-air data from operational forecast models. The mosaic is a composite of Radar Coded Messages (RCMs), constructed operationally by NWS Aviation Weather Center. A description of the development methodology was given by Kitzmiller and Sun (1997).

Reference

1. Kitzmiller, D.H., and J. Sun, 1997: Probabilistic 0-3 hour rainfall forecasts from a radar extrapolative-statistical technique. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 216-217.

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3.8 U.S. Naval Research Laboratory

3.8.1 Summary of Year's Activities

Collaborations continued with colleagues at NSSL and the University of Oklahoma/Cooperative Institute for Mesoscale Meteorological Studies on improving the following analysis packages:

1. The variational data analysis algorithm for interpolating raw radar data to a three-dimensional model grid and for filling data holes.

2. Simple adjoint and least-square algorithms for three-dimensional wind retrieval from single-Doppler wind and/or reflectivity data.

An effort has been made to combine the VAD technique with the simple adjoint and least square wind retrieval methods. The retrievals give winds on a high resolution grid, but the area-averaged divergence of the retrieved wind field is dependent on the grid resolution. On the other hand, the VAD-estimated divergence can be quite accurate as shown by our recent study. This suggests that the VAD-derived divergence profiles can be used as an additional constraint to improve the wind field retrievals.

Also, the least squares method has been upgraded to include background wind fields. The modified method has been applied to single-Doppler data collected by the Twin Lakes WSR-88D on 7 May during the 1995 Oklahoma Vortex Field Experiment. The retrieved winds are used together with surface mesonetwork data to improve the initial conditions for short-term predictions with the Advanced Regional Prediction System developed at the University of Oklahoma. Preliminary results are encouraging.

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3.9 Massachusetts Institute of Technology/Lincoln Laboratory

3.9.1 Anomalous Propagation (AP) Clutter Editing

An algorithm has been developed to edit AP ground clutter from NEXRAD composite and layer reflectivity products. The algorithm uses an altitude "floor" at close range whereby all reflectivity range gates below a site adaptable altitude (typically, 1 km) are ignored at close range. At intermediate ranges, reflectivities below a second site adaptable altitude are ignored unless there is velocity and spectrum width data that suggests that the reflectivity value arises from weather (e.g., radial velocities and spectrum widths above a site adaptable threshold which is typically 1 m s^{-1}). At long ranges, the reflectivity values are accepted as valid unless velocity and spectrum width data that suggests that the reflectivity value arises from ground clutter (e.g., radial velocities and spectrum widths below a site adaptable threshold which is typically 1 m s^{-1}).

This algorithm has been scored against normal operational NEXRAD data from Memphis, Tennessee; Ft. Worth, Texas; and Orlando, Florida. Typically, 70% of the AP is edited with about 8% probability of editing valid weather returns. The edited weather is typically low-level stratiform precipitation. [Results of this scoring exercise were reported by Isaminger et al. (1997).] Lincoln researchers are working with the OSF to transition this algorithm to the NEXRAD system for the bottom layer composite reflectivity product as a part of Build 10.

The principal cause of failure in editing AP is reflectivity data with no corresponding radial velocity or spectrum width data due to range folding. Work is underway to use additional discriminants (e.g., texture analysis) to identify ground clutter which has no corresponding velocity/spectrum width measurements. Since the reflectivity range gates that do not have corresponding radial velocity/spectrum width data typically are found in the second or third trip of the velocity data, reflectivity information from adjacent radars may be of assistance in identifying AP (especially when the AP arises due to a convective storm passing near a NEXRAD such that the outflows create a local inversion).

Reference

1. Isaminger, M.A., B.A. Crowe, B.G. Boorman, J.E. Evans, and R.A. Boldi, 1997: Performance Characteristics of an Algorithm Used to Remove Anomalous Propagation from the NEXRAD Data. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer., Meteor. Soc., 317-319.

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3.9.2 Gust Front Detection/Prediction

The Machine Intelligent Gust Front Algorithm (MIGFA) was originally developed for the Terminal

Doppler Weather Radar (TDWR) system and implemented with software written in LISP. A version which accepts NEXRAD data has been tested with very encouraging results. This algorithm is written in "C/C++" as a byproduct of technology transfer for the FAA's Integrated Terminal Weather System (ITWS) and Wind Shear Processor (WSP) systems. Hence, incorporating the MIGFA algorithm into the Open RPG should be relatively straightforward. The TDWR version will run on an Sun Ultra1 workstation in about 1 minute. Plans call for evaluating the NEXRAD MIGFA operationally at a National Weather Service and a Department of Defense site this coming year.

The MIGFA based gust front detection/prediction product would be useful for meeting the NEXRAD technical need for a straight line winds detection/prediction product as well as being useful for:

1. windshear warnings at airports not equipped with an FAA windshear detection system, and

2. predicting the growth of convective storms.

It should be noted that NEXRAD MIGFA has been used in the FAA storm growth/decay research at Memphis with good results. Typical performance is shown in Table 1. PLD is the percentage of gust front length actually detected, and PFD is the proportion of gust fronts lengths that were false.

Table 1. MIGFA Results for TDWR and NEXRAD for Memphis

DATE	PLD (NEXRAD)	PLD (TDWR)	PFD (NEXRAD)	PFD (TDWR)
6 JUNE 1995	25.5	66.7	47.2	29.8
14 JULY 1995	59.9	91.6	21.0	12.8
17 JULY 1995	85.4	91.5	19.4	9.0
17 AUGUST 1995	51.6	93.9	0.3	5.9
19 AUGUST 1995	64.7	91.5	2.9	4.4
7 JULY 1996*	62.8	60.4	13.4	5.2

*Scored for a 60 km radius region around each radar. TDWR had severe second trip contamination on this day. Other cases, scored for identical regions.

The differences shown here between the performance of MIGFA operating on TDWR data versus NEXRAD data principally reflect the higher resolution of the TDWR reflectivity data (0.25 km versus 1 km) and the better ground clutter suppression of the TDWR.

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3.9.3 Cross-Correlation Tracking

A cross correlation tracker has been used to track NEXRAD composite reflectivity storms for the past four years as a part of the Integrated Terminal Weather System (ITWS) system. This tracker has proved effective at handling storm mergers and splits which tend to confuse the current NEXRAD tracker.

The tracker (with some algorithm parameter changes) is being used for the FAA's TDWR, ASR-9 WSP, and ITWS programs. A "C" version of this program has been developed which fully complies with the formal program description language (PDL) designated as part of the ITWS procurement package. Software has been provided to the National Severe Storms Laboratory (NSSL) for use in the NEXRAD severe storms analysis packages.

FAA air traffic controllers also use the tracker's storm extrapolated position option whereby the extrapolated position of the leading edge of the storms is depicted at extrapolation times of 10 and 20 minutes. This permits them to estimate the time at which storms will impact key locations for air system planning (Section 3.9.4).

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3.9.4 Storm Location Predictions

An improved storm tracker/predictor has been developed which provides surprisingly high quality estimates of the location of organized convective cells at prediction times as great as 1 h. This has been achieved through combination of the ITWS/WSP correlation tracker and innovative data smoothing techniques which does a scale separation of the different weather components. Typical performance at predicting the future location of storm reflectivities > 40 dBZ are summarized in Tables 2 and 3.

Table 2. Growth and decay tracker performance on NEXRAD data.

DFW: June 1, 1997

Prediction Times	10	20	30	45	60 Min
Probability of correctly predicting weather with reflectivities > 40 dBZ	80 %	70 %	63 %	53 %	48 %

MEM: July 15, 1997

Prediction Times	10	20	30	45	60 Min
Probability of correctly predicting weather with	87	77	69	60	

reflectivities > 40 dBZ	%	%	%	%	53 %

Table 3. Growth and Decay 60 minute forecast performance on NEXRAD data.

Line Storms Pd (%)		Airmass Storms Pd (%)	
Growth & Decay Tracker	40	Growth & Decay Tracker	18
ITWS Tracker	27	ITWS Tracker	17
% Improvement	+48%	% Improvement	+5%
54 Hours of Data		14 Hours of Data	

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3.10 Colorado State University

3.10.1 Use of Polarimetric Radar Data to Characterize Winter Precipitation

An examination of polarimetric radar data, ground observations, snowgauge data, and disdrometer data collected during a field project conducted from January through April 1997 in Fort Collins, Colorado has begun. Polarimetric radar variables are being correlated with the precipitation type (aggregates, single crystals, snow pellets, etc) as recorded by a ground observer. Once the correlation is established, the information will be utilized to examine radar-derived snowrate algorithms, make comparisons with the snowgauge data, and possibly develop an improved quantitative estimation method based on radar-derived knowledge of the precipitation type.

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3.10.2 Hail Precursor Signatures Observed in Multiparameter Radar Data

CSU-CHILL volume scan data collected during two hail events in Colorado were analyzed. The appearance of a Z_{DR} "hail hole" signature in the lowest elevation angle echo core was taken to mark the onset of hail at the surface. Dual-polarization data fields in the volume scans immediately preceding the onset of hail were then examined. The most prominent hail precursor signature was an enhancement in the Linear Depolarization (LDR) values at subfreezing (approximately -5 to -20C) heights in the echo core. LDR values aloft were found to increase to the -24 to -20 dB range 3 to 6 minutes before hail was first identified at the surface. These LDR enhancements are thought to be due to an increase in surface wetness as the hailstones grow.

Reference

1. Kennedy, P.C., S.A. Rutledge, and V.N. Bringi, 1997: Hail precursor signatures in multiparameter radar data. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 51-52.

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3.10.3 Simultaneous Transmit Tests

First tests of the simultaneous transmit operating mode were conducted. This is similar to the polarization mode planned for the WSR-88D research system in Norman. During these tests, only a single receiver was used. The receiver was alternately switch between the horizontal and vertical channels. This produced the same sequence of data at the copolar receiver that is produced in the alternating VH transmit mode, which simplified the signal processing requirements. This Simultaneous Transmit with Alternating Receivers (STAR mode) does have some practical application in the upgrading of existing radars to multi-polarization operation. Also of interest is the mode where both receivers are processed simultaneously. This requires somewhat greater signal processing capability, but has the advantage of isolating the differential phase ($_{DP}$) measurements from the velocity measurements. It also doubles the unambiguous range of the $_{DP}$ measurements. This mode will be implemented on CSU-CHILL within the next year. Some images from alternating and simultaneous transmit modes are available on the web pages under "Misc. Research in Progress". The results look promising, although there are some artifacts apparently due to crosstalk from depolarization on cases where there is significant hail present.

Reference

1. Brunkow, D.A.,P.C. Kennedy, S.A. Rutledge, V.N. Bringi, and V. Chandrasekar, 1997: CSU-CHILL radar status and comparison of available operating modes. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 43-44.

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3.11 University of Iowa/Institute of Hydraulic Research

3.11.1 Summary of Research Related to WSR-88D Algorithms and Products

The main focus of the research work related to WSR-88D algorithm is the Precipitation Processing System (PPS). We have investigated performance of the mean-field bias adjustment algorithm. The primary tool for this investigation was a data-based Monte Carlo simulation. Several ways to improve the current algorithm were recommended and some of them are being implemented at the NWS Office of Hydrology. This research is described in Anagnostou et al. (1997a).

We have also investigated optimal calibration of the PPS parameters. A global optimization algorithm, which accounts for the parameter interactions, has been implemented. The results show that considerable improvement can be achieved (Anagnostou and Krajewski, 1997a). A new approach for realtime rainfall estimation has been proposed. It performs rainfall estimation in a recursive framework with realtime update of the algorithm parameters by considering the uncertainty in the observations and the Z-R relationship (Anagnostou and Krajewski, 1997b,c).

A fundamental problem in radar rainfall estimation is the quantification of radar accuracy through comparisons with raingauges. The results are misleading if one ignores small-scale variability of rainfall (Ciach and Krajewski, 1997a,b; Anagnostou et al., 1997b). Currently, very little is known about rainfall variability at scales on the order of 10-1000 m. An experimental facility is being established at the University of Iowa to improve this situation (Krajewski et al. 1997).

Another topic of interest is radar data compression and database organization. The objective is to develop techniques for conducting studies on multiple year data. With the current Archive II format this is practically impossible. We have developed approaches that make such large dataset studies feasible (Kruger and Krajewski, 1997). For additional information visit the web site "http://www.iihr.uiowa.edu".

References

1. Anagnostou, E.N., and W.F. Krajewski, 1997a: Calibration of the NEXRAD Precipitation Processing Subsystem. Submitted to *Wea. and Forecasting*.

Abstract

The WSR-88D Precipitation Processing Subsystem (PPS) is a multicomponent rainfall estimation algorithm with a large number of parameters controlling its performance. Currently, the parameter values of the PPS are set based on limited experimental studies and do not account for rainfall regime differences. This translates into potential increase of uncertainty in the system-estimated precipitation products.

We propose to formulate the PPS calibration as a global optimization problem. The parameter values are determined by optimizing a selected criterion at the level of gridded hourly rainfall accumulation products. The criterion is the root mean square difference between the hourly radar-rainfall products and rainfall accumulations from raingauges under the radar umbrella. The main advantages of this approach are: (1) it simultaneously estimates the optimal parameters providing an integral assessment of the algorithm's performance, and (2) it allows for an assessment of the relative importance of the PPS parameters in the full context of rainfall estimation.

The optimization approach is illustrated using two months of Melbourne, Florida WSR-88D radar reflectivity data and the corresponding raingauge rainfall measurements. We show improvements up to 22% with respect to the default system setup. The illustration is complemented by a sensitivity analysis of the PPS to identify the most significant parameters.

2. Anagnostou, E.N., and W.F. Krajewski, 1997b: Real-time radar rainfall estimation: 1. Algorithm formulation. Submitted to *J. Atmos. and Oceanic Tech*.

Abstract

A multicomponent radar-based algorithm for realtime precipitation estimation is developed. The algorithm emphasizes the combined use of weather radar observations and in-situ raingauge rainfall measurements. The temporal and spatial scales of interest are hourly to storm-total accumulations, and areas of 4 km^2 up to approximately 16 km^2. The processing steps include beam-height effect correction, vertical integration, convective-stratiform classification, conversion from radar observables to rainfall rate, range effect correction, and transformation of the estimated rainfall rates from polar coordinates to a Cartesian grid. Additionally, the algorithm applies advection correction at the gridded rainfall rates to minimize the temporal sampling effect, and subsequently aggregates the corrected rainfall rates to hourly, three hours and storm-total accumulations. The system applies different parameter values for convective and stratiform regimes. The calibration of the system is formulated as a global optimization problem, which is solved using the Gauss-Newton adaptive stochastic method. The algorithm is cast in a recursive formulation with parameters adjusted in realtime. Evaluation of the system is based on an extensive dataset from Melbourne, Florida WSR-88D radar site.

3. Anagnostou, E.N., and W.F. Krajewski, 1997c: Real-time radar rainfall estimation: 2. Melbourne, Florida WSR-88D case study. Submitted to *J. Atmos. and Oceanic Tech*.

Abstract

The performance of a realtime radar rainfall estimation algorithm is examined based on an extensive

dataset of volume scan reflectivity and raingauge rainfall measurements from the WSR-88D site in Melbourne, Florida. Radar rainfall estimates are evaluated based on the following radar-raingauge statistics: mean difference (bias), normalized root mean square difference, and correlation coefficient. The spatial-temporal scales of interest are hourly accumulations over 4 km by 4 km grid. First, we demonstrate the convergence properties of our algorithm's adaptive parameter estimation procedure, and conduct sensitivity tests of the system with respect to changes in the parameter values. Second, the major components of our algorithm are compared against the operational WSR-88D Precipitation Processing Subsystem. We show improvements up to 40% resulting from the new parameterization schemes and the realtime calibration procedure. When rainfall classification is included the improvement is higher (up to 50%). We show that correction for rain field advection moderately improves estimation accuracy (up to 20%). Finally, we show that the algorithm can effectively remove range dependent systematic errors in radar observations.

4. Anagnostou, E.N., W.F. Krajewski, D.-J. Seo, and E.R. Johnson, 1997a: Mean-field radar-rainfall bias studies for NEXRAD. *ASCE Journal of Engineering Hydrology*. (in press).

Abstract

Realtime mean radar-rainfall bias adjustment procedures for Next Generation Weather Radars, NEXRAD, are investigated. First, statistical analysis of the mean radar-rainfall bias is performed on a two-year record of radar observations from Tulsa, Oklahoma, WSR-88D radar, and rainfall measurements from a dense raingauge network under the radar umbrella. The analysis performed on two seasons (warm and cold) and three accumulation time-scales (one-, three-, and six-hour) shows strong seasonal effect and range dependence in bias statistics. Second, a data-based Monte Carlo simulation experiment is performed on the same period, to quantify the sampling error of estimated bias for varying raingauge network densities. Simulation results show that: (1) the sampling error decreases proportionally to the square of the raingauge network density, and (2) the sampling error is higher in the warm season. Finally, the performance of three mean radar-rainfall bias estimation and prediction algorithms is investigated. The algorithms are: the NEXRAD precipitation adjustment procedure, the adaptive error parameter technique, and the maximum likelihood autoregressive model. A Monte Carlo simulation experiment based on the Tulsa, Oklahoma, dataset is used to assess the algorithms' error statistics for the two seasons, three accumulation time-scales, and two modes of operation (prediction and update). Results show significant seasonal and time-scale effects.

5. Anagnostou, E.N., W.F. Krajewski, and J.A. Smith, 1997b: Quantification of radar rainfall uncertainty. Submitted to *J. Atmos. and Oceanic Tech*.

Abstract

The most common rainfall measuring sensor for validation of radar rainfall products is the raingauge. However, the high sampling error in raingauge area-rainfall estimates imposes additional noise in the radar-raingauge difference statistics, which should not be interpreted as radar error. A methodology is proposed to quantify the radar rainfall error variance by separating the raingauge sampling error variance from the variance of radar-raingauge ratio. The error in this research is defined as the ratio of the "true" rainfall to the estimated mean-areal rainfall by radar and raingauge. Both radar and raingauge multiplicative errors are assumed to be stochastic variables, log-normally distributed, with zero covariance. Two methods for evaluating the raingauge sampling error variance are described. The methods are based on the spatial correlation and variogram of log-raingauge rainfall, respectively. The proposed procedure emphasizes the range dependence of the radar error variance, and it provides error variance estimates of each radar rainfall product. Two months of radar and raingauge data from the Melbourne, Florida WSR-88D are used to illustrate our method. We concentrate on hourly rainfall accumulations at 2 km and 4 km grid resolutions. Results show that the variance of raingauge sampling error can be up to 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.

6. Ciach, J.G., and W.F. Krajewski, 1997a: On the estimation of radar rainfall error variance. Submitted to *Water Resources Res.*

Abstract

One of the major problems in radar rainfall estimation is the lack of accurate reference data on area-averaged rainfall. Radar-raingauge (R-G) comparisons are commonly used to assess and to validate the radar algorithms, but large differences of the spatial resolution between raingauge and radar measurements prevent any 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 proposed, discussed, and demonstrated. If applied to a sufficiently large sample, it allows to estimate the radar error part and to describe the uncertainties of hydrological radar products in rigorous statistical terms. An extensive dataset is used to illustrate the ESM application. Proportion of the error components in the R-G difference variance is studied as a function of rainfall accumulation time. The intervals from five minutes through four days are considered, and the NEXRAD radar grid resolution of 4×4 km is assumed. The results show that the area-point component is a dominant part of the R-G difference at short timescales, and remains significant even for the four-day accumulations.

7. Ciach, G.J., and W. F. Krajewski, 1997b: Conceptualization of radar-raingauge comparisons under observational uncertainties. Submitted to *J. Atmos. Sci.*

Abstract

An analytically tractable model of radar-raingauge comparison process including measurement errors is developed. It is applied to study properties of different reflectivity-rainfall conversions estimated based on synchronized radar and raingauge data. Three common Z-R adjustment schemes are investigated: direct and reverse nonlinear regression, and the Probability Matching Method. The three techniques result in quite different estimates of the estimated Z-R exponent. All three are also different from the intrinsic exponent of the model and strongly dependent of the uncertainties. This partially explains the diversity of Z-R relationships encountered in the literature. Performance of different Z-R's from the point of view of optimal rainfall prediction from radar data is also compared.

8. Krajewski, W.F., A. Kruger, and V. Nespor, 1997: Experimental and numerical studies of small-scale rainfall measurements and variability. *Preprints, 3rd International Workshop on Rainfall in Urban Areas*, Pontresina, Switzerland.

Abstract

A high-resolution rainfall observatory was established at the Iowa Institute of Hydraulic Research to support studies of small scale rainfall variability. It includes a vertically pointing X-band radar, a two-dimensional video disdrometer, an optical raingauge, a standard tipping bucket raingauge, and high temporal resolution sensors for measurements of wind velocity and direction, temperature, humidity, and pressure. All the instruments are collocated. The observatory is being upgraded to include a Doppler processor for the radar, a mobile platform to enable participation in community-organized hydrometeorological experiments, and a network of about 15 high-resolution raingauges to be installed at a nearby airport. The airport network design includes innovative concepts of dual sensors constituting a single observational point, connected to the same data logger. The observational points are separated with distances ranging from 10-1000 meters. We present comparisons of data collected by the various sensors and discuss implications for radar-rainfall estimation. The capabilities of the experimental setup at IIHR will facilitate numerical studies of rainfall measurements. In particular, we present results of computational fluid dynamics calculations of the measurement error of the video disdrometer based on the high resolution observations of drop size distribution and wind velocity.

9. Kruger, A., and W.F. Krajewski, 1997: Efficient storage of weather radar data. *Software Practice and Experience*, **27**, 623-635.

SUMMARY

The paper documents the development and performance of a radar data compression scheme. The scheme is based on the concept of run length coding but contains several other features which make it very efficient in both storage and readtime performance. The scheme is compared to several other popular data compression methods.

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3.12 McGill University

3.12.1 Wind Retrievals and the McGill Bistatic System

A bistatic multiple-Doppler radar network has been recently implemented at the J. S. Marshall Radar Observatory (MRO) of McGill University in collaboration with the University of Oklahoma and NCAR. The network consists of the S-band McGill Doppler radar, located 30 km west of downtown Montreal, and two bistatic receivers (Wurman et al. 1995), located 40 km southeast and 25 km northeast of the McGill radar site. The locations of the passive receivers were chosen to give triple-Doppler coverage around the Dorval airport (15 km east of the radar). The problems of intermittent failures due to software crashes at the remote sites are now completely solved, and the synchronization of the different receivers has been achieved. The bistatic data have also been integrated into the McGill Rapid data Analysis, Processing and Interactive Display system (Kilambi et al. 1997).

Broad objectives linked to the deployment of the bistatic network are to provide operational nowcasting products to the Dorval airport and to address the crucial scientific issues of mesoscale model initialization and data assimilation. The first step was to obtain the most accurate "realtime" estimate of the three-dimensional wind field. What we mean here by "real time" is a time less than that required by the Doppler radar to complete one volumetric scan (5 minutes). This goal has been achieved. The method developed is a semi-adjoint technique (see Laroche and Zawadzki 1994) that uses the bistatic network measurements and the continuity equation as a constraint (Protat and Zawadzki 1997). A unique feature of a bistatic network is that all radial velocity measurements from individual resolution volumes are collected simultaneously, which enables minimization of errors due to local evolution of the sampled weather situations. Hence, in the proposed method, linear time interpolation of the measurements to a single reference time is used to take advantage of this simultaneity of measurements. The results obtained in a variety of weather situations (snow storms, hailstorms, and stratiform precipitation) indicate that the method provides an accurate description of the airflow. As a next step, we will soon implement a realtime procedure for retrieving the thermodynamic variables (pressure and temperature) and initializing a mesoscale model.

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3.12.2 Wind Retrieval from Single-Doppler Radar Data

During the past few years, a three-dimensional wind retrieval algorithm has been developed and run semi-operationally at the J.S. Marshall Radar Observatory (Laroche and Zawadzki 1994). Results were less than satisfactory. Consequently, an analytical study of the retrieval problem was performed. It was concluded that differences between the retrieved and actual wind fields were due to the following factors:

1) The approximations made in the physical description of the phenomena are not accurate enough (e.g.,

difficulties in parameterizing the source term in the conservation equation of precipitation content),

2) The mathematical solution to the system of equations is not unique (wind fields different from the actual one can produce the observed time evolution of the data),

3) The numerical discretization of the equations introduces spurious solutions (effects similar to those encountered with many numerical models),

4) The minimization procedure does not find an absolute minimum (most methods for minimizing cost functions with many variables are not able to distinguish between local and absolute minima).

Until now, the effort for understanding and reducing these errors has focused mainly on the first three, giving special attention to the second. As a result several changes in the algorithm formulation [originally described by Laroche and Zawadzki (1994)] have been made. Comparisons with actual data obtained by the McGill/University of Oklahoma/NCAR bistatic network are very encouraging, although more effort is needed to assess the usefulness of this algorithm as an operational tool.

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3.12.3 The Use of VAD Analysis and Synthetic Dual-Doppler to Calculate a Cubic Approximation to the 2-D Wind Field

In using the VAD analysis to obtain a two-dimensional wind field, the common assumption has been that of linearity. However as shown by Caya and Zawadzki (1992), when the VAD is applied to a non-linear wind field, the VAD coefficients no longer correspond to the kinematic properties. This could cause significant errors in the retrieval. The goal of this research is to utilize the behavior of the VAD when applied to non-linear wind fields so as to obtain a better approximation. We chose a cubic expansion of a two-dimensional Taylor series to represent the u and v components of the 2-D wind. A cubic formulation is the simplest wind field that will allow for structure in the derivative fields and provide a reasonable approximation to the observed behavior of the VAD in some stratiform snow cases.

The basic idea of the calculation is to first determine the relationship between the VAD coefficients and the Taylor series derivatives. When this is done, we obtain a number of equations so that we may solve for the derivatives. However, the VAD analysis at one given time is not enough, so we also obtain similar relations from a time series of the kinematic properties over the radar. Then we calculate a quadratic wind field, in a manner similar to that of Scialom and Lemaitre (1994). In order to close the system of equations for the cubic wind field, we will use a fit to winds obtained from synthetic Doppler radar, then compare the results to those measured by the bistatic system. It is hoped that the methodology will provide a more robust way of determining 2-D winds for stratiform events than current VAD-based procedures.

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1. Caya, D., and I. Zawadzki, 1992: VAD analysis of nonlinear wind fields. *J. Atmos. Oceanic. Tech.*, **9**, 575-587.

2. Kilambi, A., A. Bellon, A. Singh, I. Zawadzki, C. Pagé, and F. Fabry, 1997: RAPID: A radar data analysis, processing and interactive display system. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 220-221.

3. Laroche, S., and I. Zawadzki, 1994: A variational analysis method for retrieval of three-dimensional wind field from single-Doppler radar data. *J. Atmos. Sci.*, **51**, 2664-2682.

4. Protat, A., and I. Zawadzki, 1997: A semi-adjoint method for real-time retrieval of three-dimensional wind field from multiple-doppler bistatic radar network data. To be submitted to *J. Atmos. Oceanic Technol.*

5. Scialom, G., and Y. Lemaitre, 1994: QVAD: A method to obtain quadratic winds from conical scans by a Doppler weather radar network. *J. Atmos. Sci.*, **43**, 356-377.

6. Wurman, J., M. Randall, and C. Burghart, 1995: Real-time vector winds from a bistatic Doppler radar network. *Preprints, 27th Conf. Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 725-727.

3.13 University of Oklahoma/Center for Analysis and Prediction of Storms

3.13.1 Overview of WSR-88D-Targeted Research

CAPS research and operational testing with WSR-88D data includes: 1) wind analysis over broad areas using WSR-88D data in combination with winds from forecast models, wind profilers, and surface stations, and 2) derivation of cross-beam wind components from a sequence of single-Doppler radar volumes (termed single-Doppler velocity retrieval or SDVR) and retrieval of thermodynamic variables from a sequence of wind analyses. Doppler radar is the primary data source.

Although CAPS is not involved in research on algorithms within the WSR-88D system, CAPS uses the radar data. The work is potentially affected by changes in quality control, scan strategies, clutter suppression, and any velocity/range unfolding algorithm that might be implemented. CAPS also has interest in developing and/or using schemes to compress the data for efficient realtime transmission.

3.13.2 Model Initialization

CAPS has developed a program to combine radar reflectivity and velocity information from the WSR-88D in realtime, archived Level-II, or NIDS datastreams with other mesoscale data to produce gridded analyses. These analyses are used for nowcasting and to initialize the CAPS Advanced Regional Prediction System (ARPS) non-hydrostatic forecast model. The program, called ADAS (ARPS Data Analysis System; Brewster, 1996) uses the Bratseth analysis technique and a Cartesian radar remapping program developed from a similar program for the Local Analysis and Prediction System of the Forecast Systems Laboratory. Separately, we have adapted the LAPS cloud analysis scheme for the ARPS model coordinate system (a relocatable sigma-z system). The cloud analysis uses data from surface stations and satellite as well as remapped WSR-88D data. In the past year, provisions for latent heat forcing and a number of other enhancements have been developed (Zhang et al. 1998; Zhang and Carr 1998).

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3.13.3 Data Compression

To fill a need for transmitting complete Level II WSR-88D radar data in real time over point-to-point networks, CAPS has developed data compression software. Data from the NSSL RIDDS data buffer are compressed in real time creating files with typical compression ratios of ten-to-one. Because the compression rate is dependent on reflectivity coverage, it was tested on what may be a worst-case scenario represented by Hurricane Opal. In that case, the least compression was five-to-one, with the largest one-volume file being 2.5 Mbytes. The software also includes commands to ship the data to an internet-addressable directory at the time of file-writing, and a library for on-the-fly uncompressing of the files using NSSL "a2io" subroutine calls. Documentation (Ali and Brewster, 1997) is available from CAPS.

3.13.4 Single-Doppler Velocity Retrieval (SDVR)

SDVR research involves the development and testing of new wind retrieval schemes. CAPS-developed schemes include 1) simple adjoint methods applied to radial winds (Xu et al., 1995), 2) conservation of conserved scalars (Shapiro et al., 1995, 1997), and 3) conservation in a moving reference frame (Zhang and Gal-Chen, 1996). Data from research radars covering several different scenarios were used in the development and testing. These cases include a microburst, quiescent boundary layer, multicell convection, a squall line, and a supercell thunderstorm. Using high temporal resolution data from a research radar, Xu et al. demonstrated that rapid scanning (frequent data availability) was essential for successful single-Doppler velocity retrieval. The Shapiro et al. (1995) scheme has been run in real time with WSR-88D data (from KTLX) from the 1996 CAPS spring operation period (SOP96). The Shapiro et al. (1996, 1997) and Xu et al. techniques were both run in research mode with KTLX data from 7 May 1996, a squall line dataset for which dual-Doppler data were available for validation.

Thermodynamic data retrieval involves applying the techniques originally put forward by Gal Chen (1978) to the ARPS model using input from a time-sequence of SDVR wind analyses. Like the SDVR techniques, the thermodynamic retrieval supplies data to the ARPS model initialization package. This scheme has been run with both research Doppler radar data and WSR-88D radar data, though, quantitative validations are difficult.

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3.14 Princeton University, Department of Civil Engineering and Operations Research

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

A major focus of the research group at Princeton University is on the hydrometeorological assessment of the NEXRAD rainfall algorithms. This 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 case studies is two-fold: 1) to illustrate 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 the ground. The focus is on range effects, brightband contamination, issues related to Z-R relationships, testing of different elements of the NEXRAD Precipitation Processing System, and the application of hail thresholds. The quality control of radar data, especially the automated identification of anomalous propagation signals in radar echo patterns, is emphasized. Climatological studies are conducted to investigate regional characteristics of the rainfall and hydrometeorological environment.

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3.15 Texas A&M University

3.15.1 Development and Evaluation of a Multi-Sensor Algorithm for the Detection and Prediction of Damaging Winds

Texas A&M has entered into a collaborative study with NSSL and the Houston WSO to evaluate the current version of the NSSL Damaging Downburst Prediction and Detection Algorithm (DDPDA) in a semi-tropical environment. Data from the Houston WSR-88D, from the Lake Charles WSR-88D (where it overlaps with the Houston WSR-88D), and the Texas A&M 10 cm wavelength Aggie Doppler radar are being used. The study will also investigate the utility of incorporating sounding and cloud-to-ground lightning information into the algorithm.

During May-June 1997, a dual-Doppler and atmospheric sounding "validation" dataset was collected as part of the Texas A&M Convection and Lightning experiment (TEXACAL 97). Several severe straight-line wind events were documented within range of the dual-Doppler network which consisted of the Aggie Doppler radar and the NOAA TOGA C-band Doppler radar on loan from NASA and deployed 40 km from the Aggie radar. This information and the WSR-88D data are the basis for the DDPDA study. The project has just begun and has an initial commitment for two years.

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3.16 Global Hydrology and Climate Center

3.16.1 Tropical Cyclone Tornadoes

Scientists at the Global Hydrology and Climate Center continue to analyze WSR-88D data from tropical cyclone tornado events. Time-height analyses have been completed for three tornadic mini-supercells that produced a total of 15 tornadoes, some F-3 in damage intensity, during the passage of Tropical Storm Beryl through South Carolina on 16 August 1994. The analyses present contours of mesocyclone rotational velocity, rotational shear, mesocyclone diameter and range in the time-height plane, accompanied by time series plots of echo top height, vertically integrated liquid, and cloud-to-ground lightning flashes during each volume scan of the radar. Tornado reports are also plotted.

The data indicate that tornado occurrences are almost always accompanied by increases in mesocyclone rotation rate, but not all increases in radar-derived rotation lead to tornadoes. Mesocyclone vorticity occasionally reaches values as large as 0.06 s^{-1}, although between tornadoes, values are characteristically 0.005 s^{-1}. The latter figure is also often encountered as the mini-supercells move beyond 100 km from the radar, regardless of the presence of intense tornado activity at the surface. Mesocyclone diameters are usually 2-4 km, and storm tops are generally less than 11 km, with occasional pulses to 13-14 km. Lightning rates are modest, seldom exceeding 10 flashes per volume scan interval and often showing no activity. Three of 12 tornadic storms in South Carolina on 16 August 1994 failed to produce any lightning, while the most active mini-supercell produced 310 flashes during its 9 h lifetime. Another supercell produced tornadoes for 6.5 h, and was identifiable on radar for a full 11 h, although it may have been non-supercellular for a portion of its lifetime. A manuscript, "Doppler radar and lightning network observations of a major outbreak of tropical cyclone tornadoes," is being prepared.

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3.17 Atmospheric Environment Service/Environment Canada

3.17.1 Descending Core Algorithm

The convergence (radial shear) profiles within severe thunderstorms have been examined with respect to the descent rate of storm reflectivity cores. An increase of convergence with height preceded a rapid drop of the reflectivity core. About 86% of all damage reports--not just microbursts--coincided with the arrival of a strong reflectivity core at the surface.

Reference

1. Li, L., and P. Joe, 1997: Descending reflectivity cores and the onset of severe weather. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 573-574.

3.17.2 Radar Echo Classification by Modified Environmental Soundings

The concept is to "preload" a nowcasting system with the expected radar echo (storm type) determined by environmental soundings, to monitor the development of radar echoes with an automated classifier (not yet built), and to provide warning to forecasters of conceptualized storm types. Among stability criteria examined, the CAPE, bulk Richardson number, shear terms, and energy helicity index showed skill in "predicting" storm type. For example, approximately 94% of the severe weather events had positive energy helicity indices.

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1. Xin, L., N. Donaldson, P. Joe, 1997: Severe weather soundings and radar storm classification. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 471-472.

3.17.3 Automated BWER Identification Algorithm

Built as part of a Radar Decision Support System, the algorithm searches for BWER's and automatically draws cross-sections.

Reference

1. Keck, A., and L. Legal, 1997: A radar decision support system for the automated recognition of summer severe weather features. *Preprints, 18th Conf. on Severe Local Storms*, San Francisco, Amer. Meteor. Soc., 609-612.

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3.18 North Dakota Atmospheric Resource Board

3.18.1 Ground-Truthing of WSR-88D Convective Precipitation Estimates

Storm-total integrated precipitation amounts obtained with the Bismark WSR-88D (KBIS) Archive IV data have been compared to total precipitation amounts recorded by observers in the Atmospheric Resource Board Cooperative Observer Network (ARBCON) for five convective storm situations. [The ARBCON gauges are post-mounted Tru-Check^{TM} "wedge" gauges of 165 mm (6.5 in) capacity, read once daily at approximately 0800 LDT, and are unshielded.] The WSR-88D algorithm employed is that contained within Build 8.

Initial intercomparisons of convective precipitation measured by the ARBCON and estimated by the WSR-88D indicate considerable radar utility for quantifying convective precipitation. While in many cases the agreement was quite good, disagreements are occasionally very significant. When data from all five cases are combined, the scatter is significant. Overall, the WSR-88D overestimated the actual precipitation by 11%. All differences greater than 2 inches occurred at ranges greater than 115 nm. With two exceptions, all differences of one inch or greater were observed at ranges greater than 55 nm.

Factors identified as contributing to the discrepancies include hail contamination, gauge siting errors, differences in sampling volumes, strong reflectivity gradients, attenuation, and the methodology employed whereby Archive IV graphical products were compared to precise point gauge readings.

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3.19 Swiss Federal Institute of Technology (ETH)

3.19.1 Overview

Radar research at ETH is conducted under the auspices of the "Mesoscale Alpine Programme" (MAP), an international research initiative devoted to the study of atmospheric and hydrological processes over mountainous terrain (Binder and Schaer 1996). Current activities aim to develop improved radar algorithms for operational applications.

3.19.2 Nowcasting Heavy Precipitation Over Complex Orography

The tracking radar echoes by correlation (TREC) technique has been extended using a variational constraint to smooth derived motion vectors. The new technique, COTREC (Li et al. 1995), allows objective short-term prediction of precipitation by considering the motion, growth, and decay of echo patterns. A climatology of the growth and decay regions of precipitation has been established for alpine regions (e.g., Li and Schmid 1994). The precipitation systems are being separated into several categories (stratiform, shallow convective, and deep convective), and the relationship between growth and decay regions and orography is being investigated for each type. Preliminary results indicate that such a climatology substantially improves the predictive performance of COTREC.

3.19.3 Dual-Doppler Methods for Operational Applications

The increasing density of weather radars in Europe permits dual-Doppler analyses in specific regions. Most of the radars operate with fixed scanning programs. Hence, algorithms using dual-Doppler data are limited by the general lack of coordination between different radar systems. The following points are especially important:

1. Data storage and quality assessment.

2. Velocity dealiasing.

3. Spatial and temporal interpolation of the data.

4. Considerations about required and reachable resolution and accuracy.

5. Tests of single-Doppler and dual-Doppler retrieval methods.

6. Development of robust techniques for specific applications [e.g., for severe wind detection and forecasting (see Schmid et al. 1997) or for insertion of dual-Doppler wind fields into numerical models].

Research considering these points has recently been initiated.

Early results can be found in Schmid et al. (1998).

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3.20 United Kingdom Meteorological Office

3.20.1 Utility of Doppler Spectral Width for Operational Applications

This research is designed to examine whether measurements of Doppler spectral width offer some potential for operational meteorology. Although Doppler signal processing is becoming increasingly common in European weather radar systems, measurements of the Doppler spectrum width have received comparatively little attention despite the fact that SW is readily available and may convey information of significant meteorological relevance. Being largely a measure of isotropic turbulence, spectral width has the advantage that it is largely independent of viewing angle, although it does also raise considerations as to how possible it is to generalize between the scales at which measurements are made and the scales at which information may be required. Initial work has focused on the analysis of fine resolution data for a series of thunderstorms in southern Germany, collected using the POLDIRAD C-band radar operated by Deutsch Luft und Raumfahrt (DLR), with whom this research is being conducted in collaboration. Estimates of kinetic energy dissipation rates have been derived using techniques similar to those described by Istok and Doviak (1986) and then examined in relation to the storm environment.

Accurately estimating the spectral broadening due to shear across the radar pulse volume does represent a significant problem and impacts estimates of the eddy dissipation rate. As might be expected, shear and turbulence regions are generally collocated, but with turbulent spectral width more sharply delineating shear boundaries. At fine resolution, spectral width exhibits four-dimensional structure and serves as an aid in interpreting airflow within a storm. However, because these features are relatively small scale, this structure is likely to be less apparent at the resolutions more typically used for operational product generation or for less organized convection. There was no evidence that instrument related factors caused significant problems.

While there are some doubts as to the physical accuracy of eddy dissipation rates derived from Doppler spectral width, this is also true of other remotely sensed quantities. In terms of practical application, the question is not so much how accurately a quantity can be measured but whether or not the estimates provide useful information. In many cases, applications will demand a degree of spatial and temporal aggregation to reduce inherent uncertainty. There is no strong case either for or against expressing radar estimates of turbulence in terms of either spectral width or as an eddy dissipation rate. Conversion to an eddy dissipation rate is straightforward, may be more convenient for some applications, has the advantage of volume filtering, but may give a false impression of accuracy. Separation of shear induced spectral broadening significantly increases the processing required, but this will largely be absorbed if there is also a requirement to estimate local winds. For some purposes, it may be sufficient to use relative variations in spectral width directly as an indicator of turbulence.

An intriguing question is whether estimates of turbulence aggregated for some appropriate volume may give an indication as to the likely severity or short-period behavior of individual storm cells. This might be inferred from the results of a study reported by Bohne et al (1995) or from the discussion in Lilly (1986). An attempt is being made to examine this with a conceptual model derived from the Met. Office GANDOLF system (Hand and Conway, 1996) as the basis for an analysis framework. This will serve both as a basis for examining the evolution of areas of high spectral width through the course of a storm event and as an indication as to how Doppler data might be used more effectively in nowcasting models. The work reported here has been funded by the European Union under the COST-75 program.

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3. Lilly, D.K., 1986: The structure, energetics and propagation of rotating convective storms. Part II: Helicity and storm stabilization", J. Atmos. Sci, 43, 126-140.

4. Istok, M.J., and R.J. Doviak, 1986: Analysis of relation between Doppler spectral width and thunderstorm turbulence. *J. Atmos. Sci.*, **43**, 2199-2214.

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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. Conference preprint volumes contain many papers that relate to the topical subjects in this report. Papers specifically mentioned were 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 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 their applications fall into the this category. "High impact" articles are thought to be 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:

Atmospheric Research

Boundary-Layer Meteorology

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 Geophysical Research

Journal of the Atmospheric Sciences

Journal of the Meteorological Society of Japan

Meteorological Applications

Monthly Weather Review

National Weather Digest

Quarterly Journal of the Royal Meteorological Society

Radio Science

Reviews of Geophysics

Signal Processing

Water Resources Research

Weather and Forecasting

13th Conference on Hydrology

28th Conference on Radar Meteorology

Papers Reviewed

Ali-Mehenni, M., and J. Testud, 1997: A new algorithm to correct polarization diversity radar data affected by long path attenuation. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 27-28.

[Moderate impact. Corrections for differential attenuation at horizontal and vertical polarization are made (1) with an iterative, classical power law relationship ($K=aZ^b$) and the differential reflectivity (Z_{DR}) (independent of N_o) and (2) with a model of the form $Z_{DR}=f(Z_H,N_o)$. The latter method yields both an improved Z_{DR} estimate and the parameter N_o. Potentially, the combination could produce more accurate rainrate estimates.]

Amburn, S.A., and P.L. Wolf, 1997: VIL density as a hail indicator. *Wea. and Forecasting*, **12**, 473-478.

[Moderate impact, could result in improved hail detection. Forecasters often use vertically integrated liquid water (VIL) as an indicator of hail threat and size. Threshold values for hail occurrence vary according to airmass characteristics. Tall thunderstorms with large VIL frequently do not produce large hail; while on other days, large hail may associate with short thunderstorms having low VIL's. The authors seek to "normalize" the VIL parameter by computing a "VIL density", defined as the VIL value divided by the storm height. Results show that the frequency of large hail (19 mm) increased for VIL densities 3.5 g m^{-3}. This threshold correctly identified 90% of the severe hail events. The VIL density is thought to have advantages over VIL for storms close to the radar that are not topped by the volume coverage pattern.]

Andreas, E.L., and G. Treviño, 1997: Using wavelets to detect trends. *J. Atmos. and Oceanic Tech.*, **14**, 554-564.

[Low impact, feature detection. Wavelet techniques are described for removing first and second order trends from datastreams. Compared to a least squares approach, wavelets are less efficient at determining the coefficients of the trend polynomial. The advantage with wavelets is that fewer computations are required to compute the coefficients. Techniques are also presented for determining when trends are important and for removing them.]

Archibald, E., and P. Hardaker, 1997: On the physical interpretation and application of Doppler spectral width. Part II Meteorological aspects of Doppler spectral broadening. Final Rep. for COST-75 Study Contract No.IC13-CT-95-0102-GB, 26pp.

[Moderate impact, spectrum width applications. The report emphasizes the estimation of turbulence for aviation. The authors note that it may be possible to determine storm stability from radar-estimated dissipation rates. Because precipitation growth by collision is determined in part by turbulence, it is also possible that drop-size distributions respond to turbulence. Spectrum width may have application for the detection of gust fronts that are aligned along radials. Other studies cited in the report have found persistent features in spectrum width measurements which correlate with storm updrafts.]

Asuma, Y., K. Kikuchu, and H. Uyeda, 1997: Organizations and the interior characteristics of winter monsoon clouds by dual-polarization Doppler radar observation in Hokuriku, Japan. *Atmos. Res.*, **43**, 297-314.

[Moderate impact, polarimetric radar application. Distributions of snowflakes, graupel, and raindrops are determined from differential reflectivity measurements within winter storms. The Z_{DR} parameter readily showed the melting layer. Periods of strong electric fields correlated with low Z_{DR} values above the melting layer suggesting that the non-inductive charging, due to collisions between graupel and ice particles, was taking place.]

Aydin, K., and C. Tang, 1997: Millimeter wave radar scattering from model ice crystal distributions. *IEEE Transactions on Geoscience and Remote Sensing*, **35**, 140-146.

[Low impact, simulation of polarimetric signals for different particle types. Calculations are performed at millimeter wavelengths for gamma distributions of hexagonal columns, hexagonal plates, and stellar crystals. Parameters investigated include radar reflectivity, differential reflectivity, linear depolarization ratio, co-polarized cross-correlation coefficient, the dual-frequency ratio (220 GHz versus 94 GHz), and specific differential phase. Columns can be discriminated from plates and stellar crystals either by making measurements at vertical incidence or by establishing trends in the measurements as the antenna elevation angle increases.]

Baeck, M.L., J.A. Smith, and M. Steiner, 1997: Sampling features of NEXRAD precipitation estimates. *Preprints, 13th Conf. on Hydro.*, Long Beach, California, Amer. Meteor. Soc., j119-j122.

[High impact. Precipitation estimates made with the precipitation processing system (PPS) are shown to have significant range bias errors. A relative maximum in rainfall between 50 and 100 km (depending on season) is attributed to brightband contamination and biscan maximization. The data also show a tendency to severely underestimate winter rainfalls. Differences between radars are attributed to system calibration problems.]

Bauer-Messmer, B., and A. Waldvogel, 1997: Satellite data based detection and prediction of hail. *Atmos. Res.*, **43**, 217-231.

[Low impact. In order to lengthen the prediction times for hail events detected with radar, a predictive scheme incorporating visual satellite images to determine cloud depth and infrared measurements to estimate cloud heights was developed. The scheme readily detected hail storms (POD's were near 100% for severe hailstorms) but had high false alarm rates (~80%). Additional criteria, e.g., areal thresholds and stability indices produced only small reductions in the FAR's.]

Bentley, M.L., and S.R. Cooper, 1997: The 8 and 9 July 1993 Nebraska Derecho: An observational study and comparison to the climatology of related mesoscale convective systems. *Wea. and Forecasting*, **12**, 678-688.

[Low impact, observational study using WSR-88D images. This nocturnal storm produced five tornadoes and strong winds over a 800 km damage path. Features included a line echo wave pattern and weak echo notches to the rear of the convection. The latter were associated with strong winds.]

Billet, J., M. DeLisi, and B.G. Smith, 1997: Use of regression techniques to predict hail size and the probability of large hail. *Wea. and Forecasting*, **12**, 154-164.

[Moderate impact. Hail size and the probability of large hail are "predicted" from a set of independent variables that include the VIL, the 850-hPa temperature, the freezing level, and the mean storm-relative wind in the lowest 2 km of the atmosphere. Tests revealed little success in predicting hail stone size but showed some skill in determining the probability of severe hail.]

Blanchet, I., C. Frankignoul, and M.A. Cane, 1997: A comparison of adaptive Kalman filters for a tropical Pacific ocean model. *Mon. Wea. Rev.*, **125**, 40-58.

[Low impact. The Kalman filter is combined with several adaptive filters in a wind driven ocean model. The adaptive filters are used to estimate the noise in the forecast system. An empirical estimator that yields both the system error and the model bias worked best.]

Bluestein, H.B., S.G. Gaddy, and D.C. Dowell, 1997: Doppler radar observations of substorm-scale vortices in a supercell. *Mon. Wea. Rev.*, **125**, 1046-1059.

[Low impact, observational study. Two counter-rotating vortices separated by 1 km and having diameters of 500 m were observed along a gustfront produced by a supercell thunderstorm. Both vortices coincided with small hook echoes. A nearby WSR-88D did not indicate the presence of a low-level mesocyclone when the vortices were first detected with a research radar. Because the non-tornadic circulations were opposite in sign it was hypothesized that the vortices were generated by the tilting of ambient horizontal vorticity rather than by amplification of shear along the outflow boundary.]

Blyth, A.M., R.E. Benestad, P.R. Krehbiel, and J. Latham, 1997: Observations of supercooled raindrops in New Mexico summertime cumuli. *J. Atmos. Sci.*, **54**, 569-575.

[Low impact, polarimetric radar application. Vertical cross-sections of radar reflectivity and differential reflectivity are presented for short-lived cumulus clouds. An elevated region of high Z_{DR} in one cell suggested that supercooled waterdrops extended to altitudes where temperatures were -13C. A second reflectivity maximum that formed within the cloud did not have an associated Z_{DR} column and was thought to have grown at the expense of the supercooled water in the first cell.]

Borga, M., E.N. Anagnostou, and W. Krajewski, 1997: A simulation approach for validation of a brightband correction method. *J. Appl. Meteor.*, **36**, 1507-1518.

[High impact, a potential technique for mitigating brightband effects. Brightbands can cause a severe overestimate of rainfall which must be compensated for if the estimates are inserted into hydrologic models or serve as the basis for flash flood warnings. Simulated three-dimensional reflectivity distributions derived from statistics of observed profiles and a simple model of melting layer processes are combined with a previously described algorithm to identify and correct contaminated reflectivity profiles. Tests compare results at S and C-band and examine the effects of range and freezing level height. The retrieval method significantly improved the reflectivity profiles, especially for low melting layers (short radar ranges).]

Briggs, W.M., and R.A. Levine, 1997: Wavelets and field forecast verification. *Mon. Wea. Rev.*, **125**, 1329-1341.

[Low impact, analysis technique. The paper reviews the theory of wavelets, methods of transform selection, and describes parameters for comparing gridded fields at different scales. The use of wavelets for verification has advantages over single value scores (e.g., correlation coefficients and root mean square errors) where the values at neighboring grid points are usually correlated. In an example with forecast and observed 500-hPa fields, the wavelet technique is used to decompose the fields according to scale and display field differences in two dimensions.]

Bringi, V.N., K. Knupp, A. Detwiler, L. Liu, I.J. Caylor, and R.A. Black, 1997: Evolution of a Florida thunderstorm during the Convection and Precipitation/Electrification Experiment: The case of 9 August 1991. *Mon. Wea. Rev.*, **125**, 2131-2160.

[Moderate impact, exploitation of dual-polarization measurements. The kinematic and microphysical properties of convective cells within a storm complex are examined with radar and aircraft observations. Microphysical properties derived with polarimetric measurements are compared to in situ observations. Of particular interest are liquid water concentrations within storm updrafts which extend well above the freezing level. The supercooled droplets associate with distinctive columns in the Z_{DR} measurements. An increase in linear depolarization ratios signaled the freezing of the droplets. Lightning activity followed glaciation by ~5 min. Applications suggested by the study include particle type discrimination in thunderstorms, the detection of supercooled water and icing locations within convective storms, and a possible method for predicting the onset of lightning.]

Buarque, S.R., and H. Sauvageot, 1997: The estimation of rainfall in the Sahelian squall line by the area-threshold method. *Atmos. Res.*, **43**, 207-216.

[Low impact. A test of the area-threshold method, which relates the average precipitation rate in a region to the fractional area with precipitation above a specified rainrate, was made for squall lines and their trailing stratiform rain regions. Optimum relations for the convective and stratiform rains had significantly different proportionality constants and rainrate thresholds.]

Bucci, N.J., H.S. Owen, K.A. Woodward, and C.M. Hawes, 1997: Validation of pulse compression techniques for meteorological functions. *IEEE Transactions on Geoscience and Remote Sensing*, **35**, 507-523.

[Low impact, information. The paper addresses pulse compression issues caused by range sidelobes and the corruption of weak signals that stems from the sidelobes. The study represents further testing of a patented procedure (Doppler Tolerant Range Sidelobe Suppression or DTRSLS technique) previously demonstrated by simulation. Both Barker coded and simple pulses were processed for comparison. Ground clutter was removed with adaptable filters. Results show excellent agreement with theory for compressed (coded) reflectivities, velocities, and spectrum widths even in the presence of large reflectivity gradients. In one case with strong reflectivity gradients adjacent to low signal-to-noise values, the Barker velocity estimates were better than those from simple pulses.]

Burlando, P., A. Montanari, and R. Ranzi, 1996: Forecasting of storm rainfall by combined use of radar, rain gages and linear models. *Atmos. Res.*, **42**, 199-216.

[Moderate impact. Radar-derived storm motion vectors are used to identify gauge observations that correlate with rainfall at "down wind" locations. The time history of gauge observations at a particular site and an upwind "leader" gauge are then weighted with a statistical model to yield 1 h rainfall forecasts. This combination outperforms are simple forecast models based on gauge or radar data alone.]

Carey, L.D., S.A. Rutledge, and T.D. Keenan, 1997: Correction of attenuation at S- and C-band using differential propagation phase. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 25-26.

[Moderate impact. A method for correcting attenuation effects on differential reflectivity and linear depolarization ratio is detailed. The basis for the adjustment is the nearly linear relationships between K_{DP} and attenuation and between K_{DP} and differential attenuation. Attenuation corrections for Z_H are based on the slope of the relationship between the observed Z_H and $_{DP}$. Corrections for differential reflectivity are computed similarly. An important assumption is that the variations in the intrinsic (unattenuated) values of Z_H and Z_{DR} are small. This is achieved by careful editing to ensure a homogeneous data sample.]

Cerro, C., B. Codina, J. Bech, and J. Lorente, 1997: Modeling raindrop size distribution and Z(R) relations in the western Mediterranean area. *J. Appl. Meteor.*, **36**, 1470-1479.

[Low impact. Thirty-second measurements of drop-size distributions and terminal velocities were obtained with an optical disdrometer. The measurements were fitted to exponential, gamma, and log normal distributions to find relationships between rainfall rate and parameters such as reflectivity and liquid water content. Modeled relationships between Z and R for a least squares fit and for exponential, gamma, and log normal models were compared to rainrates determined directly from the disdrometer measurements for a number of rainrate intensities. The Z(R) relationship derived from the exponential distribution worked better than other models]

Chandra, M., A.R. Holt, and P.J. Hardaker, 1997: S-matrix measurements of rain and snow in linear H-V basis. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 69-70.

[Moderate impact. Characteristic K_{DP} signatures in stratiform precipitation are found for rain (0.25 km^{-1}), the melting later (1.1 km^{-1}), and the overlaying snow region (0.01 km^{-1}).]

Chapman, D., and K.A. Browning, 1997: Radar observations of wind-shear splitting within evolving atmospheric Kelvin-Helmholtz billows. *Quart. J. Roy. Meteor. Soc.*, **123**, 1433-1439.

[Low impact, phenomena related to turbulence. High resolution radar observations depict the structure and evolution of Kelvin-Helmholtz waves that developed along a warm frontal boundary. The billows were within a zone of strongly veering wind, and their axes were aligned with the mean flow and perpendicular to the shear vector. The wavelength was 4-5 km. RHI's perpendicular to the billows show a spectacular braided pattern. Computed vertical velocities were ± 3 m s^{-1}.]

Ciach, G.J., W.F. Krajewski, E.N. Anagnostou, and M.L. Baeck, 1997: Radar rainfall estimation for ground validation studies of the tropical rainfall measuring mission. *J. Appl. Meteor.*, **36**, 735-747.

[Moderate impact, the paper discusses elements related to the PPS. A procedure to estimate rainfall based on the combination of radar and raingauge observations is described. Rainfall types (stratiform and convective) are determined by comparing reflectivity maxima to local averages of reflectivity. For rainfall estimation the reflectivity values are integrated vertically. Corrections for system and range biases are made. Additional temporal samples are created by advecting radar echoes according to mean storm motion. An attempt to optimize parameters by storm type was not fruitful. A cokriging procedure for estimating daily rainfall bias showed promise.]

Ciach, G.J., W.F. Krajewski, and J.A. Smith, 1997: Comments on "The window probability matching method for rainfall measurements with radar". *J. Appl. Meteor.*, **36**, 243-246. Reply: Daniel Rosenfeld, 247-249.

[Moderate impact, discussion of the WPMM method for estimating rainfall. The paper shows how the PMM and WPMM methods do not differentiate between correlated and uncorrelated distributions of two variables (e.g., radar and gauge rainrates). A functional fit is found whether or not there is a physical relationship. Simulations with uncorrelated data reproduced features found previously by Rosenfeld et al. Rosenfeld asserts that the arguments of Ciach et al. are valid for the PMM but not the WPMM. He performs a simulation with synchronized pairs using disdrometer data. Errors for random pairing are much larger than for the synchronized pairings. Results suggest that the errors in Z-R data are roughly equivalent to a desynchronization between pairs of 5 min.]

Cohn, S.E., 1997: An introduction to estimation theory. *J. Meteor. Soc. Japan*, **75**, 257-288.

[Low impact. The paper attempts to bridge the gap between basic concepts in estimation theory and practical data assimilation problems. The focus is on the theory. Section 4 gives a detailed derivation of the Kalman filter which provides a conditional mean estimate that can be shown to be unique and characterized by minimum variance for problems with Gaussian distributed errors. Applications with linear and non-linear relationships between observations and state variables are given.]

da Silveira, R.B., and A.R. Holt, 1997: A neural network application to discriminate between clutter and precipitation using polarisation information as feature space. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 57-58.

[Low impact. Radar observations from a circularly polarized radar are inserted into a neural network that classifies echoes as weather or clutter. The primary discriminators were the circular depolarization ratio and the degree of polarization. The scheme reportedly works well even for mixed AP and precipitation.]

Delrieu, G., S. Caoudal, and J.D. Creutin, 1997: Feasibility of using mountain return for the correction of ground-based X-band weather radar data. *J. Atmos. Oceanic Tech.*, **14**, 368-385.

[Low impact. The value of X-band radars for estimating rainfall in gaps within a S-band radar network and in hydrologically sensitive areas is investigated. Several tests are conducted in which the attenuation of ground targets at X-band is used to deduce rainfall rates. The procedure combines reflectivity measurements from an elevation angle free of ground targets and attenuation measurements from a low elevation angle. Several procedural configurations were tested. Best results were obtained with a system that considered an initial attenuation, the integrated path attenuation between that point and a more distant mountain, and a radar error term.]

Desrochers, P.R., and F.I. Harris, 1996: Interpretation of mesocyclone vorticity and divergence structure from single-Doppler radar. *J. Appl. Meteor.*, **35**, 2191-2209.

[Moderate impact, warrants more study. The mesocyclonic circulations in severe thunderstorms are approximated with an elliptical model. The model is shown to better represent the details of the flow structure and to provide improved estimates of the mesocyclone strength when circulations are not circular. Inconsistencies in estimates of flow divergence between two radars viewing a mesocyclone were explained by the model. How important the mesocirculation details are to the threat of tornadoes is yet to be demonstrated.]

Dowell, D.C., and H.B. Bluestein, 1997: The Arcadia, Oklahoma, storm of 17 May 1981: Analysis of a supercell during tornadogenesis. *Mon. Wea. Rev.*, **125**, 2562-2582.

[Low impact. Analyses of a tornadic thunderstorm sampled with two Doppler radars and a tall instrumented tower are described. The paper presents dual-Doppler wind fields, a vorticity analysis, and derived pressure fields. Comparison of the radar-derived and the tower measured winds reveals qualitative agreement; however, the Doppler derived winds significantly underestimated the wind speed. Also, the wind shear in the lowest kilometer was not resolved. Discrepancies are thought to stem from different heights of the measurements, differences in point (tower) and volumetric (radar) measurements, differences in how the two datasets were filtered, and ground clutter contamination of the radar data.]

Fabry, F., C. Frush, I. Zawadzki, and A. Kilambi, 1997: On the extraction of near-surface index of refraction using radar phase measurements from ground targets. *J. Atmos. Oceanic Technol.*, **14**, 978-987.

[Moderate impact, important new technology. A procedure for extracting the index of refraction from phase measurements of fixed ground targets is described. The enabling hypothesis is that for fixed ground targets the time for radar signals to reach a target and return is determined only by the index of refraction. The phase of the radar signal serves as a proxy for time. The radar-derived values of index refraction agreed with indices computed from temperature, humidity, and pressure. Examples show the moisture gradient with a front and an increase in surface moisture within a rain area.]

Farina, A., 1997: Linear and non-linear filters for clutter cancellation in radar systems. *Signal Processing*, **59**, 101-112.

[High impact. An optimum linear filter, a linear filter with Chebyshev filtering, and a non-linear filter which weighs several linear filters are compared. Implementation of specific techniques such as the optimum linear filter is hindered by computational requirements. Instead, the author proposes a non-linear combination of linear filters for side lobe repression that gives significant improvement over Chebyshev filtering and approaches the performance of the optimum linear filter but without the computational load.]

Galloway, J., A. Pazmany, J. Mead, R.E. McIntosh, D. Leon, J. French, R. Kelly, and G. Vali, 1997: Detection of ice hydrometeor alignment using an airborne W-band polarimetric radar. *J. Atmos. Oceanic Tech.*, **14**, 3-12.

[Low impact, polarimetric radar application to determine cloud properties at 95-GHz. The differential phase is much larger at W-band than at S-band and is complicated by a backscatter component for particles in the Mie scattering region. Measurements of the magnitude of $_{HV}(0)$ (the correlation between radar reflectivity at horizontal and vertical polarization at zero lag), the phase between the signals, and the linear depolarization ratio were examined for several meteorological examples with the ice phase. The data confirm observations at S-band and the feasibility of using W-band radar for cloud physics studies. Measurements of melting layers reveal signatures for $_{HV}$ and LDR. Minimum values of $_{HV}$ occurred near the center of the melting layer in a situation where radar reflectivity did not show a clear brightband. Measurements for ice needles suggest that the polarimetric measurements may provide information about the degree of particle orientation and composition when a single crystal habit is present.]

Glitto, P., and B. Choy, 1997: A comparison of WSR-88D storm total precipitation performance during two tropical systems following changes to the multiplicative bias and upper reflectivity threshold. *Wea. and Forecasting*, **12**, 459-471.

[Moderate impact. The article begins with a description of the WSR-88D precipitation processing system (PPS) and describes experiences with the Melbourne, Florida WSR-88D which indicate that the PPS underestimates rainfall, particularly with tropical cyclones. Interestingly, the default NEXRAD Z-R relationship was originally developed for convective rains in Miami, Florida (see Woodley and Herndon; JAM 1970). Examination of rainfalls from tropical storm Gordon suggested that the hail adjustment threshold should be 55 dBZ and that the multiplicative bias adjustment be changed from 1.0 to 1.4. Application of these adjustments to tropical storm Jerry resulted in a significant bias reduction (an overestimate of ~15%). The author's conclude that the large number of potential problems with radar estimates of rainfall, e.g., hybrid scan construction, anomalous propagation, and brightbands, precludes application of a single multiplicative bias adjustment.]

Gordon, W.B., 1997: An effect of receiver noise on the measurement of Doppler spectral parameters. *Radio Sci.*, **32**, 1409-1423.

[Low impact. Wind shear and turbulence are expected to produce a linear relationship between spectral width and radar range. However, the paper shows that receiver noise can produce a similar effect. The spurious signal is removed by thresholding according to the maximum spectral value. The linear relationship between spectrum width and range apparently is a consequence of narrow spectra when the variation in reflectivity is small.]

Haddad, Z.S., and D. Rosenfeld, 1997: Optimality of empirical Z-R relations. *Quart. J. Roy. Meteor. Soc.*, **123**, 1283-1293.

[Low impact. The power-law regression and probability matching methods of determining Z-R relationships from reflectivity and rainrate measurements is examined mathematically. The analysis suggests that power law relationships underestimate rainfall rates associated with high radar reflectivities and overestimate rainrates with low reflectivities. The authors conclude that power laws are approximations to optimal relationships when the data are uncategorized as being stratiform or convective; the PMM is optimal when the data are classified a priori so that a one-to-one relationship between Z and R is expected.]

Haddad, Z.S., D.A. Short, S.L. Durden, E. Im, S. Hensley, M.B. Grable, and R.A. Black, 1997a: A new parametrization of the rain drop size distribution. *IEEE Transactions on Geoscience and Remote Sensing*, **35**, 532-539.

[Low impact. Power law relationships for rainfall rate in the tropics are derived from disdrometer measurements whose coefficients are directly related to the shape parameters of the DSD and independent of rainrate. The slope, shape, and intercept terms of the gamma DSD are written in terms of normalized mass-weighed mean drop diameters and the mass-weighed relative rmse spread. The lead author has shown previously that the parameters , μ, and N_o are correlated and inconsistent with operations in which μ and/or N_o are assumed constant and is allowed to vary. Power laws are derived between the normalized parameters R and Z. Testing with radar observations and gauge amounts is not performed.]

Haddad, Z.S., E.A. Smith, C.D. Kummerow, T. Iguchi, M.R. Farrar, S.L. Durden, M. Alves, and W.S. Olson, 1997b: The TRMM 'day 1' radar/radiometer combined rain-profiling algorithm. *J. Meteor. Soc. Japan*, **75**, 799-809.

[Low impact, information only. The proposed methodology seeks to estimate the rain profile with radar reflectivity measurements and to constrain the analysis with the radiometer-derived estimate of the total attenuation. The problem is expressed in terms of drop-size distribution parameters {the rainrate, the mass-weighed mean drop diameter (D"), and the deviation about the mean (s")} (see Haddad et al. 1997a). The last two terms, determined from DSD samples, were previously found to be independent of the rainfall rate and are assumed to be constant. The parameters of the gamma DSD are computed from D", s", and the rainrate (R). A Bayesian approach is used to combine the rainrate determined by radar and the attenuation from the radiometer. An example is presented for a dataset obtained by aircraft.]

Hagemeyer, B.C., 1997: Peninsular Florida tornado outbreaks. *Wea. and Forecasting*, **12**, 399-427.

[Low impact, application. The paper presents a climatology of tornado outbreaks in Florida. Tornado threat for specific storm situations is evaluated in part with WSR-88D derived hodographs.]

Hagen, M., 1997: Identification of ground clutter by polarimetric radar. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 67-68.

[Moderate impact. Ground clutter depolarizes transmitted signals whenever the incident wave induces a field vector which is not parallel to the transmitted wave. LDR values for clutter can be quite large (LDR 0 dB). On the other hand, the orientation of raindrops is nearly horizontal, and LDR is relatively small (< -27 dB). The likelihood that radar signals are due to weather falls off rapidly as LDR increases above -15 dB. Exploiting this property of LDR and applying a despeckling algorithm resulted in a 86% detection probability for clutter echoes.]

Han, Y., E.R. Westwater, and R.A. Ferrare, 1997: Applications of Kalman filtering to derive water vapor profiles from Raman lidar and microwave radiometers. *J. Atmos. and Oceanic Tech.*, **14**, 480-487.

[Low impact, analysis technique. A Kalman filter is applied to a time series of Raman lidar measurements and surface observations. The analysis is constrained by the integrated water vapor and cloud water from the radiometer.]

Howard, K.W., J.J. Gourley, and R.A. Maddox, 1997: Uncertainties in WSR-88D measurements and their impact on monitoring life cycles. *Wea. and Forecasting*, **12**, 166-174.

[High impact, forecaster awareness issue. With a simple model of single-celled storms the limitations of the VCP-11 and VCP-21 scanning modes for determining storm tops and trends are investigated by varying storm durations, distances from the radar, and cell heights. "Errors" in echo height can be on the order of 4 km; estimated trends may differ in sign from actual trends.]

Hsu, K.-L., X. Gao, S. Sorooshian, and H.V. Gupta, 1997: Precipitation estimation from remotely sensed information using artificial neural networks. *J. Appl. Meteor.*, **36**, 1176-1190.

[Moderate impact, concerned with precipitation measurement. The paper describes an application with a neural network to estimate large-scale precipitation with a combination of satellite, radar, and raingauge information. Key components of the network are a self-organizing feature map that automatically discretizes the input and an improved hidden layer-output transformation. The input-hidden and hidden-output transforms can be performed separately. In addition, there is a recursive feature which allows the transformation weights to vary as new information becomes available.]

Jones, C.D., and B. Macpherson, 1997: A latent heat nudging scheme for the assimilation of precipitation data into an operational mesoscale model. *Meteor. Applications*, **4**, 269-277.

[Low impact, application. The paper describes a procedure developed by the Meteorological Office in the United Kingdom for assimilating radar data into a mesoscale numerical model. The scheme scales the latent heat profile from the model according to the heat implied by the radar detected precipitation. Three hours of hourly radar data are projected to the numerical model grid. The weight given the radar observations falls off with increasing range. Corrections are made for differences in forecast and analyzed precipitation rates. In this application the choice of the heating profile shape is based upon a three-dimensional cloud analysis that incorporates surface cloud observations, satellite imagery, and radar data. The scheme improves precipitation forecasts out to ~6 h.]

Kennedy, P.C., S.A. Rutledge, and V.N. Bringi, 1997: Hail precursor signatures observed in multiparameter radar data. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 51-52.

[Moderate impact. The Z_{DR} parameter is of little value for discriminating between rain and hail above the freezing level. The presence of hail can be inferred from high LDR values (> -25 dB) and high reflectivity. The signature stems from the fact that hail tumbles as it falls giving a broad spectrum of orientations. Increases in LDR at temperatures of -11 to -13C were found to precede hail at ground by 6-8 min.]

Kilambi, A., A. Protat, A. Singh, I. Zawadzki, J. Wurman, M. Randall, and C. Burghart, 1997: A bistatic radar system at McGill University. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 45-46.

[High impact, important technology. McGill University has an operational bistatic radar system composed of an S-band radar and two bistatic receivers. The receivers are located 24 km north and 40 km southeast of the primary unit and permit local dual and triple-Doppler analyses. The data are being used to verify single-radar wind retrieval algorithms and for comparison with profiler winds, but they also have import for detecting hazardous wind phenomena such as gust fronts and microbursts.]

Kitchen, M., 1997: Towards improved radar estimates of surface precipitation at long range. *Quart. J. Roy. Meteor. Soc.*, **123**, 145-163.

[High impact, hydrological application. An empirical method for estimating rainfall at ground from measurements above the brightband is described. The method is based on an idealized radar reflectivity profile which is weighted according to measurements at multiple elevation angles above the melting layer. Simulations suggest the correction scheme reduces bias errors by ~64%. However, tests on real data did not show general improvement over previous methods except when the reflectivity profile deviated substantially from climatological averages.]

Kumar, P., and E. Foufoula-Georgiou, 1997: Wavelet analysis for geophysical applications. *Reviews of Geophysics*, **35**, 385-412.

[Low impact, analysis technique. A nice overview of wavelet analysis with beginning references is presented. Topics include a short review of the history of wavelets, parallels with Fourier analysis, and basic principles. Several examples are presented. Of particular interest is an analysis of a mesoscale convective system showing the power of the method for scale decomposition and suggesting an application for stratiform/convective rainfall discrimination.]

Li, L., and S. Sénési, 1997: Properties of the threshold method on a radar rain cluster basis. *J. Appl. Meteor.*, **36**, 1493-1506.

[Low impact. The authors apply the ATI method to individual thunderstorms with areas < 1000 km^2. The particular application did not involve time integration but rather considered single snapshots of storms. High correlations between mean rainfall rates and fractional areal coverage are found for storms as small as 40 km^2. The proportionality factor between mean rainfall rate and areal coverage are found to vary significantly by season.]

Lin, H.-C., L.-L. Wang, and S.-H. Yang, 1997: Fast heuristics for polygonal approximation of a 2D shape boundary. *Signal Processing*, **60**, 235-241

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[Low impact, analysis technique. Algorithms for representing two-dimensional features are described. In one approach, a Gaussian filter is used to smooth the feature boundary and the resulting curvature extrema become the vertices of a polygon representing the feature. Iterations continue until the number of vertices stabilizes. With a second method, the user specifies the compression ratio of the image represented. The advantage with the proposed schemes is a capability to process features composed of different scales.]

Liu, A.K., S. Martin, and R. Kwok, 1997: Tracking of ice edges and ice floes by wavelet analysis of SAR images. *J. Atmos. and Oceanic Tech.*, **14**, 1187-1198.

[Low impact, feature detection. Multiple passes are made with a wavelet shaped by the second derivative of a Gaussian function. Successive passes define greater detail in reconstructed images of polynyas (open leads in ice packs), the edges of ice packs, and ice floes.]

López, R.E., and J.-P. Aubagnac, 1997: The lightning activity of a hailstorm as a function of changes in its microphysical characteristics inferred from polarimetric radar measurements. *J. Geophys. Res.*, **75**, 16799-16813.

[Low impact, polarimetric radar application. Radar reflectivity, differential reflectivity, and specific differential phase measurements form the basis for designating regions of graupel, hail, supercooled water, and rain and for computing mixing ratios of ice and water in a supercell thunderstorm. Derived properties are then related to the evolution of lightning activity within the storm. Graupel production is believed to have initiated electrical activity, but cloud-to-ground discharges were postulated to have been caused by falling hail. The hail is thought to become positively charged through collision with ice crystals and to induce cloud-to-ground discharges from a region of negatively charged graupel held aloft.]

Matsoukas, C., S. Islam, and R. Kothari, 1997: The multisensor fusion of precipitation measurements. *Preprints, 13th Conf. on Hydro.*, Long Beach, California, Amer. Meteor. Soc., j113-j114.

[High impact, hydrological application. The paper describes a neural network approach for estimating rainfall from gauge and radar measurements. In the study, gauges are simulated by taking random data points in the radar field. The network, trained with the "gauges", subsequently produces estimates precipitation at other locations. An advantage of the neural network over distance weighing schemes for estimating precipitation was demonstrated when white noise was added to the data.]

Mead, C.M., 1997: The discrimination between tornadic and nontornadic supercell environments: A

forecasting challenge in the southern United States. *Wea. and Forecasting*, **12**, 379-387.

[Low impact, paper contains information which when combined with radar observations may help forecasters determine tornado threat of observed storms. The empirical study tests findings with numerical models which indicate that the character of the storm relative winds in the 3 to 7 km layer dictate whether or not strong rotation develops at low levels in thunderstorms. The author argues that while parameters such as the storm relative helicity indicate supercell potential, the strength of the storm relative wind is important for determining whether or not tornadoes will form.]

Meischner, P., C. Collier, A. Illingworth, J. Joss, and W. Randeu, 1997: Advanced weather radar systems in Europe: The COST 75 action. *Bull. Amer. Meteor. Soc.*, **78**, 1411-1430.

[Low impact, information on European radar network. COST (Cooperation in Science and Technology) is a European effort to coordinate the development of advanced radar systems. The community operates over 100 radars, 10 of which have polarization diversity. Many have Doppler capability. The paper gives a status report and outlines future plans. Of particular concern are the calibration of radar systems for quantitative measurement, adjustment of rainfall estimates with rain gauges, scanning strategies, and the elimination of clutter, anomalous propagation, and brightband effects. A general discussion of potential products with Doppler radar follows. Future products of interest to the European community are the probability of icing through the detection of shear zones and embedded convection, algorithms that determine the stage of storm development, the retrieval of thermodynamic variables, and AP detection by eddy dissipation-derived measurements. COST working groups are also evaluating the benefits of multiparameter radars for precipitation estimation and hail detection. Parameters being investigated are the differential reflectivity, the linear depolarization ratio, and the specific differential propagation phase. Many of the radars operate at C-band where propagation effects are more critical.]

Metcalf, J.I, 1997: Temporal and spatial variations of hydrometeor orientations in thunderstorms. *J. Appl. Meteor.*, **36**, 315-321.

[Moderate impact, polarimetric radar application. Differential phase shifts of radar signals and inferred particle orientations are compared to lightning activity in thunderstorms. Characteristic propagation patterns existed prior to lightning, immediately afterwards, and during electric field recovery. Hence, it may be possible to detect changes in the electric fields and in particle types.]

Miller, S.W., and W.J. Emery, 1997: An automated neural network cloud classifier for use over land and ocean surfaces. *J. Appl. Meteor.*, **36**, 1346-1362.

[Low impact, analysis method. The purpose of the study is to develop an automated system for classifying cloud systems from satellite imagery. The paper gives a nice description of neural networks and the particular application. Computations are simplified by the choice of an activation function that sums signals from previous layers. Input consists of eleven cloud descriptors; output consists of nine cloud-type designations. Ninety-six percent of the training cases and an average of 82% of test cases were correctly identified.]

Ohsaki, Y., and K. Nakamura, 1997: Possibility of rainfall rate estimation using Z_{DR} alone measured by a Ku-band dual polarization radar with simultaneous reception. *J. Meteor. Soc. Japan*, **75**, 95-99.

[Low impact. A procedure for computing rainfall rate largely from Z_{DR} using simultaneous measurements of Z_H and Z_V is tested for possible application with earth satellite radars. Although the error in Z_{DR} is much reduced by simultaneous measurement, rainrates computed essentially from Z_{DR} alone are highly sensitive to measurement errors. Utility is also complicated by operation at antenna elevation angles close to nadir.]

Oki, R., A. Sumi, and D.A. Short, 1997: TRMM sampling of radar_AMeDAS rainfall using the threshold method. *J. Appl. Meteor.*, **36**, 1480-1492.

[Low impact, a method for computing long-term areal precipitation. The paper gives a nice review of previous applications of what is essentially the area-time-integral method for estimating precipitation within large watersheds. The technique, which makes use of the high correlation between spatially averaged rainfall rate and the fraction area of rainrate above a preset threshold, is proposed for the TRMM (Tropical Rainfall Measuring Mission) program. The variation in the slope of the relationship, which can be quite large, is examined for various thresholds and by season.]

Pfost, R.L., and A.E. Gerard, 1997: "Bookend vortex" induced tornadoes along the Natchez Trace. *Wea. and Forecasting*, **12**, 572-580.

[Low impact, analysis of a bow echo-shaped storm supported by radar images. The northern end of the bow echo was dominated by a cyclonically rotating vortex, which varied between 5 and 13 km in diameter and persisted for several hours. The line spawned several small tornadoes as the vortex shrank in diameter. The tornadoes formed on the southeast side of the comma head, behind the convective line, and in a region of strong shear created by a rear inflow jet.]

Russell, R.W., and J.W. Wilson, 1997: Radar-observed "fine lines" in the optically clear boundary layer: Reflectivity contributions from aerial plankton and its predators. *Boundary-Layer Meteor.*, **82**, 235-262.

[Low impact, application. Previous studies have shown that fine lines represent populations of insects concentrated by updrafts having roots in the boundary layer. Insect concentrations along fine lines may be 10 times that between lines. (Particulate scattering generally dominates at low levels in the boundary layer, while Bragg scattering becomes more important toward the top of the layer.) The study examined the contribution that potential predators of the insects (specifically birds and dragonflies) might have on the observed reflectivity. It is concluded that reflectivity is little affected by predators. Consequently, the reflectivity associated with fine lines may give an indication of insect numbers if their dimensions are known.]

Ryzhkov, A.V., and D.S. Zrni, 1997: Polarimetric radar discrimination between snow and rain. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 19-20.

[Moderate impact. K_{DP} signatures for snow are found at weak reflectivity when sufficient averaging is performed. Values as small as a few hundredths of 1 km^{-1} were determined. For snow, K_{DP} was generally < 0.08 km^{-1} and Z_{DR} was typically < 0.6 dB. In convective winter storms the transition between rain and snow was marked by a jump in Z_{DR} and a decrease in $_{HV}$.]

Ryzhkov, A., D. Zrni, and D. Atlas, 1997: Polarimetrically tuned R(Z) relations and comparison of radar rainfall methods. *J. Appl. Meteor.*, **36** 340-349.

[Moderate impact. Rainfall estimates from reflectivity factor, specific differential phase, a R(Z) relationship tuned by K_{DP}, and the area-time-integral method are compared. K_{DP} rainfall estimates agreed well with gauge amounts in 4 of 5 cases, R(Z) matched well in 1 case, while the combination of R (Z) and K_{DP} worked well in 3 events. The ATI method was comparable to R(Z).]

Schmid, W., H.-H. Schiesser, and B. Bauer-Messmer, 1997: Supercell storms in Switzerland: Case studies and implications for nowcasting severe winds with Doppler radar. *Meteor. Applications*, **4**, 49-67.

[Low impact, application of Doppler radar. Three severe (supercell) storms which produced large hailswaths containing concentrated regions of wind damage are investigated in terms of the relative positions of low-level convergence and shear, mid-level vorticity, and storm-top divergence. The storms were characterized by mid-level circulations that appeared 40 to 50 min prior to surface wind damage. Damage corresponded to the development of new cells within the storms and was attributed to acceleration of low-level outflows by increased convergence rather than an extension of the mid-level circulation. Cell growth was indicated in all storms by an increase in storm-top divergence.]

Sevruk, B., 1996: Adjustment of tipping-bucket precipitation gauge measurements. *Atmos. Res.*, **42**, 237-246.

[Low impact, information only. Observations from a manual rain gauge and a tipping bucket gauge at the same height are compared. The tipping-bucket gauge measured 14% less rain. The data exhibit considerable noise but reveal undercatchments increased as the wind speed and the precipitation intensity increased.]

Smith, J.A., and M.L. Baeck, 1997: Radar studies of flash flood producing storms. *Preprints, 13th Conf. on Hydro.*, Long Beach, California, Amer. Meteor. Soc., J123-j125.

[Low impact, application. Radar-derived rainfall amounts for five flash flood situations are examined. The storms were characterized by high reflectivity values--in some cases suspiciously high (72 to 76 dBZ). Comparison with streamgauge observations shows that the temporal relationship between rainfall flux and runoff is largely determined by the slope of the watershed. In three storms the runoff was close to or exceeded the gauge-adjusted radar rainfall.]

Smith, J.A., D.-J. Seo, M.L. Baeck, and M.D. Hudlow, 1996: An intercomparison study of NEXRAD precipitation estimates. *Water Resources Res.*, **32**, 2035-2045.

[High impact, product evaluation. Using hourly precipitation products, the paper documents range dependent biases in mean rainfall and in the frequency of rainfall. At short distances from the radar, anomalously low reflectivity values in the third and fourth tilts create significant rainfall underestimates in the WSR-88D precipitation products. Comparison between rainfall estimates in the overlap areas between two radars revealed differences in areal coverage of 13 to 34% and 20 to 42% in conditional mean rainfall (depending on season). Biases were attributed to systematic differences in radar calibration. Gauge/radar comparisons revealed precipitation underestimation at a number of WSR-88D sites. The underestimate was severe at near and far ranges especially for winter events. An analysis with heavy rainfall events shows that the radar has an advantage over sparse raingauge networks for detecting heavy rainfalls.]

Smyth, T.J., and A.J. Illingworth, 1997: Correction for severe attenuation at S-band. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 7-8.

[Low impact. A procedure for correcting S-band radar reflectivity and differential reflectivity is outlined. The differential attenuation of horizontally and vertically polarized returns is estimated from Z_{DR} measurements obtained behind intense rain echoes. The differential attenuation (manifest by negative values of Z_{DR}) is then distributed over the gates with heavy rain (large K_{DP}). The drop-size parameters N_o and D_o are then computed and used to find the attenuation at horizontal polarization.]

Spratt, S.M., D. W. Sharp, P. Welsh, A. Sandrik, F. Alsheimer, and C. Paxton, 1997: A WSR-88D assessment of tropical cyclone outer rainband tornadoes. *Wea. and Forecasting*, **12**, 479-501.

[High impact, research relates to tornado detection in tropical cyclones. Tornado occurrences along rainbands in tropical storms are examined. Small horizontal dimensions and shallow mesocyclonic circulations distinguish the storms from Great Plains supercells. The paper examines the effectiveness of the mesocyclone algorithm and evaluates supplemental information gathered from such products as VIL, echo tops (ET), and spectrum width (SW) for detecting tornadoes. In several storms echo tops descended as tornadoes formed. Large spectrum widths coincided with the tornadoes, and trends in intensity seemed correlated with intensity changes in the mesocyclones. The paper presents criteria for recognizing tropical cyclone tornadoes and proposes a change in the volume coverage pattern, whereby high elevation scans are given up in favor of more frequent low-level scans.]

Steiner, M., and R.A. Houze Jr., 1997: Sensitivity of the estimated monthly convective rain fraction to the choice of Z-R relation. *J. Appl. Meteor.*, **36**, 452-462.

[Moderate impact. Depending on the Z-R relationships chosen, the convective fraction of rain was found to vary from 30 to 80% for monsoonal rains in Australia and to be more than 80% in Florida. Varying Z-R relationship parameters to maximize the correlation between monthly gauge accumulations and radar estimates was not significantly better than employing a single relationship. The ambiguity arises from uncertainty in the classification of echo patterns as stratiform or convective. The one month accumulation period may be too long for applying particular Z/R relationships.]

Stuart, N.A., 1997: The Wakefield, Virginia WSR-88D depiction of the 6 September 1994 split cell thunderstorm over southern Virginia. *National Wea. Digest*, **21**, 18-30.

[Low impact, application. An interesting paper of splitting storms characterized by right and left-moving components dominated by a mesocyclone and a weak mesoanticyclone respectively. Mesoanticyclones are not detectable with the current WSR-88D mesocyclone algorithm. While both storms produced hail, only the right mover was designated as a hail storm.]

Symons, L., and A. Perry, 1997: Predicting road hazards caused by rain, freezing rain and wet surfaces and the role of weather radar. *Meteor. Applications*, **4**, 17-21.

[Low impact, information only. Rain and freezing rain slow road traffic, increase accident rates, and impact road maintenance. Radar should depict problem areas and be useful for issuing short term forecasts. The paper is an appeal to highway authorities for a nation-wide program for monitoring precipitation in the United Kingdom.]

Takayama, H., H. Niino, S. Watanabe, J. Sugaya, and members of Tsukuba Area Precipitation Studies, 1997: Downbursts in the northwestern part of Saitama prefecture on 8 September 1994. *J. Meteor. Soc. Japan*, **75**, 885-904.

[Low impact, case study. The evolution of a long-lived severe thunderstorm which produced large hail and downbursts is described. The downburst occurred 6-10 km behind the storm's gust front and seemed tied to the production of hail and the lowering of reflectivity maxima. Increased precipitation loading and evaporative cooling by melting hail apparently accelerated the downdraft.]

Tawfik, B.B.S., M.J. Gaitan-Gonzales, and H. Liu, 1997: Wavelet analysis of multiparameter radar images. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 59-60.

[Low impact. Wavelet applications for brightband detection, image compression, and describing spatial variability in radar images are presented. Brightbands are detected in range-height images with an edge detection method that operates on the derivative of a smoothing function. Image compression is accomplished by applying vector quantization to the wavelet coefficients resulting from the transform of a decomposed set of sub-images. Finally, wavelets were applied to convective and stratiform rain events to determine their dominant scales.]

Tian, L., and R.C. Srivastava, 1997: Measurement of attenuation at C-band in a convective storm by a dual-radar method. *J. Atmos. Oceanic Tech.*, **14**, 184-196.

[Low impact, utility at S-band needs to be demonstrated. A technique for computing specific attenuation from the measurements of two C-band radars is illustrated. The method involves the solution of a second order differential equation formulated in coplanar coordinates. Results agreed with theoretical expectations but exhibit considerable scatter that was attributed to mixed phase precipitation and variable cloud water concentrations. Errors in the retrieved attenuation fields and small signal losses make it unlikely that rainfall estimates will be much improved if the technique were applied at S-band.]

Wilson, D.R., A.J. Illingworth, and T.M. Blackman, 1997: Differential Doppler velocity: A Radar parameter for characterizing hydrometeor size distributions. *J. Appl. Meteor.*, **36**, 649-663.

[Low impact, requires dual-polarization measurements for implementation. The differential Doppler velocity (DDV), defined as the mean difference in the velocities at horizontal and vertical polarization, is combined with the Z_{DR} measurement to estimate the shape parameter of the gamma drop-size distribution. A series of sensitivity tests are performed. The DDV is insensitive to drop-size variations, turbulence, and shear. The parameter has potential for improving rainfall estimates and for discriminating between aggregates and pristine snow crystals.]

Wilson, W., M. French, N. Baskar, and R. Anderson, 1997: Rain gage and WSR-88D rainfall accumulation comparison in Jefferson County, Kentucky. *Preprints, 13th Conf. on Hydro.*, Long Beach, California, Amer. Meteor. Soc., 111-112.

[Low impact, information only. WSR-88D accumulated rainfalls for a single event are compared to observations from a dense network of raingauges. Rainfall totals were computed with WSR-88D Algorithm Testing and Display System (WATADS) software. Gauge amounts were compared to the mean radar estimate derived from 3x3 and 5x5 matrices of radar bins centered on the gauge. Mean biases were defined as the total of the gauge observations divided by the radar amounts. For the storm the mean bias was 2.0 and grew with time.]

Wurman, J., J. Straka, E. Rasmussen, M. Randall, and A. Zahrai, 1997: Design and deployment of a portable, pencil-beam, pulsed, 3-cm Doppler radar. *J. Atmos. Oceanic Tech.*, **14**, 1502-1512.

[Low impact, information only. The paper presents a description of a truck-mounted X-band research radar. The system is designed to provide high-resolution observations of phenomena that rarely pass close to fixed radar sites. The data are invaluable for determining the detailed evolution and structure of small scale features. Examples given include a nascent tornado circulation and dust devils.]

Xiao, R., and V. Chandrasekar, 1997: Development of a neural network based algorithm for rainfall estimation from radar observations. *IEEE Transactions on Geoscience and Remote Sensing*, **35**, 160-171.

[Moderate impact, hydrological application. Rainfall estimates are made with a neural network using radar reflectivity and a combination of Z and differential reflectivity. Four storm days are studied. Training involved 6 of the gauges. Rainfall estimates with the neural network were generally better than those determined from a Z-R relationship and from a relationship that combined Z and Z_{DR} measurements. Improvement occurred both in bias reduction and increased correlation between the radar estimates and the gauge observations. The neural network combination of Z and Z_{DR} out performed estimates derived from Z alone.]

Yuter, S.E., and R. A. Houze Jr., 1997: Measurements of raindrop size distributions over the Pacific warm pool and implications for Z-R relations. *J. Appl. Meteor.*, **36**, 847-867.

[Moderate impact, rainfall type discrimination. Drop-size distributions obtained during TOGA COARE were classified as being stratiform or convective according to their echo characteristics. Computations of reflectivity and rainfall rate from drop-size distributions showed considerable overlap for the two rainfall types. Hence, the authors conclude that separate Z-R relationships for stratiform and convective rainfalls are not likely to improve rainfall estimation.]

Zrni, D.S., 1997: Weather radar polarimetry for intelligent laymen. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 1-4.

[Low impact, information only. The paper gives an overview of radar polarimetry. Signal properties, derived parameters, and potential applications are described.]

Zrni, D.S., and A.V. Ryzhkov, 1997: Recognition of nonmeteorological echoes with a dual-polarization radar. *Preprints, 28th Conf. on Radar Meteor.*, Austin, Texas, Amer. Meteor. Soc., 5-6.

[Moderate impact. The paper describes how ground targets, AP, insects, and birds can be detected with polarimetric measurements. Ground targets associate with cross-correlation coefficients < 0.7 or large standard deviation (more than 12) in differential phase measurements. Insects associate with Z_{DR} values as large as 10 dB and backscatter differential phase () values of 50 or less. For birds Z_{DR} ranges from -1 to 3 dB and may be 120 or more.]

APPENDICES:

APPENDIX A: LIST OF ACRONYMS AND SYMBOLS

AP anomalous propagation

ARPS advanced regional prediction system

ATI area-time-integral

AWIPS Automated Weather Interactive Processing System

BWER bounded weak echo region

CAPE convective available potential energy

CAPS Center for the Analysis and Prediction of Storms

DSD drop-size distribution

FAR false alarm ratio

K_{DP} specific differential phase

MDA mesocyclone detection algorithm

MIGFA Machine Intelligent Gust Front Algorithm

N_o drop-size distribution intercept

NASA National Atmospheric and Space Administration

NCAR National Center for Atmospheric Research

NIDS NEXRAD information dissemination service

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

PMM probability matching method

POD probability of detection

PPS precipitation processing system

PRF pulse repetition frequency

R rainfall rate

RDA radar data acquisition

RIDDS radar ingest and data distribution system

rmse root mean square error

SCIT storm cell identification and tracking

SDVR single Doppler velocity retrieval

TOGA COARE Tropical Ocean-Global Atmosphere Coupled Ocean-Atmosphere Response Experiment

TRMM tropical rainfall measuring mission

TTS threshold TVS shear

TPV threshold pattern vector

TVS tornado vortex signature

UCP unit control position

UTC universal time coordinated

VAD velocity azimuth display

VIL vertically integrated liquid water

WATADS WSR-88D algorithm testing and display system

WDSS warning decision support system

WER weak echo region

WPMM window probability matching method

VCP volume coverage pattern

VDA velocity dealiasing algorithm

Z radar reflectivity

Z_{DR} differential reflectivity

Z_H radar reflectivity at horizontal polarization

Z_V radar reflectivity at vertical polarization drop-size distribution slope

μ gamma drop-size distribution shape parameter

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) Velocity dealiasing/range unfolding improvements

2) Data quality assessment

3) Base data or Level II (see Crum et al. 1993) archive of storm phenomena

4) Severe weather detection and forecasting

5) Feature detection, tracking, and forecasting techniques

6) Precipitation analysis techniques

7) Wind analysis techniques

8) Data acquisition rate needs and strategies

9) Interpretive techniques/human interface techniques

10) Tropical cyclone analysis techniques

11) Data compaction and transmission techniques

12) Icing analysis techniques

13) Turbulence analysis 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), 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 will be distributed to all respondents. The report will also be placed on the OSF's Applications Branch Web site (http://www.osf.noaa.gov/app). [A limited number of reports from last years survey are still available.] The deadline for submissions is October 31,

1997. 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

Air Force Research Laboratory

Atmospheric Environment Service/Environment Canada

Bureau of Reclamation

Center for Analysis and Prediction of Storms/University of Oklahoma

Colorado State University

Global Hydrology and Climate Center

Hughes STX

Iowa Institute of Hydraulic Research

Massachusetts Institute of Technology/Lincoln Laboratory

McGill University

NASA/Goddard Space Flight Center

National Severe Storms Laboratory

NEXRAD Operational Support Facility

North Dakota Atmospheric Resource Board

NWSFO, Chanhassen, Minnesota

NWSFO, North Little Rock, Arkansas

NWSFO, Salt Lake City, Utah

NWSO, Melbourne, Florida

NWSO, Greenville-Spartanburg, South Carolina

Princeton University/Dept. of Civil Engineering and Operations Research

Swiss Federal Institute of Technology

Techniques Development Laboratory/NWS Office of Systems Development

Texas A&M University

United Kingdom Meteorological Office

U.S. Naval Research Laboratory

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