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

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APPENDICES:

I. INTRODUCTION

This year's research survey was more broadly based than in previous years. A total of 271 survey announcements were mailed in an attempt to reach as many individuals and organizations as possible. Responses were received from more than 40 organizations in 6 countries. Research laboratories, universities, and operational groups are represented. Organizational responses often included contributions from many individual researchers. The reported research addresses nearly all technical needs expressed in the survey announcement.

The maturation of NEXRAD and associated algorithm development is readily apparent in research conducted within the U.S. There is considerable on-going effort to enhance the existing suite of NEXRAD algorithms, to improve the quality of the base data, and to develop new algorithms. The need to integrate other sources of information, such as environmental soundings, spotter reports, and information from numerical forecast models, in the warning process is well recognized.

Efforts to reduce velocity dealiasing and range folding problems are shifting to multiple pulse repetition frequency (PRF) methods. There is wide interest in the mitigation of anomalous propagation and clutter for improved algorithm performance.

Because of their close association with severe weather, there is also much interest in improving the detection of thunderstorm mesocyclones. Users seek to detect mesocyclones in geographical regions where severe weather events usually are not associated with archetypal mid-western supercells but are often characterized by smaller-scale circulations that first form along gust fronts, sea breezes, and tropical storm rainbands. While operational meteorologists wrestle to optimize adaptable parameters in the existing algorithm, others are developing new mesocyclone detection algorithms that incorporate additional parameters. Vertically integrated liquid (VIL) remains the parameter of choice for hail detection within the operational community. Research activity at the laboratories has shifted to polarimetric methods of detection.

Several organizations continue to be active in the retrieval of two and three-dimensional wind fields from single-Doppler radar observations. An important alternative to this approach may be the direct measurement of the wind with a bistatic system such as that being tested at McGill University.

The single most active area of research is the measurement of precipitation. A number of organizations are involved in operational projects to measure snowfall with the WSR-88D. Others are engaged in more basic investigations with vertically pointing radars and polarimetric systems. Rainfall measurement issues being addressed include radar networking, the production of rainfall mosaics, and the inevitable discrepancies that occur in the overlap regions between neighboring radars. Some groups are evaluating probability matching methods of rainfall estimation. Several studies examined the effects of the coefficient and exponent in Z-R relationships on rainfall estimates, the natural variability that occurs in these parameters for stratiform and convective rainfalls, and the impact of vertical drafts on Z-R relationships. Still others are investigating the use of polarimetric measurements for estimating rainfall.

No papers or research activities specifically addressed issues related to "data compaction and transmission techniques" and "data acquisition rate strategies". "Human factors" research, although implicit in the activities of many research groups is an expressed task only at the Operational Support Facility.

The format of this report closely follows that of last year. The Topical Activities Summary (Section II) roughly conforms with the technical needs identified by the NEXRAD Technical Advisory Committee (see Appendix A).

II. TOPICAL ACTIVITIES SUMMARY

A. Archive of Storm Phenomena

NSSL continues to develop an archive of storm events that includes Archive II radar data and severe weather reports. To determine what information has been archived, users specify a radar and event. Approximately 6000 hail, 1500 tornado, and 4000 severe wind events are contained in the archive. For details see Sections III.I.3.e and III.H.3.

B. Velocity Dealiasing and Range Unfolding

Kusunoki et al. (1997) present a scheme for dealiasing velocity data with dual-PRF measurements. Velocity differences at the two PRF's are used to produce a first guess dealiased field. The field is then edited to remove residual regions of strong shear, data points that do not appear at both PRF's, and observations at the edges of echoes. The original and edited datasets are then checked for continuity and final dealiasing.

NSSL reports (Section III.I.5.b.) that it has solved the problem with the current velocity dealiasing algorithm on the WSR-88D that resulted in some tornado vortex signatures being removed from the data. The improved method determines the proper Nyquist interval before data replacement. Testing of a multi-PRF technique for reducing range folding and improving velocity dealiasing is progressing (Section III.I.5.c).

NCAR, FSL, and NSSL have begun a study to mitigate velocity and range folding problems with the WSR-88D. Techniques to be tested include spectrum decomposition, phase coding, spectral processing, staggered PRT's, and the determination of Nyquist intervals by within-the-pulse Doppler processing (Section III.P.1.f).

C. Anomalous Propagation and Clutter Removal

A joint project between NCAR and FSL seeks to improve clutter rejection techniques and minimize reflectivity losses (Section III.P.1.a). A recognition scheme patterned after neural network and fuzzy logic approaches suppresses clutter areas and compensates for reflectivity losses.

The University of Washington has developed an automated procedure for removing AP and clutter from WSR-88D data (Section III.Y.1). The method compares each pixel to surrounding values. The technique hinges on the identification of local maxima in the reflectivity field and comparison with preselected threshold values.

Lincoln Laboratory also has a clutter removal product (Section III.O). The technique is based on the observations that clutter reduces velocities and spectrum widths and that clutter generally occurs near the radar.

D. Severe Weather Detection

1. MESOCYCLONES

Researchers at the NWSO at Melbourne, Florida have been adjusting the adaptable parameters with the Mesocyclone Detection Algorithm to improve the detection of small-scale mesocyclones that spawn tornadoes (Section III.J.6.c). For a summary of activities at the NEXRAD OSF regarding studies with the adaptable parameters in the mesocyclone algorithm see Section III.H.1.

A summary of an independent effort at McGill University to develop a mesocyclone algorithm is described in Section III.U.4. A mesocyclone detection algorithm that incorporates an elliptical model and wavelet analysis continues to be developed by Phillips Laboratory (Section III.M.2).

An application of a neural network to detect mesocyclones likely to produce tornadoes is described by Marzban and Stumpf (1996). Network training and validation were performed on a dataset of 23 Doppler-derived variables generated by the NSSL Mesocyclone Detection

Algorithm (MDA). The dataset includes 3258 circulations of which 235 were tornadic. The CSI for the neural network on the validation data was 34.4%. This compared to 26.0% for the MDA and 28.7% for a discriminant analysis. The probability of detection (POD) for the neural network was 52% and the false alarm rate (FAR) was 49.5%. Plans call for the inclusion of radar reflectivity and storm environmental parameters in future studies. For additional information on NSSL efforts to improve mesocyclone detection see Section III.I.2.b.

2. TORNADOES

According to Bieringer and Ray (1996), several factors have contributed to the improved tornado detection and warning function with the WSR-88D. These are (1) the Doppler capability for depicting velocity patterns related to mesocyclones and other precursors of tornadic activity, (2) increased resolution in the measurements, and (3) the radar and severe weather training received by forecasters. This conclusion was drawn from data obtained before and after installation of WSR-88D's. Six climatologically diverse locations were included in the study. Categories were established for tornadoes beginning and not beginning while a warning was in effect and for warnings issued within 30 min after an occurrence.

Statistics tabulated for the first tornadic event of each day and for all tornadoes show a significant improvement in warning lead time. For all tornado events, the mean lead time was 13.0 min in the after WSR-88D era versus a lead time of 8.0 min for the before WSR-88D era. The probability of detection (POD), defined as the ratio of correctly forecasted tornadoes to the total number of known tornadoes, rose from 60.9 to 73.4% in the after WSR-88D period. However, a significant 40% of all first tornadoes and 27% of all tornadoes did not prompt a warning within 30 min of the start of the event. Before WSR-88D installation only 22% of first tornadoes had a positive lead time. This increased to 45% with the WSR-88D. While it may not be possible to quantify the roles that radar, spotters, training, and communication may have played in the results, the public has clearly benefited from an improved warning capability.

The evolution of a tornado that formed well outside a preexisting mid-level mesocyclone was described by Wakimoto and Atkins (1996). The F3 tornado, which struck Newcastle, Texas on 29 May 1994, was spawned by a second circulation that was first detected near ground along a flanking line of new cells emanating from the supercell. The circulation intensified when it became collocated with the updraft of a developing cell.

The Little Rock WSFO has been evaluating the use of the Combined Shear product to detect small-scale vortices that develop along frontal boundaries and often associate with weak tornadoes (Section III.J.5.a). In an attempt to improve detectability of tornadoes, the NEXRAD OSF completed a TVS adaptable parameter study (Section III.H.1.). They recommend lowering the default Threshold TVS Shear (TTS) from the current value of 72 h^{-1}. Discussion regarding the next generation Tornado Detection Algorithm can be found in Section III.H.2. NSSL efforts to improve tornado detection using maximum gate-to-gate velocity differences at 0.5°, the maximum difference at any elevation, and the circulation depth are described in Sections III.I.2.c and III.H.2. Results show significant improvement over the existing algorithm. Studies of tornado outbreaks with tropical storms (Section III.AA.1) reveal that the tornado generating storm cells often resemble miniature supercell storms. Shear thresholds with the WSR-88D generally were too high to ensure detection of associated mesocyclones.

3. WATERSPOUTS

An on going study at the WSFO in Melbourne, Florida (Section III.J.6.d) has been investigating the interactions between convective cells and storm outflow boundaries that trigger waterspouts.

4. MICROBURSTS

A 16 July 1993 wet microburst in eastern Colorado, observed by the Denver WSR-88D, was the subject of a study by Holmes and Imy (1996). Output from two mesoscale models and observations from the WSR-88D enabled forecasters to recognize the storm threat and provide accurate warnings to the public. The models were the Mesoscale Analysis and Prediction System (MAPS) and the Local Analysis and Prediction System (LAPS) developed by the NOAA Forecast Systems Laboratory. [MAPS provides hourly information on a 60 km horizontal (mesoscale) grid; LAPS provides hourly data on a 10 km grid.] The morning sounding from Denver (DEN) indicated conditions were too stable for thunderstorms due to a lack of moisture at low levels. However, the LAPS model revealed that the moisture was much deeper farther east and that moisture would increase with time. The storm of interest developed along an outflow boundary produced by earlier convection. A second boundary produced by another storm then overtook the storm of interest and caused its intensification. A LAPS-generated sounding for Akron, Colorado (AKO) indicated potential thunderstorm outflow speeds of 105 kt and consequently a severe thunderstorm warning was issued. With time the storm produced a significant reflectivity overhang and a mid-level circulation. A new storm warning noted that the storm was capable of producing damaging winds, hail, and brief heavy rain. VIL values increased to 96 kg m^{-2} and then began a rapid decrease. The decline signaled the descent of the reflectivity core and the triggering of a microburst which produced winds of 130 kt and golf ball sized hail.

Using a fuzzy logic approach, NSSL has been developing an algorithm for identifying downbursts and their precursors (Section III.I.2.e). Key parameters include the height of the reflectivity core, its rate of descent, and the convergence into the downburst.

5. HAIL

The Vertically Integrated Liquid water content (VIL) has long been recognized as an indicator of hail. However, the threshold for hail varies according to environmental conditions. In an attempt to improve the detection of hail with VIL and circumvent the air mass dependency, Amburn and Wolf (1996) tabulated "VIL densities" (VIL divided by the height of the echo top) and compared the result to surface reports for 221 thunderstorms. The analysis was restricted to: (1) storms known to have produced severe hail (> 19 mm in diameter), (2) storms that did not produce large hail but affected populated areas, and (3) storms with maximum VIL's $\geq$ 15 g m^{-2}. A VIL density threshold of 3.5 g m^{-3} correctly delineated 90% of the severe hail cases. Tabulation also showed that the parameter discriminates between small and large hail. One advantage with the VIL density parameter may be that it can be computed within the "cone-of-silence". Additional information can be found in Section III.J.9.a.

A study that combines the VIL parameter and environmental variables has been conducted by Wagenmaker (1996). The paper reviews a number of studies that use both radar reflectivity measurements and environmental conditions to maximize hail detection capability. A number of issues relating to the calculation of VIL are also discussed (e.g., the thresholding of reflectivity, the inability to sample the upper regions of storms close to the radar, the effects of poor vertical sampling on distant storms, storms that tilt with height, and rapidly moving storms). A sample of 94 spring and summer storms, roughly split between hailstorms and non-hailstorms, was assembled. For storms producing hail, maximum VIL values were tabulated for the period 30 minutes before to 15 min after the hail event. The environmental data included the height of the freezing level, 500 mb temperature, and 500 mb geopotential height. Plots of the environmental parameters versus the maximum VIL show clear separation between hail and non-hail storms. A statistical analysis revealed that the POD for hail was 0.91, while the FAR was 0.09.

It is well known that the presence of hail enhances radar reflectivity measurements and can cause rainfall amounts to be overestimated. One solution, as is done in the present WSR-88D precipitation processing system, is to set an arbitrary maximum reflectivity for rainrate calculations. Measurements above the threshold are assumed to be contaminated by hail and are reduced to the threshold value. Another approach, proposed by Hardaker and Auer (1994), attempts to estimate the hail contribution to reflectivity by incorporating satellite measurements of infrared cloud-top temperatures. A previous study (reference given) produced a nomogram in which a plot of radar reflectivity versus IR cloud-top temperatures showed separation of hail and no hail cases. Interestingly, the plot shows decreasing propensity toward hail as temperatures decrease. (At an IR cloud-top temperature of -50°C, hail is indicated for reflectivities > 54 dBZ; at a temperature of -40°C, the hail threshold is 46 dBZ.) From the derived relationship, one can estimate a climatological maximum rainfall rate. Using the boundary definition the authors then derive rainrate relationships for hail contaminated and non-hail events. If the hail size is monodispersed, stone size can be estimated from the reflectivity.

An evaluation of the National Severe Storms Laboratory's Hail Detection Algorithm has begun at the Cleveland, Ohio NWSFO (Section III.J.2.a). An evaluation is also underway at the NWSO at Wilmington, Ohio (Section III.J.10.a). A cone-of-silence flag has been added to the latest version of the NSSL hail detection algorithm (Section III.I.2.d). The flag alerts users to situations where storms close to the radar are not topped by the scanning strategy and the hail threat may be underestimated.

Hail detection with dual-polarization continues to show promise. A study conducted at Colorado State University (Section III.S.1) found that large hail associated with negative Z_{DR} values and reduced $\rho_{HV}(0)$. A moderate correlation was found for hail stone size and a hail indicator investigated by NCAR (Section III.P.2.b).

6. TURBULENCE

Researchers at the University of Western Ontario have been engaged in the detection of turbulence with radar. Recent studies have been concerned with the designation of an appropriate "outer" scale. Results indicate that the larger of the radar beam width or the data gate length should be used as long as the length is less than one half that of the buoyancy scale of the turbulence. If the beam width or pulse length become comparable in size, the buoyancy scale should be used (see Section III.Z.1 for more information).

7. FLASH FLOODS

Davis and Jendrowski (1996) continue to develop an operational system called AMBER (Areal Mean Basin Estimated Rainfall) for detecting flash floods. Implemented at the Pittsburgh National Weather Forecast Office, the software computes averaged rainfalls every 5 to 6 min for some 2427 basins. Comparison with the Flash Flood Guidance determines the likelihood of flooding. The program utilizes the 1° by 1 km resolution of the WSR-88D hybrid scan and monitors rainfall within a large number of small watersheds (most < 50 mi^2). Whenever the estimated average basin rainfall exceeds 60% of the Flash Flood Guidance a display is activated. Additional accumulation results in the issuance of "yellow" and finally "red" alerts. A distinct advantage of the system is the reliance on watershed averages rather than point values of rainfall. This work is also reported in Section (III.J.7.a).

A program to evaluate flood risks within watersheds by combining information from a WSR-88D, hydrological information, risk categories, rain gauges, storm spotters, and population statistics has begun at the NWSFO in Columbia, South Carolina (Section III.J.3.a).

8. TROPICAL CYCLONES

One of the important applications of the WSR-88D is the monitoring of tropical storms at landfall. Of particular interest are the location of wind maxima and changes in wind intensity. Also, tornadoes are frequently spawned by tropical storms upon landfall. As the number of storms viewed by the WSR-88D increases, techniques for monitoring these storms are being refined and developed. Stewart and Lyons (1996) describe observations of Tropical Cyclone Ed made with the WSR-88D on Guam. Although classified as a depression when approaching Guam, the radar indicated at the outset that the storm was more properly a tropical storm. Findings include the observations that increases in wind speed associated with increases in reflectivity and that maximum winds coincided with reflectivity cores and bands. Surface wind speeds were roughly 80% that measured at 1500 m height. Apparently, the reflectivity eye and the circulation center (inferred from inbound and outbound velocity maximum) differed in location by 5 to 8 km. The reflectivity center was closer to the radar. The offset is thought to be due to the a reorganization of the storm center. (It's not clear whether or not storm motion was subtracted from the displayed velocities.) Ed triggered several long-lived small-scale circulations which were detected by the mesocyclone algorithm. One mesocyclone, which formed close to the storm's wind center and had a large vertical extent, seemed a precursor to eye development. Other mesocyclones formed close to the eye wall and eventually merged with the larger-scale circulation. The authors conclude that, because the mesocyclones were not at the center of the larger circulation, algorithm output should not be used to designate the storm's center. Also, because the detected mesocyclones were relatively small compared to midwestern mesocyclones in the U.S., they recommend that the number of pattern vectors that define a shear region in the algorithm be reduced.

Efforts to quantify tropical cyclones with Doppler radar data are reported by Hughes STX (Section III.M.7). Current work is attempting to estimate the translational velocity.

9. BOUNDARY-LAYER PHENOMENA

The interaction of wind boundaries generated by convective storms and sea breezes and the role that interaction plays in waterspout formation continue to be studied at the Melbourne, Florida NWSO (Section III.J.6.d). An algorithm to quantify the structure, motion, and wind hazards with fronts, gust fronts, and thin lines has been developed by Hughes STX (Section III.M.4.a).

10. ICING

The Federal Aviation Administration (FAA) has begun a program to improve utilization of the WSR-88D for detecting in-flight icing (Section III.P.2.a). An important goal of the program is to combine WSR-88D measurements with numerical model and sounding data to improve the detection of icing conditions. A program to remotely sense icing conditions (freezing drizzle) with K_a-band radar exists at the Environmental Technology Laboratory (Section III.G.1).

11. SNOWFALL

Hudak and Nissen (1996) studied snowstorms in Toronto with an X-band radar that operated both in PPI and vertical pointing modes. Mesoscale wind parameters (horizontal velocity, convergence, and deduced vertical velocity) were derived from the Extended Velocity Azimuth Display (EVAD) method. Precipitation terminal velocities and spectral width data were obtained from the vertically pointing data. When combined with knowledge of the synoptic situation and the temperature profile, the data yielded information concerning precipitation processes.

Profiles in which radar reflectivity, terminal velocity, and spectrum width all increased toward ground were attributed to accretion. A distribution with enhanced terminal velocities and widths in the layer 1.2 to 1.5 km and with reduced values below was interpreted as aggregation. Slight increases in all three parameters toward ground was believed to signify diffusion growth. Knowing which processes dominate could lead to better radar estimates of precipitation.

Snowfall measurement studies are being conducted at a number of locations. The National Weather Service Office at Binghamton, New York has been combining WSR-88D data with thermal and moisture information from numerical forecast models to estimate snowfall rates and water equivalents for storms in upstate New York (Section III.J.1.a). A snow gauge network is being installed by the NWSFO in Salt Lake City, Utah for "calibrating" real-time WSR-88D snowfall estimates (Section III.J.8.a). The Bureau of Reclamation is engaged in a snowfall measurement program at several geographical locations (Section III.B.1). Algorithms are being developed for snow depth and for water equivalent.

Great Lake-effect snow storms affect numerous population centers and can profoundly impact national transportation systems. A two year program at Illinois State Water Survey seeks to improve snowfall estimation in lake-effect storms observed with the WSR-88D (Section III.N.1). Linear regression relationships between possible predictors and snowfall rates are being evaluated. Parameters positively correlated with snowfall are visibility, wind strength, the difference between surface and 850 mb temperatures, differences between lake surface temperatures and the 850 mb temperature, and surface dew point temperatures (see also Laird et al. 1996).

NSSL has been studying polarimetric measurements of snowfalls (Section III.I.4). Preliminary results suggest that snowfall at warmer temperatures has characteristically different polarimetric signatures than snow at colder temperatures. Further, differential reflectivity appears to be a good discriminator between rain and snow.

E. Feature Detection, Tracking, and Forecasting

The GANDOLF (Generating Advanced Nowcasts for Deployment in Operational Land surface Flood forecasting) system, being developed in the United Kingdom, is designed to provide nowcasts of heavy rain within watersheds. Storm cells are represented as "objects" which are followed in time using radar observations with 2 km spatial resolution and 5 min temporal resolution. A set of cell attributes (e.g., cloud top height, precipitation rate, location, and movement) are determined. Rainfall forecasts are issued based on pre-specified life cycles. Cell stages are determined by comparison with idealized radar reflectivity profiles that place each cell in one of 5 evolutionary categories. For example, cells with low rainfall rates below cloud base and high rates aloft are classified as young and growing cumulonimbus giving precipitation near ground. Cells close to the radar that are unlikely to be scanned to their tops, and cells at excessive distances without measurements below cloud base are simply classified according to the available data. Each pixel comprising a cell is assigned a numerical value corresponding to one of the five evolutionary categories. For a cell to be classified as a particular type the total numerical value must fall within a certain range. Precipitation rates are assigned according to average reflectivity; cloud bases and motion are determined with a numerical model. A development potential attribute is defined by comparison with earlier data collections. Cells are then advected with their velocity and evolve according to their development potential. Special rules apply for new cell growth and decay of old cells. An example is provided and results are compared to another operational nowcasting system (FRONTIERS). In general, the object-oriented approach out performed FRONTIERS by 0.1 to

0.2 in CSI scores.

As part of its modernization program, the Australian Bureau of Meteorology (Section III.BB.2) has been testing radar analysis packages developed by other organizations. The evaluation includes the Thunderstorm Identification, Tracking, Analysis, and Nowcasting (TITAN) package and the COLIDE package for detecting gust fronts and air mass boundaries. Future testing will include the MIGFA method for detecting gust fronts.

Several organizations, e.g., McGill University (Section III.U), the National Severe Storms Laboratory (Section III.I), the Techniques Development Laboratory (Section III.L), Phillips Laboratory (Section III.M), and the Swiss Federal Institute of Technology (Section III.DD) all have broad programs in feature detection, tracking, and forecasting.

F. Precipitation Analysis Techniques

Many hydrological applications, particularly those on regional and larger scales, require that data from more than one radar be composited. Potential difficulties arise from different scanning times, radar calibration errors, loss of range information, and decisions about what to do in overlap regions sampled by more than one radar. A paper by Crosson et al. (1996) examines the accuracy of composite reflectivity imagery produced by the WSI Corporation. Composite maps, drawn from WSR-57 observations, having 2 km grid resolution, were available at 15 min intervals and 0.5 dB resolution. Gauge observations collected during the Convection and Precipitation/Electrification Experiment (CaPE) provided ground truth. Rainfall estimates made with $Z=300R^{1.4}$ [a Z-R relationship first used in the Florida Area Cumulus Experiment (FACE)] exhibited significant bias prompting study of the probability matching method (PMM) for determining Z-R relationships. An important assumption with the method is that the time domain must be sufficiently long to include a number of storm systems at various stages of development. A number of temporal and spatial scales were tested in the evaluation.

Rainfall rates were computed several ways, but the method that best agreed with the gauges was to determine a mean rainfall rate by integrating over the range of Z for the entire 15 min period. The NEXRAD Z-R relationship overestimated precipitation amounts by 90-110%. Largest departures occurred at large distances from the radar sites. The problem relates to the grid filling procedure of selecting the maximum radar value in overlap areas; thereby incorporating bright-band contaminated measurements. Comparison with a narrow beam research radar suggested that a threshold of 36.5 dBZ be applied to the radar data. Precipitation estimates were in better agreement but were still too high.

Crosson et al. give a nice pedagogical description of an experiment in which the PMM is applied to the data and a "climatologically tuned" Z-R relationship is determined. Comparison of this relationship with the NEXRAD relationship showed that the PMM had slightly smaller errors. Both methods underestimated heavy precipitation and overestimated light precipitation. Based on analysis of data plots, showing increased scatter as the rainfall amount increased, the authors conclude that neither the NEXRAD nor PMM relationship is appropriate for retrieval of point rainfalls on time scales of less than two weeks. The problem may be explained by the fact that the temporal and spatial scales of the radar and gauges differ markedly. Other contributors were thought to be timing errors and uncertainty of the geometry between gauges and radar. For long-term watershed averages, consistent with its inherent assumptions, the PMM had smaller mean biases, higher correlations, and lower root mean square (rms) errors than those found with the WSR-88D Z-R relationship.

Proponents of the PMM for estimating rain also include researchers at the NASA/Universities Space Research Association (Section III.F.1). They argue that point comparisons between radar and gauges are fraught with statistical errors which are lessened by the PMM because it matches the observed reflectivity to rain gauge rates in a probabilistic manner. Several references to recent work are given.

Potential network problems are also addressed by Makihara (1996). Of particular concern are discontinuities that arise in regions sampled by more than one radar. The problem is eliminated by a technique that combines radar and raingauge information. The data are adjusted with a two parameter relationship of the form F=Af where A is the ratio of the gauge measurement and the radar estimate at ground and f is the ratio of the radar estimate at ground to the elevated radar estimate. The paper presents an elaborate method for calculating f based on assumed profiles of reflectivity and beam illumination. The parameter A responds to radar calibration errors and variations in drop-size distributions. While A varies spatially and its variation could be tied to echo characteristics, in this application A was taken as constant except for the differences between radar sensitivity and differences in radar beam height in overlap regions. Modified ratios of gauge measurements and radar estimated rainfalls in overlap areas are made to be equal by minimization procedure that incorporates the gauge observations. The process clearly reduces discontinuities between radar domains in the mosaic. However, no quantitative measure of the improvement is given.

A procedure to classify stratiform and convective rainfalls in national composites of radar data is under development at the NASA/Global Hydrology and Climate Center (Section III.E.1). National radar images from a NEXRAD Information Dissemination Service (NIDS) vendor are classified according to stratiform and convective echoes. An analysis procedure applies two different Z-R relationships to the data and accumulates daily rainfall totals. The data support climatological studies of rainfall variability.

The accuracy of radar-derived rainfall estimates is dependent upon the radar sampling interval. Sampling errors accrue when storms move or evolve rapidly and "point" radar estimates are compared to gauge observations in order to determine system bias. Several investigators have developed schemes whereby the spatial characteristics of echo patterns serve as a surrogate for temporal samples. In their study, Liu and Krajewski (1996) compare a space-time Kriging method and an advection method in an attempt to improve rainfall estimates. With the advection model the rainfall rate at intermediate times is computed by weighing prior and subsequent observations. Mean motion is computed from the cross correlation between scans. The discussion outlines the application of the Kriging method. Spatial and temporal correlations are computed assuming that the process is stationary and isotropic. A stochastic space-time model (references provided) generated the rainfall rate fields. "True" rainfalls are determined from 1 min samples. Results showed that the advection method had smaller mean and absolute errors when advection velocities were high but estimates could be slightly biased.

Burlando et al. (1996) present a method for estimating point rainfalls that incorporates radar and gauge information. The input data calibrate a Multivariate AutoRegressive Integrated Moving Average model (MARIMA). Radar maps (actually their autocorrelation function) give information on storm motion and are used to select those raingauges which have the highest Lagrangian cross-correlation and hence, are most applicable for estimating precipitation at other locations. Parameter sets are determined for each event and are updated as new information becomes available. Parameter estimation is accomplished with the "method of moments" procedure. This entails solving a system of equations consisting of covariance matrices and a noise term. Forecasts are based largely on "upwind" gauge observations. An implicit assumption is that point rainfalls are correlated. Predicted and observed hourly rainfalls agreed quite well. When the autocorrelation function for the gauge observations was used as input to the model, errors were larger. The procedure seems most applicable for large-scale precipitation systems.

An application in which mosaics of WSR-88D radar information were coupled with a runoff model developed by the Hydrologic Engineering Center was described by Peters and Easton (1996). Specifically, hourly Stage III products available at River Forecast Centers provided input to the Modified Clark runoff model. Knowing the distribution of rainfall within the watershed and accounting for the time lag for the runoff from various locations to exit the basin, resulted in excellent agreement with the observed runoff profiles.

In their paper Seed et al. (1996) examine the impact of sampling errors in the estimation of the parameters A and b of the relationship $Z=AR^b$. A simulation shows that 100 gauge/radar comparisons are required to estimate A with an accuracy of better than 15% and b better than 10%. First, the paper begins with a nice summary of the contributors to differences between radar and gauge measurements and a literature review of earlier studies to determine A and b by regression and probability matching methods. The effect of vertical motion on the rainfall rate is examined with a simple one dimensional model (the flux of raindrops from the sides of the updraft is not considered). Results suggest that the exponent b decreases as the strength of an updraft increases. A lowering from 1.44 to ~1.1 occurred as updrafts increased to 4 m s^{-1}. A multiplicative error term was added to the Z-R relationship and dataset of Z,R pairs was created assuming that the system errors varied from 1 to 3 dB. The mean standard errors in A and b where then determined. The authors assert that recalibrating the radar to reflect storm-to-storm variability is futile given the large errors in A and b. Next the authors compared the probability matching method and least squares regression method for estimating rainfall rates. They conclude that the least squares method provides better estimates at higher rainrates because of their low probability of occurrence. A case study with a vertically pointing radar and a collocated high-resolution raingauge is presented. One minute averages of rainfall rate from the radar and the gauge were examined. The autocorrelation function for the residuals from the least squares method declined rapidly even for a 1 min lag prompting the authors to say that, while precipitation events may have characteristic models, attempts to continuously vary relationship parameters are not likely to outperform relationships with fixed parameters.

Ulbrich et al. (1996) investigated the impact of variations in drop-size distribution, i.e., in the coefficient and the exponent of simple Z-R relationships, on the accuracy of rainrate estimates. They find that typical errors when an incorrect coefficient A is used are 25-34%. When combined with errors of only 2 dB in hardware calibration, the total error can be a factor of 1.85 for an actual coefficient of 200. There is almost no bias if the coefficient is 450.

An empirical study conducted by Tokay and Short (1996) with disdrometer data found that jumps in the intercept parameter of the drop-size distribution (N_o) occurred as rainfall character changed from convective to stratiform. The authors explain that stratiform precipitation begins with ice crystal growth in upper levels of clouds by vapor deposition. Aggregation and riming start once the particles descend and temperatures approach 0°C. Subsequent melting produces relatively large drops. Convective precipitation is thought produced largely by the accretion of liquid water. The result is that there are more small to medium size drops and fewer large drops in convective clouds and vice versa in stratiform clouds, at the same rainfall rate. The net effect is that coefficients (exponents) in Z-R relationships are larger (smaller) for stratiform rain (convection).

The finding that stratiform rains have larger Z-R relationship coefficients was also found by Atlas at the NASA/Goddard Space Flight Center (Section III.D.1). Further, observed differences between stratiform rain drop-size distributions at ground and aloft in tropical storms were explained in part by evaporation of small droplets in a dry elevated layer between 2 to 4 km.

Vertical motion influences on Z-R relationships have been investigated at the Hurricane Research Division at the Atlantic Oceanographic and Meteorological Laboratory (Section III.K.1). The work concludes that Z-R relationships are meaningless when updrafts exceed 2 m s^{-1}.

A study of precipitation estimates in a severe ice storm which struck northern Mississippi during 9-11 February 1994 is featured in the paper by Pfost (1995). Observations from the Little Rock, Arkansas and Jackson, Mississippi radars are compared. Estimates from the Jackson radar significantly underestimated the precipitation, while the Little Rock radar overestimated the rainfall. The differences were explained in part by bright band contamination with the Little Rock radar. Another contributor seemed to be differences in hardware calibration.

Sharp circular discontinuities often appear in rainfall maps generated by the current Precipitation Processing System (PPS) on the WSR-88D. The problem stems from the generation of the "Hybrid Scan" and the criteria to select elevation angles for specific range bins in the scan. Significant improvement occurs when the lowest uncontaminated and unblocked tilt angle provides the rainfall estimate (Section III.H.6).

For information regarding precipitation measurement with dual-polarization radar readers are referred to Section (II.K). An operational system utilizing WSR-88D products for estimating mean rainfall within watersheds has been presented by Davies and Jendrowski (1996) (see also Section II.D.7). A collaborative rainfall study between the NWSO at Greenville-Spartanburg, South Carolina and scientists at Clemson University (Section III.J.4.a) seeks to remove bias from WSR-88D rainfall estimates (see also Section III.R.2). Studies of rainfall estimation at the NWS office in Melbourne, Florida are discussed in Section III.J.6.2. Examination of the potential of VIL for estimating rainfall over complex terrain is progressing at McGill University (Section III.U.5).

Princeton University (Section III.X.1) conducts a comprehensive program to improve rainfall estimates with the WSR-88D. Research topics are concerned with range biases, study of flood and flash-flood producing storms, the impact of hail, and AP detection. Numerous references to recent work are provided.

The Australian Bureau of Meteorology is investigating the use of radar for hydrology. Of particular interest are the Window Probability Matching Method and polarimetric measurements (Section III.BB.3). Preliminary results indicate that the specific differential phase measurement overcomes many of the problems with traditional Z-R relationship technology. On-going, broadly based programs in precipitation measurement include those at the Iowa Institute of Hydraulic Research (Section III.T) and the Swiss Meteorological Institute (Section III.EE).

G. Wind Analysis Techniques

Qiu and Xu (1996) present a least squares method of retrieving winds from single-Doppler radar data and compared results with a previously developed simple adjoint method. A radial momentum equation serves as the primary constraint for the analysis. The velocity and a residual forcing term, composed of vertical velocity, pressure, and mixing terms, are partitioned between mean and temporal fluctuation parts. The fluctuation part of the forcing term is then ignored. Noise reduction is accomplished with a smoothing constraint that includes divergence and vorticity terms. With a dual-Doppler analysis as truth, six experiments that neglected various forcing terms and employed different time levels for data insertions, were performed. The least squares method fared best for the full model run and for experiments ignoring the mean forcing. The adjoint method did better for experiments in which the smoothing constraint was relaxed. The reason being that the least square solution is dictated by noisy local data while the adjoint solution at grid points is affected by the entire grid. The least squares method deteriorated as the time interval between data insertions increased. An advantage with the least squares approach was that fewer iterations and less computation time was required to reach a solution.

A method to retrieve two-dimensional winds from single Doppler radar observations for a single time level is being developed by Suzuki at the Meteorological Research Institute of Japan (Section III.CC). The method is applicable to wind fields with embedded mesocyclones, microbursts, and gust fronts. A variational minimization problem is formulated with a cost function that constrains vorticity and divergence terms. Results show that simple wind fields, e. g., rankine combined vortices, axisymmetric divergence patterns, and convergence lines, are readily recovered.

Information on radar-based wind field analysis techniques being developed at the University of Oklahoma/Center for Analysis and Prediction of Storms can be found in Section III.V. Wind field analysis techniques are also reported by the University of Oklahoma/Cooperative Institute for Mesoscale Meteorological Studies (Section III.W). A similar project between NSSL and the University of Oklahoma is described in Section III.I.6. NCEP is using a variational approach to insert winds from WSR-88D's into a forecast model with 10 km resolution (Section III.C.2). Despite the poor quality of the input data, NIDS images for the lowest four elevation angles, the radar data are thought to add value to the forecasts.

The installation of a network of bistatic receivers at McGill University for real-time acquisition of 2 and 3 dimensional wind fields is described in Section III.U.1. A reflectivity-based method for predicting damaging winds being developed at McGill University can be found in Section III.U.3.

Hughes STX has been investigating the use of spectrum width for the detection and forecasting of storm hazards. Regions of large spectrum width correlate with fluctuations in storm intensity. Also, spectrum width has been found to be more closely correlated with mesocyclone intensity than maximum mesocyclone shear or diameter. For details see Section III.M.6.

H. Data Acquisition Strategies

No reviewed papers or reported research specifically addressed data acquisition strategies.

I. Interpretive Techniques/Human Interface Techniques

Several organizations are involved with the development of display packages for radar data. The Iowa Institute of Hydraulic Research has produced a "radar browser" and display package which permits random access to stored data volumes (Section III.T.2). System integration of multiple data streams and outputs from severe weather detection algorithms and subsequent display of results continues at NSSL (Sections III.I.3.c and d). Similar developments are in progress at Phillips Laboratory (Section III.M) and at McGill University (Section III.U).

J. Analysis Techniques

Neural networks hold great potential for feature detection and pattern recognition. Rather than relying on statistical relationships, they adaptively estimate continuous functions from data without specifying relationships outputs and inputs. The advantage comes from not having to make a priori assumptions about normality and ease in working with multidomain datasets. The technique is useful for solving problems in pattern recognition and classification and for an detecting nonlinear relationships between variables. [Gopal and Woodcock (1996) and Marzban and Stumpf (1996) give nice descriptions of neural networks. Marzban and Stumpf also compare the neural network approach to more traditional linear regression and discriminant analysis methods.] Artificial neural networks are large networks of simple processing elements that are interconnected and run in parallel. Weights for the connections are established through a learning process. The problem is to find a set of input and output parameters that approximate the problem to be solved. Neural networks can produce highly accurate predictions, but physical understanding may be lacking. Gopal and Woodcock (1996) apply the network to a temporal series of images to determine the health of a forest, but the methodology can be applied to detect changes in any parameter, e.g., a change in radar echo intensity. A tutorial describes a two-layer feedforward network operation.

Marzban and Stumpf (1996) apply a neural network to detect tornadoes. The input data are from the NSSL mesocyclone detection algorithm. The paper reviews assumptions inherent in more traditional statistical analysis techniques and gives a description of the neural network. The network was run on a dataset of 23 variables considered as important for discriminating between tornadic and nontornadic mesocyclones. Critical success indices for the neural network exceeded those for the MDA expert system and for the discriminant analysis. The authors explain that the rules within the expert system may be wrong or do not cover every contingency. The discriminant analysis assumes that the distributions are normal and that the covariance matrices of individual parameters are similar. Neural networks do not suffer from these constraints.

A review of several techniques to quantify the size, shape, texture, and context of cloud images is presented by Pankewicz (1995). The automatic detection of comma clouds, vortices, lee waves, and fronts is sought. The problem is posed as having three stages: (1) a tranducer stage in which images are converted to digital format, (2) feature extraction, and (3) pattern classification according to the statistical properties of the features. Classification requires a training set of data.

Features may have multi-spectral, textural, or spatial qualities. An example of multi-spectral properties is gray level intensities. Textural features are often statistical characterizations (the spatial distribution of gray levels) or structural representations (such as contrast, power spectra, autocorrelation functions, and homogeneity). Other image qualities relate to spatial features (usually determined by segmentation). For example, growing cumulus appear as bright pixels at 1 km resolution, thunderstorms may have dimensions of 10 km, while mesoscale convective systems and frontal systems may have dimensions of 100 to 1000 km. Yet another class is that of contextural features such as wave clouds in mountain areas or convective clouds in areas of surface heating behind cold fronts. The paper goes on to describe "supervised" feature classifiers such as nearest neighbor techniques, parallelepiped classifiers, discriminant functions, minimum-distance-to-means classification, Gaussian maximum likelihood classifier, and several "unsupervised" classifiers (e.g., partitional techniques and dynamic clustering). A simple explanation of neural network classifiers follows. The above methods are used primarily to classify individual samples. Image segmentation methods, also presented, can classify larger scale features.

Bankert and Aha (1996) examined the use of forward and backward sequential selectors for reducing the number of input features considered in a cloud classification system. A forward sequential selector whereby features are added one at a time (based on the performance of a "nearest neighbor" classifier) performed best. Features which did not add to the cloud classification were removed because their information is redundant or irrelevant. Compared to a previous study, cloud classifications improved by 7% despite a reduction in the set of input features.

K. Polarimetric Radars

Polarimetric measurements such as specific differential phase (K_{DP}) and the differential reflectivity (Z_{DR}) show considerable promise for estimating precipitation. The advantage comes from insensitivity to radar hardware calibration, to variations in drop-size distributions, and, in the case of K_{DP}, to beam blockage. The measurements provide additional information about the particles illuminated by the radar beam. Bright bands are readily seen in the observations. Hail detection is by direct measurement rather than inference from storm structural features. Also, measurements from meteorological and ground echoes are readily distinguished. Consequently, considerable activity continues within the research community to perfect polarimetric techniques and search for new applications.

Gorgucci et al. (1996) compare estimates made with radar reflectivity and with differential reflectivity measurements obtained with a C-band radar located near Florence, Italy. The sampling interval was 10 min, and the antenna elevation angle was 1.8°. Forty-one gauges, distributed in complex terrain between 12 and 90 km from the radar, provided ground truth. Contamination from ice and hail was mitigated by setting reflectivity and differential reflectivity thresholds of 55 dBZ and 0 dB, respectively. The single storm analyzed persisted for 36 hours. For point comparisons the Marshall-Palmer Z-R relationship produced fractional standard errors of 84%, a climatologically representative relationship had errors of 64%, and a dual-polarization algorithm had errors of 59%. Gorgucci et al. then determined optimum Z-R relationships and polarimetric relations by matching cumulative distribution functions of the parameters with gauge data. Optimization yielded a fractional standard error of 66% for the optimized Z-R relationship and 53% for the optimized polarimetric relationship.

Radar reflectivity, differential reflectivity (Z_{DR}), and specific differential propagation phase (K_{DP}) are all related and usually form a self-consistent set of variables, i.e., knowing reflectivity and differential reflectivity it should be possible to calculate K_{DP}. This self-consistency is demonstrated in the article by Scarchilli et al. (1996). Departures from self-consistency can be useful, e. g., the lack of consistency between Z_H and Z_{DR} or between Z_H and K_{DP} could indicate the presence of hail, ground clutter, or calibration errors. In the paper K_{DP} is derived from Z_H and Z_{DR}. The three parameters are related by

$$K_{DP} = C Z_H^{\alpha} 10^{-\beta Z_{DR}}$$

where α and β are determined by nonlinear regression over a wide range of rainfall intensities. The drop-size distribution is represented by a gamma distribution whose parameters (N_o, D_o, and μ) are varied to determine their effect on the three radar variables. A plot of measured and estimated K_{DP} values, in the absence of measurement errors, revealed a correlation of >0.998 and no bias. In a simulation considering measurement error and physical processes, the fractional standard error in the estimated K_{DP} for point comparisons is ~20% for $K_{DP} > 2°\ \mathrm{km}^{-1}$. The authors state that the retrievals of Z_H and Z_{DR} are not as robust due to measurement error.

Because radar reflectivity depends on the 6th power of the diameter of particles illuminated by the radar beam and because hail stones are usually much larger than raindrops, the presence of hail can significantly affect rainfall estimates made from reflectivity measurements. Simply truncating reflectivity measurements to a specified value, say 53 dBZ, is a simple solution. But it is well recognized that on occasion hail may contaminate measurements with reflectivities < 40 dBZ, and at times hail may not be present at reflectivities > 60 dBZ. Many look to polarimetric measurements to solve the problem. A comparison of rainfall rate estimates made with Z_H, K_{DP}, and the attenuation at X-band (A_X) in a hailstorm has been conducted by Aydin et al. (1995). K_{DP} is relatively insensitive to hailstones that have mean axial ratios which are close to 1.0 or to hailstones that are tumbling. Note that to measure A_X requires two radar. Only a single rain gauge formed the basis of comparison. However, inspection of the differential reflectivity measurements (Z_{DR}) for this storm indicated that hail resided in regions with $Z_H > 55$ dBZ--a rainfall rate of 144 mm h^{-1}. Estimates of rainfall rates with K_{DP} were > 190 mm h^{-1} in the reflectivity core. Radar estimated rainfalls were calculated by integrating the radar data along the cell path and by considering only the range gate in which the gauge resided. The findings were that rainfall estimates with A_X, K_{DP}, and Z_H were comparable if a hail threshold of 55 dBZ was used. The authors conclude that this threshold worked well in mixed phase precipitation and provides "ground truth" for evaluating algorithms that utilize only Z_H.

In similar study, Ryzhkov and Zrnić (1996a) compared rainfall estimates made with the Marshall-Palmer Z-R relationship and with the specific differential phase (K_{DP}). The Marshall-Palmer Z-R relationship gave good rainfall estimates for a summer squall line but not for a winter squall line. When a research radar and a WSR-88D were used, the Marshall-Palmer relationship underestimated the rainfall from the winter storm by a factor of 3. In contrast, rainfall estimates derived from K_{DP} were good in both cases. The authors speculate that the winter storm had a high concentration of relatively smaller drops that was a consequence of a relatively lower melting level. An initial distribution of smaller ice particles above the freezing level was thought to have been responsible.

Relatively recent applications of dual-polarization measurements have been in the study of electrical activity within thunderstorms. Jameson et al. (1996) examined multi-parameter measurements made in Florida thunderstorms during the CaPE experiment. The presence of ice is important for electrification and charge transfer through the collision process. Microphysical processes that influence electrification also influence the radar backscatter. Hence, changes in electrical activity, tied to the freezing of drops and subsequent growth of graupel and smaller ice particles, may be predictable through observed changes in the polarimetric measurements. Before they freeze, drops resemble oblate spheroids and have a characteristic Z_{DR} signature (> 1 dB). Frozen drops are less reflective, tend to develop asymmetries, and gyrate as they fall. This drives the Z_{DR} parameter toward 0 dB. A cross-polarized signal, expressed as the linear depolarization ratio (LDR), also appears. Freezing is characterized by a reduction in Z_{DR} and an increase in LDR. Examination of field mill data indicated that an abrupt increase in supercooled water above the -7°C level roughly coincided with the onset of negative charging. The electrification process, signified by an increase in LDR, was tied to the production of graupel.

When nonspherical particles are illuminated by the radar beam, a portion of the incident polarized wave is depolarized and scattered into other planes. Drops are approximated by oblate spheroids. When viewed at nadir, they are generally thought to appear circular; and radar measurements would not be expected to show significant depolarization. However, recent observations from airborne polarimetric radars reveal surprisingly large depolarization ratios (Jameson and Durden 1996). The interpretation is that collisions with smaller drops can cause larger drops to oscillate in the plane perpendicular to the vertical. Even if a random distribution of disturbed drops are produced, depolarization takes place. The authors conclude that adjustments may have to be made in some precipitation algorithms that use polarimetric measurements to estimate rainrate.

The advantages of estimating rainfall with specific differential phase measurements are described in the article by Zrnić and Ryzhkov (1996b). The advantages arise because the phase measurement is independent of the echo return amplitude and because the K_{DP} parameter is relatively insensitive to variations in drop-size distribution and to the presence of hail. Also, the measurements are not susceptible to attenuation by rain. In the paper the authors show immunity to beam blockage, ground clutter cancelers, and anomalous propagation. With K_{DP} it is possible to scan close to ground which minimizes problems associated with the advection of particles beneath the beam and with changes in the precipitation as it falls. In one test with a blocked radar beam having an average obstruction angle of 0.2° elevation the average reflectivity at 0° was 6.4 dB less than at 0.5° antenna elevation. In contrast, the average difference in K_{DP} at the two elevation angles was 0.01° km^{-1}. In another test examining the influence of an azimuthal step discontinuity in rainfall within the beam the differential phase measurement gave a better representation of the discontinuity. Notch filters are widely used to remove ground clutter but have the undesirable result of removing spectral power at and near zero frequency. Return signals are underestimated and hence lead to underestimates of rainfall rates. Differential phase measurements were shown to be less affected by clutter filters. Estimates were unbiased but subject to minor random errors. Finally, an example is shown whereby anomalous propagation can be detected by performing a continuity check on the ϕ_{DP} measurement.

Early studies indicated that there could be significant error with K_{DP}-derived rainfall estimates for rates < 50 mm h^{-1}. The problem, examined in detail by Ryzhkov and Zrnić (1996a), comes from the difference in forward-scattering amplitudes at orthogonal polarizations. For the smaller drops, the relationship between K_{DP} and rainrate is of higher order than that for the larger drops. Disdrometer measurements reveal that the R-K_{DP} relationship reported previously by the lead author gives excellent results even at rates < 20 mm h^{-1}. Significant departures also exhibited unusual Z_{DR} values. Consequently, rainrate relationships have been developed that combine the K_{DP} and Z_{DR} measurements. The authors then show how the standard deviation of K_{DP} can be reduced by increased averaging of ϕ_{DP} in range and time. This effectively reduces the measurement error of the mean K_{DP} value and also the mean rainfall rate estimate within a watershed. They suggest that low rainfall rates require heavy filtering (48 gates). Rate classification is set by imposing a threshold of 40 dBZ. In an interesting experiment with K_{DP}, rainfall rates made from data obtained at 0 and 0.5° antenna elevation were compared. K_{DP} values at 0° elevation angle were higher in three cases studied despite that fact that beam blockage was greater at the lower elevation (see also Zrnić and Ryzhkov 1996). Although the bias between rainfall totals and gauges was small (1.24), a significant error reduction occurred when the advection of rain was accounted for (1.04).

A physical model for predicting profiles of radar reflectivity, radial velocity (for vertically pointing radars), linear depolarization ratio, and differential reflectivity in the melting layer is described by Russchenberg and Ligthart (1996). The model is based in part on observations obtained with the Delft University radar (The Netherlands). Input parameters include the rain intensity and snow density (before melting). [Neither parameter is known generally. Reflectivity can be used to estimate rainfall intensity. The effect of snow density is thought significant only for small densities (< 0.1 g cm^{-3}).] Model features include the thickness of the melting layer, particle size and concentration, fall speed, melting snowflake shape, and a variable permittivity. For the cases illustrated, good agreement was found between the model and polarimetric measurements. The authors caution that model parameters may have to be tweaked to retrieve detailed measurements.

Studies using polarimetric observations to detect hail are in progress at Colorado State University (Section III.S.1) and NCAR (Section III.P.2.b). A program begun at NCAR to compare WSR-88D estimates of rainfall with polarimetric measurements is described in Section

III.P.2.c.

L. Data Quality Assessment

NCAR and FSL have built an enhanced data analyzer that permits examination of WSR-88D Archive I measurements and writes the data to 8 mm tape. The acquisition system permits real-time development of new radar data acquisition (RDA) processing techniques (Section III.P.1.b).

M. Data Compaction and Transmission Techniques

No papers were found that explicitly addressed data compaction techniques. The Iowa Institute of Hydraulic Research has modified the "run length coding" method for storage of radar data (Section III.T.4).

N. Human Factors

No papers specifically addressed human factors issues. Human factors activities within the NEXRAD OSF are discussed in Section III.H.4.

III. ACTIVITIES ACCORDING TO ORGANIZATION

A. Agricultural Research Service

1. INSECT MIGRATION ALGORITHMS

The Agricultural Research Service (ARS), U.S. Department of Agriculture, has initiated a field research program to develop algorithms for estimating the Insect Abundance (IA) and Insect Velocity (IV) of migratory insect pests. The research will also help quantify the impacts of night-flying insects on WSR-88D base reflectivity (Z), velocity (v_r), and spectrum width (SW) measurements.

Algorithms are being developed for estimating IA and IV for migrating adult corn earworms, Helicoverpa zea (Boddie), and other nocturnal insects. Previous research by the ARS in the south-central U.S. has shown that individual corn earworm moths can fly more than 700 km, covering as much as 400 km in a single night. Migrating moths may congregate in narrow atmospheric layers, frequently within the nocturnal low-level jet. Populations of migrating insects are often collectively aligned, sometimes at oblique angles with respect to the wind direction. X-band radars are used to quantify the abundance and flight velocity of corn earworm-size radar targets within a horizontal range of ~5 km and vertical range of 2 km. Concurrent atmospheric profiles are measured vertically using rawinsondes and along quasihorizontal (insect migration) trajectories using Cross-chained Loran Atmospheric Sounding System (CLASS) radiosondes attached to superpressure balloons. WSR-88D Level II data are being analyzed using IRAS-Motif software to calculate the nocturnal evolution of Z, v_r, and SW at ARS field measurement sites. Regressions are being developed between nightly values of Z, v_r, and SW and IA, IV, wind velocity, and thermodynamic state variables. Further, synoptic surveillance by the WSR-88D is being used to evaluate the origins and areawide dispersal of populations of migrating crop insect pests.

Prototype algorithm development is underway using data from WSR-88D facilities in Texas at Brownsville, League City, New Braunfels, Forth Worth, Del Rio, and Waco. New WSR-88D facilities at San Angelo and Corpus Christi, Texas, will complement the surveillance of insect migrations from northeastern Mexico and south-central Texas that annually contribute to infestations of crop production regions throughout the central U.S.

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B. Bureau of Reclamation

1. SNOW ACCUMULATION ALGORITHM

A prototype snow algorithm has been developed that estimates both snow water equivalent (SWE) and snow depth (SD) for 1 h, 3 h, and storm total periods. Estimates are updated each volume scan. The algorithm is undergoing real-time operational testing in Cleveland, Ohio and Minneapolis, Minnesota during the 1996/1997 winter using NSSL's WDSS platform.

The algorithm uses accurate hourly surface SWE and SD observations from selected wind-protected sites representing various snowfall regimes. Thus far, observations from Albany, New York; Cleveland, Ohio; and Denver, Colorado have been used in algorithm development. During the 1996/1997 winter, observations are being obtained in or near Anchorage, Alaska; Minneapolis, Minnesota; California's Sierra Nevada; the Cascades near Seattle, Washington; and western Colorado's Grand Mesa.

An optimization scheme determines regional relationships between equivalent reflectivity factor (Z) and SWE by combining the snowfall observations with WSR-88D measurements. Estimates of SD are based on these relationships and observations of median snow density. Because low-level scanning is important with shallow snow-producing clouds, the lowest practical elevation scan for each range bin which has a minimum of 500 feet separation (for standard refraction) between the local terrain elevation and the radar beam's bottom is used. The algorithm is intended for use with dry snow. It does not detect or compensate for bright band effects from melting snow.

A wind advection scheme has been developed but has shown no skill over the use of Z in the nearest-neighbor range bin. It is suspected that temporal and spatial variations in snow particle fall velocities and departures in the local winds from calculated VAD winds add considerable uncertainty to the advection scheme's calculated snow particle trajectories.

While no range correction has yet been incorporated, future work will address this important issue. For example, observations from many Cleveland area lake effect storms show an average 50 percent underestimation at 100 km range because of earth's curvature, beam spreading, and other factors.

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C. Environmental Modeling Center, National Centers for Environmental Prediction

1. REGIONAL THREE-DIMENSIONAL VARIATIONAL ANALYSIS FOR THE ETA MODEL

A three-dimensional variational analysis has been developed for use with the NCEP (National Centers for Environmental Prediction) Eta model. It is patterned loosely after the NCEP global Spectral Statistical Interpolation (SSI) analysis system (Parrish and Derber, 1992, Derber et al. 1991). There are several differences however. First, the background error statistics are simulated in grid space instead of spectral space, using a recursive filter designed by J. Purser (Hayden and Purser, 1995). Second, there are no slow and fast variables. Approximate balance is maintained only through the addition of a weak constraint on the thermal wind. Finally, the primary analysis variables are at observation locations, not at model grid points.

In spite of these differences, initial indications are that the 3-D Regional Variational Analysis (3DVAR) can be adjusted to fit observations as well as the currently operational Optimum Interpolation (OI) system, both at 80 and 29 km resolutions, but with substantially smoother analysis increments. This confirms early experiences with the global SSI analysis. To date there have been no objective comparisons of parallel forecasts from OI and 3DVAR analyses.

2. RADAR WINDS AND 10 KM GRID ANALYSES

At NCEP, experimental 10 km 3DVAR analyses and forecasts are now being run twice daily at 0300 and 1500 UTC. The first guess for the analysis is obtained from a 3 hour forecast of the 29 km grid Eta model, which is initialized with a global model guess and OI analysis. Doppler winds from the NEXRAD radar network are available at NCEP in real time, and are included in the 3DVAR. The analysis procedure is ideally suited for assimilating Doppler radar data. Because the wind measurements are incomplete (only the component along the radar beam is available), conventional methods require overlapping beams from two radars to get the full wind vector (dual-Doppler method). With the variational procedure, all that is necessary is a forward model, which in this case is just the projection of the model wind along the beam direction.

The Doppler data received at NCEP are NIDS vendor image files with 1 km x 1° resolution and only for the lowest 4 tilt angles. Also, the wind values are stored in only 4 bits as color ranges for an image. Through time and space averaging, filtered observations are obtained with an average spacing of 10 km. Most of the observations are located in the boundary layer. Despite the degradation from the original data, it appears that useful information can be extracted at the 10 km scale.

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D. NASA/Goddard Space Flight Center

1. TROPICAL RAIN MICROPHYSICS AND RADAR PROPERTIES

The availability of simultaneous airborne observations of drop-size distributions (DSD) and vertical air motions in the Tropical Ocean-Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) allows study of the inter-relationships among the microphysical and radar properties of the rain rate (R), reflectivity (Z), and vertical drafts (w). The DSD population was partitioned into stratiform and convective rains using a draft magnitude ($|w|$) of ±1 m s^{-1} averaged over 6 s (~0.8 km path). The stratiform samples ($|w|<1$ m s^{-1}) were further partitioned using a statistical subsample of data with $R \geq 5$ mm h^{-1} which were subjectively determined to be convective. The convective and stratiform rains were characterized by specific Z-R relationships (defined by $Z=AR^b$), i.e., $Z=142R^{1.41}$ (convective) and $207R^{1.43}$ (stratiform). The major difference between the two rain types is the larger total number of small drops with convective rains.

The convective Z-R relation agrees very well with that of Tokay and Short (see Section IV) based upon 1-min surface DSD samples at Kapingamarangi Atoll, but their stratiform coefficient (A) is considerably larger and their exponent (b) is smaller. The difference in stratiform rain is the result of a real change in the Z-R relation with height, as confirmed on a day when the aircraft sampled at both high and low altitudes.

Other studies have addressed the reasons for the similarity between the reflectivity factor-rainfall rate (Z-R) relations in convective rains and the differences in stratiform rains between observations made at the surface and those made aloft during TOGA COARE. Z-R relations are found to be consistent with the relations between the median volume diameter D_o and R in all cases for both the airborne and surface disdrometer measurements. In all but the surface-measured stratiform rain, the D_o-R relations are similar to that of Marshall and Palmer. Using the airborne drop-size measurements, it is demonstrated that much of the difference between the surface and airborne measurements in stratiform rain can be attributed to truncation of the drop-size spectra at small diameters. This results from a combination of evaporation, which decreases the size of the smaller drops, and the minimum drop size measurable by the disdrometer. The effect is to increase A and decrease b in the $Z=AR^b$ relation. The result is a general variation of the Z-R relation with height in the western tropical Pacific. The influence of evaporation on the DSD is enhanced both by the great height of the melting level in the tropics and by the observed existence of dry air in the 2 to 4 km layer in that region. The present results are consistent with findings by prior investigators concerning the occurrence of evaporation and cooling in the stratiform regions of mesoscale convective complexes.

The height dependence of the Z-R relations might also be caused by systematic truncation at the small size end of the drop spectrum by windshear sorting. However, this effect is unlikely in a large sample in which the long-term average distribution approaches exponentiality. But it is common for individual cases where the shear produces anomalously large or small particles preferentially on one side of precipitation cells. This effect will be manifested in surface-based disdrometer measurements and is thought to contribute to the scatter in Z-R relations found in the literature. Although these effects have been demonstrated to be noticeable in the tropics where the stratiform rain region is relatively deep, they are applicable everywhere.

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E. NASA/Marshall Space Flight Center, Global Hydrology and Climate Center

1. A CONVECTIVE-STRATIFORM RAINFALL CLASSIFIER FOR COMPOSITE RADAR REFLECTIVITY MAPS

a. Introduction

The objective of this study is to develop a dataset to characterize rainfalls with a multi-year database of high spatial and temporal resolution radar reflectivity measurements. The radar reflectivity data product, NOWRAD, is a composite of U.S. National Weather Service network radar information as provided by Weather Services, Inc. The spatial resolution of each pixel is 2 km across the United States; the temporal resolution is 15 minutes.

Individual radar images are classified into convective and stratiform rainfall components.

The integration of the 96 images received each day yields a daily rainfall estimate. Estimated rainfalls are also accumulated for monthly and seasonal intervals. The datasets are being used to examine the year-to-year natural variability of rainfall in the United States for the period 1994-1996. Once, convective and stratiform regions are identified, rainfall amounts are computed using appropriate Z-R relationships.

b. Results

A training dataset comprising ten days in April 1994 was used for development and testing. Rainfall episodes on April 11, 1994 and April 21-22, 1994 within the Arkansas-Red River Basin were then examined to evaluate algorithm performance. The first objective was to establish a threshold function to select convective centers. Next, the gradient between each pixel and its neighbors was computed to isolate the centers. The neighborhood reflectivity was specified to be the linear average of non-zero reflectivities, Z, in a 100 km^2 region centered at a pixel. Finally, the rainrate, R, in convective and stratiform rain areas is computed by applying $Z=300R^{1.4}$ to the convective areas and $Z=200R^{1.6}$ to the remaining rain areas.

Area-averaged hourly rainfall estimates derived from the NOWRAD data for an entire month were separated into convective and stratiform components and were compared with the NWS Stage-III River Forecast Center (RFC) rainfall estimates during the same period. The hourly RFC estimates were derived from raingauge-adjusted WSR-88D reflectivity fields. The trends in both estimates are similar and the differences over the basin are a few mm day^{-1}.

c. Conclusions

The attempt at classifying rainfall over one large river basin on a monthly time frame gave promising results. The 28-day sample dataset for April shows low rms error values of 0.12 mm (or 45% of the Stage-III area-averaged hourly mean rainfall) with a bias of 0.01 mm. It appears that the methodology should produce sufficiently accurate estimates of rainfall over large spatial domains and over multi-year time periods to characterize the year-to-year differences in rainfall. The rainfall distributions and characterizations can be used as input or validation to regional modeling experiments to learn more about the seasonal-to-interannual behavior of rainfall and its response to larger scale atmospheric forcing. The database may also be of use in recomputing extreme rainfall statistics for improved water management models and decision aids.

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1. DEVELOPMENT OF RADAR RAIN RETRIEVAL ALGORITHMS BASED ON PROBABILITY MATCHING METHODS

The main difficulty of radar rainfall measurement is the lack of uniqueness in the relationship between the radar measured precipitation echo intensity (Z) and the surface rain intensity (R). Z-R relationships are highly variable in time and space because of inherent constraints, e.g., changes in drop-size distributions, partial beam filling, and attenuation. Due to distortion of the true reflectivity field, the relationships can not be solved by an analytical algorithm. The difficulties are minimized by the Probability Matching Method (PMM) which matches the observed reflectivity to raingauge measured rates in a probabilistic manner. Using a statistical approach, such as the PMM, appears to be especially appropriate to the estimation of the average rainfall over space/time domains because such estimates are free of many of the corrupting influences of point measurements. Additional improvement in the accuracy of the retrievals is found upon application of the PMM to data that have been objectively classified into different rain types. The classification is done by analyzing the 3-dimensional structure of the observed reflectivity field in small windows (in time and space) according to several parameters that best explain the variability in the Z-R relationships. The classification allows the utilization of monotonic Z-R relationships--an assumption which is implicit in PMM schemes.

An algorithm for radar rain retrieval based on PMM has been developed as part of NASA-TRMM ground validation project and the Israeli rain enhancement program. Recently, the algorithm was selected as the principal TRMM ground validation rain retrieval algorithm. Extensive testing of the algorithm was performed on the Melbourne, Florida WSR-88D radar. It was shown that the PMM performed significantly better than the standard WSR-88D rain estimation algorithm. The improved performance of the algorithm in general and upon its application to WSR-88D for rainfall estimation was summarized in a number of publications.

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G. NOAA/Environmental Technology Laboratory

1. DIFFERENTIATION OF FREEZING DRIZZLE FROM ICE HYDROMETEORS AND FREEZING RAIN WITH DUAL-POLARIZATION RADAR

Freezing drizzle has been identified as a primary in-flight icing hazard. Because freezing drizzle may form by droplet coalescence without a melting process, it can be more difficult to detect than freezing rain. Theoretical calculations of microwave scattering and verification by initial field studies with the NOAA ETL K_a-band (8.66 mm) radar demonstrate that freezing drizzle should be detectable and distinguishable from other hydrometeor types in radar measurements of elliptical and linear depolarization ratios. A practical procedure has been suggested for identifying and monitoring this aviation hazard with polarization radar and concurrent atmospheric temperature measurements. Although the methodology and potential corresponding algorithms for operational application require further field testing, the technique is applicable to the WSR-88D radar with certain constraints.

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H. NOAA/NEXRAD Operational Support Facility

1. MESOCYCLONE AND TVS ADAPTABLE PARAMETER STUDIES

In 1995, the Operational Support Facility (OSF) and NWS made recommendations to NWS field sites for modifying an adaptable parameter (TPV) in the Mesocyclone Algorithm. [The Mesocyclone optimization studies are documented in conference papers listed below.] In 1996, a field survey was conducted concerning tornado occurrences and TVS detections. An overwhelming number of respondents indicated that the TVS algorithm was rarely triggered by tornadic storms. Consequently, several adaptable parameters studies were performed in order to optimize the algorithm. The studies revealed that it was possible to improve the performance of the TVS algorithm by modifying one adaptable parameter. Hence, the OSF and NWS recommended that field sites consider lowering the Threshold TVS Shear (TTS) parameter from its default value of 72 h^{-1}. [A value of 72 h^{-1} corresponds to 0.02 s^{-1} and is equivalent to a shear of 50 m s^{-1} over a distance of 2.5 km.] The recommended starting point of 36 h^{-1} allows the TVS algorithm to find and detect circulations with weaker shears. The OSF will continue to evaluate the performance the TVS algorithm at sites which implement the parameter modification.

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2. TORNADO DETECTION ALGORITHM

NSSL has developed a next generation Tornado Detection Algorithm (TDA). Its performance proved to be better than the currently fielded TVS algorithm; hence, the upgraded algorithm was recommended for inclusion in the OSF "Build 10" software release. Preparation of the new algorithm was begun. OSF and NSSL scientists began converting the TDA FORTRAN code into a formalized functional document, called Algorithm Enunciation Language (AEL), which describes the algorithm, details the processing steps in pseudo-code, defines variables, lists numerical processing steps, and specifies output and possible future enhancements. When the AEL is complete, it will be delivered to OSF software engineers who will develop the algorithm for the Concurrent computer system used by the WSR-88D radar.

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3. NSSL DATABASE ENHANCEMENT

NSSL continues to collect information about severe weather events and correlate occurrences with WSR-88D radar data. The goal is to allow users to query a database of weather events and find Archive Level II tape information associated with the event. A user can also specify a radar and a weather event type; the program automatically shows what Level II data, if any, has been archived. The search procedure can also take a Level II tape number and look up what weather occurred on that day for that location. Users will need to order all data from The National Climatic Data Center (NCDC), but the database and search capability will make it easier to determine what radar data exists for a given event. The database and search procedure has been updated in the last year and is available on the World Wide Web (http://www.nssl.uoknor.edu/projects/nexcat/).

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4. HUMAN FACTORS

The following is a brief summary of projects undertaken by the OSF Human Factors Group during 1996. The tasks represent activities within the OSF Applications Branch that are associated with human performance engineering endeavors. Broadly speaking, involvement in problems, solutions, subsequent changes related to human-computer interaction, and user interfaces of the WSR-88D are of greatest concern.

a. A New WSR-88D Unit Control Position

1) Development overview

A project is underway between the National Severe Storms Laboratory (NSSL) and the OSF to rehost the Radar Product Generator (RPG) to non-proprietary hardware and a POSIX-based operating system. The Open Systems Radar Product Generator (OS RPG) project involves several concurrent system and software development efforts. One of these efforts has tasked the OSF Human Factors Group to redesign the WSR-88D Unit Control Position (UCP).

The current UCP is based upon a command language hierarchy, a nested menu interface scheme that has been shown to be difficult and inconvenient to use operationally. A new Graphical User Interface (GUI) UCP based on human performance engineering methods is being developed by a small group called the GUI Team. This new interface will be more intuitive while providing users with a more effective "tool" in daily operations of the WSR-88D.

After six months of prototype development, the GUI Team has already discovered many ways that a graphical user interface can simplify and clarify important capabilities of the UCP to enhance daily forecast office operations.

The GUI Team holds weekly meetings to analyze, discuss, and shape the evolving GUI prototype. With a commitment to the user and usability, several controlled studies are underway to objectively measure the "goodness" of the human-computer interaction and to feed the results back into the GUI design. The GUI Team realizes the importance of involving the user and understanding the tasks performed at the UCP. Consequently, ideas from operational personnel have already been incorporated and efforts remain to establish a user profile and task analysis. Work flows and real scenarios are considered essential to the design of the GUI UCP.

Methods used by the GUI team to acquire user feedback in the interface development process include electronic mailing lists and email, contacts with triagency points-of-contact, interviews, field visits, questionnaires, audio and video recordings, and exchanges with formal user groups.

2) Specific GUI testing

Efforts are underway to formally test the graphical user interface replacement to the UCP. Plans include testing users against the GUI UCP and quantitatively measuring aspects of interaction.

Some of the relevant dependent and independent variables in the test are: (1) usage considerations comparing the legacy UCP and the new GUI, (2) alternatives of a new GUI interface, and (3) the types of tasks performed on both interfaces. Likewise, there are various tasks which can be performed that have been conveniently categorized as easy and complex and as very frequent and rare. Hence, the objective is to measure complexity, workload, and frequency of a task.

Identified items which may be measured are the time needed to perform a task, the number of operations to be performed, the user accuracy, the dexterity required, the frequency of errors (cognitive and clerical), and the number of help requests. A formal experimental design plan is under development.

The time to perform a predetermined task is one measure of improvement. Hence, time is expected to be used as a dependent variable for statistical analysis. Plans include establishing the GUI version as independent variable. The complexity of the task and the number of operations to be performed are other factors to be considered. Notes from recent GUI Team meetings can be found in the OSF Web pages (address: http://www.osf.uoknor.edu/app/gui/gui.htm).

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b. NSSL/OSF Human Factors Group MOU

1) Human Factors WDSS Input Logger

Contacts with NSSL, refinements to the input logger specifications, and prototype evaluations led to a workable version of the Input Logger for the Warning Decision Support System (WDSS). Plans exist to insert the Input Logger during the spring of 1997 in several WDSS systems configured with the WSR-88D Radar Ingest and Data Distribution System (RIDDS).

In addition, the Input Logger will be inserted into a special Applications Branch version of the WSR-88D Algorithm Testing and Display System (WATADS) for experimentation, testing, and evaluation.

The fundamental purpose of the Input Logger is to record WATADS or Radar Analysis And Display System (RADS) operational user actions in the form of numbers and other coded values which represent usability metric variables. From these data, user interface problems can be identified and improvements made. The log files will serve as a substitute for the video recordings that were obtained in the OSF Human Factors portion of the 1994 NSSL Phoenix Beta test. There are advantages to the purposed method of collecting use information. First, the collection process is nearly automated, the usability figures are available at each site that runs RADS without added expenditures or set-up efforts. Second, the sampling of several sites offers a favorable experimental environment that extends the sample population.

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5. VELOCITY DEALIASING

Recent work has been to validate results obtained by NSSL scientists. Both the OSF and NSSL have been testing changes to the current WSR-88D Velocity Dealiasing Algorithm (VDA) that force it to find a solution for all velocity bins rather than allowing it set some bins to "missing", i.e., the background below signal-to-noise value. The rationale is that important mesocyclonic and tornadic signatures can be lost when such data are set to missing. Conway et al., 1994, tested changes to the adaptable parameters to force a solution everywhere. Their changes are referred to as the NSSL "optimized" set (See Attachment). NSSL had also identified a potential logic flaw that allowed the existing algorithm to re-dealias velocities along a radial well beyond the region where it had detected a large number gates with high azimuthal shear. We believed it was important to check the performance of their proposed correction as described in Conway et al., 1995. The changes were detailed in the Appendix A of that report and are referred to hereafter as Appendix A changes.

As part of the MOU work, NSSL visually scored a subset of at least 10 volumes from each of six datasets they had previously scored using statistics generated by bin comparisons against "truthed" data. For this work, they scored six versions of the VDA code besides the default software code with default adaptable parameter settings currently fielded. The six variants borrowed from results obtained in previous reports. The first VDA variant adjusts the existing set of adaptable parameters to force a solution everywhere. The second variant tests the Appendix A changes with the default adaptable parameter settings. A third variant combined the NSSL "optimized" adaptable parameters with the Appendix A changes. The fourth variant was the same as the third except that the number of adjacent pairs of bins with high azimuthal shear which the algorithm tolerates before re-dealiasing was increased from 10 to 25. The fifth variant was the same as the fourth except that internal counters related to azimuthal jumps were not reset. The last variant combined the Appendix A changes, the increase to 25 bins for large azimuthal shears, the default adaptable parameters, and a module that made one final attempt restore data bins using relaxed radial continuity both in the outward direction from the radar and the inward direction toward the radar. If no solution was found, the original velocity was restored to the bin.

This module was invoked after all other logic was completed so that the original VDA logic did not use data replaced by this module to influence dealiasing of other radials later.

The velocity fields were scored using a 5 point system in half-point increments. The numerical scale is as follows:

5 Velocity field appears meteorologically believable with no dealiasing errors.

4 Some small spikes or wedges are present in ground clutter or strong shear regions. Small isolated regions may appear to be in the wrong Nyquist interval. Leading edges of echoes may be incorrectly dealiased over a sweep of 10 degrees or less. Important velocity features and the large-scale flow are recognizable.

3 Dealiasing failures such as spikes and wedges extending over tens of kilometers and tens of degrees are present. Some velocity areas may be missing from the field. Overall flow is recognizable but singular velocity features may be corrupted. Large regions appear to have been dealiased in the wrong Nyquist interval. Leading edge echoes may be dealiased incorrectly for up to 90 degrees or 100 km chord length.

2 Dealiasing discrepancies extend over 50 percent of the echo. Major flow patterns have been corrupted. Singular velocity features are uninterpretable. Major regions of velocities are omitted from the field.

1 Velocity fields are uninterpretable. The major flow patterns are corrupted. The algorithm failed to perform any dealiasing. Over 50 percent of the field was removed by the algorithm.

If there were no errors in any of 156 velocity fields examined, a perfect score of 780 points was possible. Points were deducted for visible dealiasing errors in the fields and subtracted from the perfect score. The percent correct was the ratio of the resulting score to the perfect score. The results for the default VDA and the six variants tested are as follows:

Percent Correct

Default	Var. 1	Var. 2	Var. 3	Var. 4	Var.5	Var. 6

13 Mar 93	95.1	93.0	96.7	93.0	92.5	93.1	96.0
17 Aug 94	94.4	94.2	96.8	87.8	94.3	94.6	96.5
11 May 92	99.8	99.1	100	99.2	98.7	98.2	99.6
3 Jun 93	96.3	96.0	98.9	95.3	94.7	85.3	98.3
3 Sep 92	98.8	97.4	99.3	96.2	95.5	94.0	98.4
7 May 95	97.8	97.8	92.3	94.4	96.7	97.6	97.7
Average	97.0	96.4	97.3	94.4	95.4	93.9	97.7

Variant 6, besides having the highest overall score of 97.7, also showed consistently high scores for each of the six datasets ranging from a low of 96 percent correct to a high of 99.6 percent correct.   Variant 2, with the next highest overall score, had values that ranged from 92.3 percent correct to 100 percent correct. The default VDA had the third highest overall score of 97.0 percent correct with a low of 94.4 percent correct and a high of 99.8 percent correct.

NSSL has recommended implementing either variant six or yet another variant that would simply add the module that replaces velocity bins in variant six with the default VDA code. The Applications Branch of the OSF has begun testing the latter variant VDA as a candidate for implementation in the WSR-88D Build 10 software slated for release in of spring 1998. This VDA would be installed as an adjunct to a new Tornado Detection Algorithm also slated for Build 10.

Velocity Dealiasing Adaptable Parameters used in comparison.

Parameter	Default	NSSL "Optimized"
NUM_BIN_FSTCHK	5 bins	7 bins
NUM_REP_LKAHD	10 bins	5 bins
NUM_REP_LKBK	4 bins	10 bins
NUM_LKFOR	15 bins	15 bins
NUM_REUNF_CAZS	30 bins	30 bins
NUM_REUNF_PRAZ	10 bins	10 bins
TH_CONBIN_REJ	5 bins	1 bin
TH_MAX_CONAZJMP	5 radials	2 radials
TH_MXMISS	30 bins	30 bins
TH_MXBINS_JMP	75 bins	75 bins
TH_BINS_LRG_AZJMP	10 bins	15 bins
TH_DIFF_UNFOLD	10.0 m/s	14.0 m/s
TH_VEL_JMP_FRAD	0.75	0.75
TH_VEL_JMP_FAZ	0.60	0.60
TH_SCL_STDEV	0.40	0.60
TH_SCL_DIFF_UNFOLD	1.50	1.25

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6. PROPOSED OPERATIONAL TEST OF A TERRAIN-BASED HYBRID SCAN DATA FILE

This past year or so, the OSF has developed a potential replacement for the current Precipitation Processing System (PPS) Hybrid Scan file that should mitigate some of the concentric circular artifacts in the PPS products. This modified Hybrid Scan file can be quickly generated for each site, requiring only a change in an adaptable parameter in the offline WSR-88D software that generates the Hybrid Scan file. The modified Hybrid Scan file has been evaluated by playing back Level II data from several WSR-88D sites. Results have been positive enough to operationally test the files at two Western Region WSR-88D sites, Eureka, California and Salt Lake City, Utah. The following paragraphs describe the problem, the creation of the Hybrid Scan and the "Terrain-based" Hybrid Scan files, and some early results.

Field sites have frequently reported sharp circular discontinuities in WSR-88D Precipitation Processing Subsystem (PPS) rainfall estimates within 50 kilometers of the radar, particularly in stratiform and orographic rainfalls. These discontinuities are not representative of the true rainfall pattern and frequently associate with significant underestimates of precipitation, at times by an order of magnitude. The radar's poor performance in estimating heavy rainfall near the radar in these situations can contribute to missed flash flood warnings and may represent a hazard to life and property, particularly in coastal mountain areas where heavy orographic rainfall is common.

Investigations at the OSF and the Office of Hydrology show that the discontinuities are primarily caused by a requirement in the off-line WSR-88D software that generates the site-specific Hybrid Scan file. The Hybrid Scan is derived from digital terrain height information and it defines, at each range and azimuth, which of the lowest four tilts radar of reflectivity data will be used by the PPS software.

The elevation angle to be selected for a given range bin and azimuthal slice in the Hybrid Scan Data Set is specified as being the lowest elevation angle whose beam center is closest to an "optimal height" (1000 meters) above radar level which meets the following criteria:

1) The height of the bottom of the radar bin will be greater that any obstruction at that range...by at least 500 feet.

2) The range bin will not have any shorter range bin in the same 1-degree azimuth slice which has a blockage factor of more than 0.5 (50%).

3) If no elevations satisfy condition 1) or 2), then the lowest elevation will be used.

The "optimal height" requirement creates sharp height discontinuities in the Hybrid Scan file at the ranges where the "optimal" tilt changes. The height discontinuity is about 320 meters at a range of 19 kilometers (tilt 3/tilt 4), 460 meters at a range of 28 kilometers (tilt 2/tilt 3) and 820 meters at a range of 50 kilometers (tilt 1/tilt 2).

Discontinuities beyond 50 kilometers are caused by the proximity of the bottom of the radar beam to the terrain. Inside 50 kilometers, the discontinuities are annular and are forced by the 1000 meter "optimal height" requirement. The annular discontinuities in the Hybrid Scan create the "rings" in the PPS product, particularly in stratiform rain and orographic rain, or whenever the precipitation has a strong vertical reflectivity gradient at low levels.

The "optimal height" requirement was based on the assumption that clutter and anomalous propagation would significantly contaminate WSR-88D precipitation estimates at low tilts close to the radar. This assumption does not appear to be valid operationally since WSR-88D clutter filtering seems to be very effective at eliminating or minimizing clutter and anomalous propagation contamination, particularly near mountain tops. Considering that the "optimal height" was causing annular artifacts in the PPS products and beginning with an assumption that the reflectivity data from the lowest uncontaminated and unblocked tilt is most likely to be representative of the precipitation which reaches the ground, the OSF Applications Branch began investigating "terrain-based" Hybrid Scan files. These "terrain-based" files are produced from the same software that generates the operational Hybrid Scan files, but through a single adaptable parameter change, the 1000 meter "optimal height" requirement is eliminated. At a mountain top location the "terrain-based" Hybrid Scan may use the lowest tilt to within a couple of kilometers from the radar.

The Applications Branch has evaluated the effect of using the "terrain-based" files using off-line PPS software, Level II data, and some concurrent raingauge data. So far, the results have been very encouraging, particularly at Eureka (KBHX). For the 2/21/95 KBHX dataset, the "terrain-based" Hybrid Scan improved the gauge/radar ratio for three gauges near the radar from 1.85 to 1.16. The radar estimate at one gauge increased from an anomalously low 0.15 inches to 1.13 inches (agreeing with the gauge value). In a second KBHX dataset (2/23/95), the "terrain-based" Hybrid Scan improved the gauge/radar ratio for the three gauges from 2.53 to 1.29 and corrected the radar estimate for one gauge from 0.01 inches to the gauge value of 0.54 inches. The gauge was about 45 kilometers from the radar, a range at which the operational Hybrid Scan might be expected to generate poor gauge/radar agreement. In the cases studied to this date, the "terrain-based" Hybrid Scan has caused no observable degradation of PPS products.

Two Western Region sites, KBHX and KMTX (Salt Lake City), have requested permission to test the "terrain-based" Hybrid Scan files operationally to see if they improve serious precipitation underestimation problems the sites are experiencing in their PPS products. In addition, the Applications Branch will study cases using data from other regimes (valleys, plains, near cities, etc.) to determine if the "terrain-based" scan causes any PPS product degradation.

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I. NOAA/National Severe Storms Laboratory

1. INTRODUCTION

The National Severe Storms Laboratory (NSSL) has spent considerable time and effort in the analysis of Doppler radar data and the development and enhancement of hazardous weather detection algorithms. Algorithm testing is accomplished both in a post-analysis research environment and in real-time at NWS 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 implementation on the WSR-88D and AWIPS systems.

In addition, the Verification of the Origin of Rotation in Tornadoes Experiment (VORTEX) was conducted during the 1995 and 1996 convective seasons (in conjunction with several other organizations). The analysis of VORTEX datasets is ongoing and will be used to gain insight into the origin and characteristics of tornadoes for use in present and future automated algorithms.

2. ALGORITHM DEVELOPMENT AND ENHANCEMENT

a. Storm Cell Identification and Tracking (SCIT) Algorithm

The SCIT algorithm was approved and transferred to the WSR-88D system and implemented in Build 9. This version of SCIT identifies cells using multiple reflectivity thresholds and is capable of identifying embedded cells in multi-cellular formations. The new version also provides time-trends and time-height trends of various observed storm characteristics, such as the height of maximum reflectivity, maximum reflectivity, cell base and top, vertically integrated liquid (VIL), and information from other NSSL algorithms.

NSSL is examining output from the SCIT algorithm and the other algorithms to determine which diagnosed parameters are related to storm longevity. Numerous time series datasets are being acquired to complete this task. Thus far, datasets have been produced for 15 storm days using observations from Memphis, Tennessee. In addition, numerical cloud models are being run in ensemble to make probabilistic forecasts about convective activity characteristics for each storm day. This work is being done in collaboration with NCAR and MIT/LL.

NSSL plans to implement a continuous update processing technique in SCIT. This upgrade will provide updated storm cell detections after each elevation angle rather than at the end of each volume scan.

b. Mesocyclone Detection Algorithm (MDA)

A rigorous offline performance analysis of the NSSL MDA was completed. Twelve days, comprising ~70 tornadoes and 96 hours of radar data, were evaluated. Six of the cases were used as a dependent dataset used to train a Neural Network (NN) to diagnose the probability that MDA-detected circulation signatures were either tornadic or non-tornadic, or severe or non-severe (using ground truth as validation). The other six cases were used as the independent dataset, where NN output as well as rule-base classification schemes in both the NSSL MDA and the baseline WSR-88D Mesocyclone Algorithm (88D-Meso) were compared.

This original NN was developed using only Southern Plains isolated tornadic supercells for the 6 dependent datasets. Ten additional cases were added to the 6 dependent data cases and the 6 independent datasets to create a new 22-case dependent dataset to train a new NN. This expanded dataset had a variety of storm types (e.g., low-topped mesocyclones, bow-echo storms) from a variety of geographic areas in the U.S.

Output from the MDA code was modified to provide additional input to an improved NN. These new outputs contained trends of various attributes and Near-Storm Environmental (NSE) data. Also, the output variables from the NSSL Tornado Detection Algorithm (TDA) were merged with the MDA output. The total number of cases in this new dependent dataset used for NN training and statistical analyses was 29, comprising about 120 tornadoes and 210 hours of radar data.

NSSL also plans to begin the investigation and development of a storm-scale Vortex Detection and Diagnosis Algorithm (VDDA) which will combine the MDA and TDA into a single storm-scale vortex detection algorithm.

c. Tornado Detection Algorithm (TDA)

The Tornado Detection Algorithm (TDA) has been tested using geographically diverse dependent and independent Archive II datasets consisting of 23 and 31 tornadoes, respectively. This study focused upon optimizing the NSSL TDA using three parameters which were found to best distinguish between tornadic and non-tornadic gate-to-gate (azimuthally adjacent and constant range) circulations. The dependent dataset was used to determine the optimal values of the three parameters which maximized the critical success index (CSI). These parameters and their values were the maximum gate-to-gate velocity difference at the 0.5 degree elevation angle (25 m s^{-1}), the maximum gate-to-gate velocity difference (36 m s^{-1}), and the circulation depth ($\geq$ 1.5 km). The independent dataset was then used to verify the performance of the TDA using the optimized parameters.

Results using the independent dataset indicated a significant increase in the TDA's capability to identify tornadic circulations in comparison to the WSR-88D TVS Algorithm (88D

TVS). As a result of this performance comparison, the TDA was approved for implementation in Build 10 of the WSR-88D system as a replacement for the current WSR-88D TVS algorithm.

Future plans include combining the outputs from the TDA and the Mesocyclone Detection Algorithm (MDA) to train a neural network to discriminate between tornadic and non-tornadic storm-scale circulations. Also, the NSSL will investigate a means by which to combine the techniques used in the TDA and the MDA to design an overall vortex detection algorithm to detect and diagnose storm-scale circulations.

d. Hail Detection Algorithm (HDA)

A cone-of-silence flag was added to the HDA to alert users to those situations when a storm is too close to the radar for it to be fully scanned. The flag is triggered if a detected storm cell has a 2-D component observed at the top elevation angle of the Volume Coverage Pattern (19.5 degrees) with a maximum reflectivity of 45 dBZ or higher. When this happens, the HDA output displayed via the Radar Analysis and Display System (RADS) Cell Table is highlighted with a purple background color to indicate that the output is likely underestimating the hail threat.

During the summer months of 1996, forecasters from two Warning Decision Support System test sites (Melbourne, Florida and Minneapolis, Minnesota) reported that the maximum hail sizes predicted by the HDA were too large. To investigate the extent of the problem, NSSL plans on conducting a detailed evaluation of the HDA for numerous summertime storm cases using WSR-88D Level II data recorded at these sites. A sensitivity study was performed to determine if the over warning was due to bad environmental data (temperature profile), but this was not the case. To determine if the over warning is largely the result of limitations in ground-truth verification, NSSL has obtained a population density database, and will score the HDA performance as a function of different population density thresholds.

e. Damaging Downburst Prediction and Detection Algorithm (DDPDA)

NSSL has developed an experimental Damaging Downburst Prediction and Detection Algorithm (DDPDA) which identifies both downburst signatures and precursors to downbursts. Precursors are combined using a fuzzy logic weighting scheme to provide a prediction of wind intensity at the surface. The weight given to each identified precursor in a storm cell is based on a database of more than 50 cells which produced outflows of varying strengths. Analysis of this database indicates that the most statistically relevant precursors are the initial height of the high-reflectivity core, strong convergence in the layer 2-7 km above the surface, and the descent of the high-reflectivity core.

The results of real-time DDPDA testing at several NWS Forecast Offices will be examined in the coming months. Future versions of the algorithm will incorporate Near Storm Environment (NSE) data. Meanwhile, better prediction equations will be developed to encompass a wider seasonal and geographical range of environmental conditions.

f. *Near Storm Environment (NSE) Algorithm*

The Near Storm Environment (NSE) algorithm was developed to provide current environmental information [via the Rapid Update Cycle (RUC) model] to the NSSL radar-based algorithms. The NSE algorithm provides the height of the 0 and -20°C temperature levels to the Hail Detection Algorithm (HDA).

The NSE algorithm was extended to allow algorithms access to Meso-eta and Eta model output. The Meso-eta model output contains 3-hourly information from an array of gridpoints spaced 29 km apart. The Eta model output consists of 6-hourly information on a 48 km grid. The Meso-eta model output currently is being used in storm growth and decay studies. Over the past year several new parameters have been derived from the model output. Most of the new parameters diagnose environmental wind shear. Finally, offline runs of NSSL algorithms that include RUC NSE information are now possible by allowing previously-generated NSE files to be incorporated.

g. *Simulated Vortices*

Software was developed to simulate the characteristics of tornado and mesocyclone vortices as observed by the WSR-88D system. The software can account for the azimuthal separation between radials, antenna rotation rates, and the number of velocity samples. The characteristics of the simulated vortices aid in the development of algorithms capable of discriminating various scales of rotation at various ranges from the radar.

3. RADAR DATA PROCESSING SYSTEMS

a. *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 data stream in real time. The system uses a SUN Sparc 5 to communicate with the WSR-88D Wideband User Port to ingest the Level II data and distribute the data over an Ethernet to other workstations for processing. The RIDDS system is also capable of archiving the Level II data. There are currently 15 NWS and DOD sites that are using the RIDDS software for various purposes.

New developments in the RIDDS software include the use of a more stable windows environment to eliminate system failures that occurred while booting in "console" mode. Also, the RIDDS User's Guide has been updated, a RIDDS Interface Control Document (ICD) was created, and a RIDDS software distribution package has been developed. Software in this package reads the RIDDS circular buffer, ingests the data, and displays and loops velocity, reflectivity, and spectrum width information. It has two purposes: 1) to be used on a portable SUN computer for field testing during installation of a new system and 2) to be made available to designated users writing their own interface.

b. Warning Decision Support System (WDSS)

NSSL has developed a system to execute our full suite of severe weather detection and prediction algorithms in real-time and to display base data and algorithm output in innovative ways. The Warning Decision Support System (WDSS) is intended to help forecasters make informed decisions about severe weather warnings. The WDSS processes real-time Level II data from the WSR-88D (via the RIDDS software) and executes the algorithms outlined above. The algorithm output is displayed using the Radar Analysis and Display System (RADS; Section I.3.d) along with base data products. In addition to WSR-88D data, the WDSS has the ability to integrate other data streams 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 to provide both an integrated look at a potential warning situation and serve as "environmental" input to the algorithms.

NSSL has conducted several real-time operational tests of the WDSS since 1994 in National Weather Service offices. During 1996, tests were conducted in Minneapolis, Minnesota; Indianapolis, Indiana; Melbourne, Florida; Charleston, South Carolina; Atlanta, Georgia; Pittsburgh, Pennsylvania; Fort Worth, Texas; Phoenix, Arizona; Norman, Oklahoma; Denver, Colorado; Jackson, Mississippi; and Salt Lake City, Utah. The real-time operational tests are designed to gain feedback from forecasters to help with the continuous enhancement of both the algorithms and display concepts. The NWS offices have participated in these tests with extreme enthusiasm because of the direct input that the participants have in the development of tools for future NWS use.

During the past year, NSSL has also worked with the U.S. Bureau of Reclamation to integrate their Snow Accumulation Algorithm into the NSSL WDSS system. This newest version of WDSS is running in Minneapolis, Minnesota and Cleveland, Ohio where NWS forecasters are currently evaluating the products.

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

The WSR-88D Algorithm Testing and Display System (WATADS) software was developed for use by the Science and Operations Officers (SOO's) of the NWS. The WATADS software is an off-line version of the WDSS that can be used to perform adaptable parameter evaluations on both NSSL algorithms and current WSR-88D algorithms. In addition, WATADS can be used to re-examine interesting cases in great detail. The user has the ability, through a graphical user interface, to change adaptable parameters and input environmental information (such as a sounding) before executing the software. The WATADS software also includes a version of RADS (Section I.3.d) that was created specifically to display output from both the current WSR-88D algorithms and NSSL algorithms.

WATADS 8.0 was released in 1996 with the WSR-88D Build 8.0 algorithms. A new version will be released in early 1997 that will include updated algorithms from Build 9 (SCIT and HDA) and additional display products. The new display products will include a VIL image, Build 9 WSR-88D SCIT trends, enhanced HDA icons, and the capability to display vertical cross-sections.

d. *Radar Analysis and Display System (RADS)*

RADS allows quick and easy viewing of base radar data and algorithm information in both real-time and for post-analysis. RADS has the ability to display algorithm information in a time series format (single parameter as a function of time and height), in a tabular format with the output ranked according to storm severity, or in iconic format which can be "overlaid" on base radar data.

During the past year, a multiple-panel display function was added to RADS. This function allows the user to display up to eight different base or derived products simultaneously. RADS also has the ability to display GOES satellite data from the infrared, visible, and water vapor channels in the same domain and magnification as the radar data. All maps and algorithm information can be overlaid on the satellite data as well. RADS is used as part of the WDSS for real-time testing of the NSSL algorithms and offline as part of WATADS for testing current NSSL and WSR-88D algorithms.

e. *Inventory of WSR-88D Level II Data*

The NSSL/OSF Level II database has grown to a total of 823 tapes. The tapes have been acquired in cooperation with the NCDC and via tape archival of Level II data by NSSL during its testing of the Warning Decision Support System (WDSS). Furthermore, ground truth data associated with the Archive II data tapes dating 1995 and before are also 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 5962 hail, 1437 tornado, and 4024 severe wind events are included. In order to better facilitate requests related to the Level II database, NSSL has created a WWW site (NEXRAD Events/Tapes Tracking System [NETTS]) that allows for systematic searching of the Archive II database according to event, event intensity, radar site, date, and time. The site is located at "http://www.nssl.uoknor.edu/projects/nexcat".

Furthermore, NSSL has created WWW pages to facilitate access to Level II inventories, tape indexes, and the ground truth information. Links are also provided for quick access to the NETTS and the NCDC. The site is located at "http://www.nssl.uoknor.edu/~mitchell/l2_dbase.html".

These sites provide useful WWW tools for finding severe and tornadic events that have been captured by Archive II data. Note that all Level II data should be acquired through the NCDC.

f. *Open System Radar Product Generator (ORPG) Development*

An MOU between the ERL and the NWS has tasked NSSL to lead the software development efforts for the Open Systems Radar Product Generator (ORPG). Open Build 1 will be the first operational release of the ORPG and will minimally be of the existing RPG's Build

10 functionality. This release is currently scheduled to be delivered to the OSF for testing at the end of 1998.

The ORPG is being engineered for expandability to accommodate future growth and resource demands. An ability to easily incorporate new meteorological algorithms, product generators, and other functionality will be provided through the encapsulation of services and modules as well as the "loosely" coupled relationship of the processes making up the system. As resource demands for processing, memory, and storage increase, the ORPG will be able to expand without changes to the existing software. The ORPG software is also being developed to be portable across POSIX compliant systems, making relatively inexpensive COTS hardware available for the ORPG and thereby mitigating technological obsolescence.

An iterative development model was chosen for the ORPG project. Tasks are expected to be completed over five "Mini-Builds", each lasting approximately six months. Mini-Build 1 (MB1), completed near the end of December 1996, primarily involved the development of an entirely new software infrastructure for the ORPG, i.e., support for distributed processing, porting of the FORTRAN meteorological algorithms and product generators, and the establishment of a new graphical user interface (GUI) for the Unit Control Position (UCP). Work has begun on Mini-Build 2. The primary emphasis of MB2 will be in the areas of Product Distribution, RDA Monitoring and Control, Communications, and continued GUI UCP development.

g. Open System Radar Data Acquisition (ORDA) Development

To support long-term evolutionary and revolutionary changes on the WSR-88D network, NSSL has acquired the prototype WSR-88D radar system from the National Weather Service. This research and development tool will serve to test improvements and new ideas, simultaneously satisfying longer-term and immediate needs. Ideas proven to enhance WSR-88D performance will be transferred to the network. Some of the changes include replacing the existing signal processor and computer system with the latest technology to allow additional capability, flexibility, and growth in computing resources. Machine independent software will be used to provide enhanced capacity for communication and data processing as well as facilitating system upgrades and maintenance. Initially, two modes of operations will be achieved. In one mode, the radar will duplicate the existing functionality of the WSR-88D and permit evaluation of possible improvements. The other mode concerns polarimetric measurements and will constitute a major research and development effort.

4. RADAR POLARIMETRIC TECHNIQUES

NSSL has developed a methodology to estimate the vertical distribution of liquid water and rainfall from polarimetric radar measurements. This methodology utilizes the specific differential phase K_{DP} and two types of range filtering. In lighter rain (reflectivity factor < 40 dBZ) the range over which the derivative is estimated is 10 km; at higher rain rates it is about 3 km. A large amount of polarimetric data has been collected and is being used to study rainfall measurements. In particular, range limitations are being examined by comparing rainfall estimates with accumulations at distant Oklahoma Mesonet gauges.

Data from ten winter storms having different types of snow have been collected along with in situ verification. Analysis indicates that snowfall at warmer temperatures has distinctly different polarimetric characteristics than snow at colder temperatures. Also, it has been determined that differential reflectivity is a good discriminator between rain and snow.

5. RANGE/VELOCITY AMBIGUITY MITIGATION

a. Hardware Solutions

NSSL, NCAR and FSL begun a study to determine suitable methods for resolving range and velocity ambiguities in the WSR-88D system. NSSL is concentrating on various phase coding techniques and on assessing the practical implications of such schemes. Intense simulations are being made and will be documented in a forthcoming report.

b. Velocity Dealiasing Algorithm (VDA)

The WSR-88D Velocity Dealiasing Algorithm (VDA) has been studied for several years at NSSL in an attempt to remove errors while providing the best available data for input into other algorithms. The current VDA removes high shear estimates if the algorithm is unable to determine the correct Nyquist interval for the aliased data. This was particularly troublesome in storm-scale circulations where a Tornadic Vortex Signature (TVS) could be removed from the data. The problem was fixed by changing an adaptable parameter to replace each data value that was removed. However, this change was also shown to create errors in other areas. NSSL has tested and implemented a save/replace module for the VDA that stores the preprocessed velocity data, applies the VDA as is currently done, and then replaces the removed data with the stored data. The replacement method uses current VDA modules to determine in which Nyquist interval the velocity data should be located before replacing the value. This technique has been shown to preserve TVS signatures in radial velocity data and is planned for implementation in Build 10 of the WSR-88D system.

c. Multi-PRF Dealiasing Algorithm (MPDA)

A new technique using current WSR-88D hardware has been developed that vastly reduces range folding and improves velocity dealiasing. This technique uses multiple scans of different PRF data (while keeping the elevation angle constant) and combines them using software developed at NSSL. Several datasets have been collected using modified Volume Coverage Patterns (VCP's) on the OSF test-bed WSR-88D. The Multi-PRF Dealiasing Algorithm (MPDA) was then run on the cases and evaluated. Compared to the operational WSR-88D Velocity Dealiasing Algorithm (VDA), The MPDA technique markedly reduced the amount of range folded echoes and preserved velocity features of meteorological significance.

The technique is currently being converted to run in real-time on the WDSS system. NSSL has plans to evaluate the algorithm in real-time during 1997 using the NSSL WSR-88D radar. If possible, NSSL will examine output from the mesocyclone and tornado detection algorithms using output from both the MPDA technique and the operational WSR-88D VDA.

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6. DOPPLER RADAR WIND ANALYSIS FOR CLIMATE MODEL VERIFICATION AND NUMERICAL WEATHER PREDICTION

Researchers at NSSL and the University of Oklahoma are developing methods, with the support of the U.S. Air Force, to analyze Doppler radar and ancillary data which could lead to better estimates of large and small-scale atmospheric flows. Simple adjoint techniques and kinematic models of the air flow are being applied to find the best estimate of the velocity field transverse to the radar beam. The scalar fields of reflectivity and spectrum width and their time evolution are being studied to determine conditions under which they provide additional information for improving estimates of the vector wind field. Two objectives of this research are:

(1) To estimate synoptic-scale horizontal and vertical winds from Doppler observations by using reflectivity and/or momentum conservation equations coupled with kinematic models of synoptic-scale flow. Verification will be based on data from 2 or more collocated Doppler weather radars in Central Oklahoma, the Oklahoma Mesonet, and the dense profiler network located in Oklahoma and Kansas. The data will be combined to produce winds suitable for the verification of General Circulation Models.

(2) To use the high spatial/temporal resolution and areal surveillance capabilities of Doppler radar to estimate hazardous winds and to retrieve the vector wind fields on high resolution grids (i.e., $\approx$ 1 km).

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J. NOAA/National Weather Service Offices

1. BINGHAMTON, NEW YORK

a. Snowfall Measurement Studies

A COMET Partners project between the State University of New York (SUNY) College of Environmental Sciences in Syracuse and the National Weather Service Office in Binghamton, New York (BGM) has examined the feasibility of using WSR-88D reflectivity data in the prediction of snowfall rate and snow water equivalent for several types of snowfalls that affect upstate New York.

Measurements of snowfall and snow water equivalent taken at the Heiberg Research Forest, located 55 km north of the Binghamton WSR-88D, were compared with Archive II and IV reflectivity data (Archive II was only available for the second season). Regression analyses were performed for several snowfalls during the 1994-1995 and 1995-1996 snowfall seasons. Correlations were computed for the individual snowfall events, for several storm types, and for all events combined.

The results were somewhat discouraging especially for the combined dataset. It was found that individual storm events taken alone produced relatively high correlations. As found in previous studies, a dataset composed of synoptic scale events without lake-effect snow cases also produced relatively good correlation. The lake effect cases alone produced very low correlations, possibly a result of snow measurement errors, highly variable crystal structure, incomplete radar beam filling, and snow drift below the radar sampling volume. These factors likely affected other storm types but possibly to a lesser degree.

Thermal and moisture variables retrieved from Nested Grid Model (NGM) and Eta model soundings were also incorporated into the dataset. Variables at five pressure levels between the surface and 700 mb were used in multiple regression analyses. Initial results showed very little improvement in the correlations, however we were restricted in our calculations to a linear correlation model.

A Z-S equation derived from the data will be used by the WSFO in Buffalo and the NWSO in Binghamton to estimate snowfalls with the WSR-88D during the winter of 1996-1997. The software, developed at the Buffalo WSFO, also incorporates thermal and moisture variables in solving multiple variable equations.

Several presentations, two papers, and a master's degree thesis have resulted from this research to date. A summary project report is available from COMET.

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2. CLEVELAND, OHIO

a. Assessment of the NSSL Hail Detection Algorithm

The National Weather Service Forecast Office at Cleveland, Ohio has undertaken an evaluation of the National Severe Storms Laboratory's new Hail Detection Algorithm (HDA) soon to be available in software Build 9.0 of the WSR-88D. Archive II data from the Cleveland WSR-88D for 17 days during 1995 when large hail was observed over northern Ohio are being studied. Ground truth observations are from *Storm Data.*

Verification statistics include the false alarm rate, probability of detection, and critical success indices. Other parameters being investigated are the lead time of the HDA in forecasting large hail and the prediction of hail stone size.

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3. COLUMBIA, SOUTH CAROLINA

a. A Program to Assess Flood Risks

The WSFO at Columbia, South Carolina (CAE) is collaborating with the Geography Department at the University of South Carolina on a project to integrate WSR-88D Hourly Digital Precipitation (HDP) estimates into a Geographic Information System (GIS). Using Arcview as the GIS, a comprehensive database was constructed that includes hydrologic information, a catalog of dams, dam owners, risk category, a mesonet of precipitation gauges, storm spotters, Emergency Management System (EMS) personnel, and population characteristics. This information has been compiled for two flood prone counties in the WSFO CAE County Warning Area (CWA). Hourly Digital Precipitation estimates from the WSR-88D were successfully integrated into the GIS. This application has great potential for providing real-time information to forecasters to assess flooding risks. We are currently in the process of implementing the system on the WSFO Scientific Applications Computer (SAC) for real-time use. We hope to continue working with the University of South Carolina to expand coverage to the entire CWA.

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4. GREENVILLE-SPARTANBURG, SOUTH CAROLINA

a. Rainfall Estimation Studies

During the short period that the WSR-88D has been operational at the Greenville-Spartanburg (GSP) NWSO, forecasters have become aware of the need to improve the rainfall estimation capabilities of the radar. For example, rainfall totals of 15 to 20 inches occurred in the vicinity of GSP during Tropical Storm Jerry in August 1995. The WSR-88D storm total estimates were approximately 4.5 to 5.0 inches. Other events within the GSP County Warning Area (CWA) also show significantly lower radar rainfall estimates than the observed precipitation totals. The underestimation of rainfall seems to occur most frequently in what are perceived to be "tropical" environments.

Identifying and monitoring excessive rainfall in the GSP County Warning Area is one of the most important components of the office's forecast and warning program. The region (southern Appalachians, foothills, and piedmont) is susceptible to flash flooding and has experienced occasional flood events with significant property damage and loss of life.

During the past year, the NWSO GSP has been working with Dr. Carl Ulbrich of the Department of Physics at Clemson University to improve WSR-88D estimates of rainfall. Preliminary suggestions and identification of possible research topics were discussed in Ulbrich et al. (1996). This work indicates that the systematic differences between rain gauge observed and radar-estimated rainfalls are related to two factors: 1) Z-R relationships and 2) assumptions regarding parameters in the radar constant (see also Section III.R.2).

Plans for future work include collaboration between Dr. Ulbrich and the NWSO GSP staff to use the facilities of the Clemson Atmospheric Research Laboratory to improve radar rainfall estimates. The atmospheric research group at Clemson is developing a remote sensing laboratory that includes two Doppler radars (vertically pointing), a Doppler lidar, lightning detection sensors, atmospheric electricity apparatus, a disdrometer, and other meteorological equipment. The instrumentation will allow the collaborators to: 1) establish whether or not a systematic offset exists in the radar constant of the GSP WSR-88D, 2) identify improved scan strategies, and 3) examine possible vertical variations of the WSR-88D Z-R relationship that respond to seasonal or synoptic conditions.

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5. LITTLE ROCK, ARKANSAS

a. Use of the Combined Shear Product to Evaluate the Severity of Small-Scale Vortices

There is an ongoing study at the Little Rock, Arkansas WSFO (LIT) to examine the use of the Combined Shear (CS) product for detecting small-scale frontal vortices and weak tornadoes. From the description of the CS product in Federal Meteorological Handbook (FMH) 11, it would seem that the CS product is ideal for assisting in the determination of wind shears that might be associated with such phenomena and require severe weather warnings. The Combined Shear product may help forecasters determine the potential severity of frontal vortices which often generate multiple shear alerts and manifest themselves as uncorrelated 3-D shear and mesocyclone signatures.

Four storm systems have been studied with the CS product. One storm involved a weak tornado that killed two people. The CS product accurately depicted storm severity in terms of the shear magnitude and by the configuration of azimuthal and radial components. As found in previous undocumented cases, the tornado associated with a shear value of 100 units. Radar observations before tornadogenesis did not reach this critical value, but the evolving shear configuration provided some indication of the impending severe weather. It is supposed that, if the product had been used for this event, at least a 6 to 12 minute lead time might have been available to the PUP operator.

A second event involved a bow echo-shaped storm. Again, the configuration of shear components played an important part in determining storm severity, which was not obvious in the reflectivity and radial velocity data. The CS product, which showed 100 units of shear at the time of the reported damage, could have provided a lead time of 6 minutes or more.

The third event involved thunderstorms approaching the Little Rock metropolitan area and was actually a "negative" event in that shears and mesocyclones were observed but wind damage was not reported. The CS product did not show a particularly suspicious CS configuration. Shear values at their peaks were at least two levels below the 100 unit empirical value for severe weather.

The fourth event was also a "negative" event in that no damage or significant storm winds were reported. As it approached the Little Rock metropolitan area, the line generated many alerts due to a number of detected mesocyclone signatures. However, there were no CS values above the 100 unit level.

The CS product is very noisy, but it may hold promise for detecting severe frontal vortices and small-scale tornadic events in convective lines and hurricanes. More datasets are needed to determine the product's viability and whether or not it supports warnings with sufficient lead times. The work is continuing.

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6. MELBOURNE, FLORIDA

a. Introduction

Recent studies at the Melbourne, Florida NEXRAD Weather Service Office have addressed: 1) improving precipitation estimates within tropical regimes, 2) improving detection and warnings of small-scale, tornado-producing mesocyclones within tropical cyclone rain bands, 3) assessing severe storm characteristics to improve warning lead-times, and 4) developing a radar-based forecast strategy for waterspouts. Some of the studies address possible modifications to WSR-88D adaptable parameters, with the remainder offering operational strategies to improve the detection of severe weather. When relevant, references to published material or home-page addresses (as extensions to the MLB home-page http://sunmlb.nws.fit.edu) are provided.

b. Rainfall Estimation for Tropical Cyclones

Several local studies have compared actual rainfall accumulations during tropical cyclone events with WSR-88D storm total precipitation (STP) estimates. These studies have lead to OSF approved changes of MLB adaptable parameters including multiplicative bias, maximum dBZ, and maximum rainfall rates.

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2. Glitto and Mazarowski, 1996: WSR-88D Estimated Rainfall from Tropical Storm Gordon, NOAA Tech. Attach. NWS SR-168 (see also MLB home-page: /dwsrpd.html).

3. Glitto and Choy, 1997: Changing the Multiplicative Bias and Upper Reflectivity Threshold to Improve WSR-88D Storm Total Precipitation Performance during Tropical Systems. Submitted to *Weather and Forecasting*.

c. Mesocyclone Detection

Local research has also confirmed the ability of the WSR-88D mesocyclone algorithm to detect a larger number of small, shallow severe weather signatures when adjusting the threshold pattern vector adaptable parameter downward. More recent work on tropical cyclone datasets have identified characteristics of small spectrum mesocyclones which have produced tornadoes (see Spratt, et al., 1997: A WSR-88D assessment of tropical cyclone outer rainband tornadogenesis, submitted to *Weather and Forecasting* or MLB homepage: /waf1.html). Real-time testing during Tropical Storm Josephine yielded very beneficial tornado (warning) lead-times. A recent endeavor is a feasibility study for a new volume coverage pattern (VCP) which would sample gaps within the lower elevations of VCP 11 and 21. This new VCP would undoubtedly improve detection of shallow, tropical mesocyclone features. (For additional information see the MLB homepage: /gordonnwa.html, /erinnwa.html, /tc97sms.html, /tropchar.html and /tropspec.html).

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d. Waterspouts

Several severe local storm events have been re-analyzed using Archive II and Archive IV data. Cell interaction with boundaries (both outflow and sea-breeze) have led to some important findings applicable to warning decisions (see Sharp and Hodanish, 1996: A survey of supercells over east central Florida, Preprints, 18th Conference on Severe Local Storms pp. 335-339).

Previous studies have resulted in a waterspout forecasting strategy which focuses upon boundary identification and tracking (see Choy and Spratt, 1994: A WSR-88D Approach to Waterspout Forecasting. NOAA Tech. Memo. NWS SR-156 or MLB home-page: /spout.html and the preprint Choy and Spratt, 1995: Using the WSR-88D to Predict East Central Florida Waterspouts, 14th Conf. on Weather Analysis and Forecasting or MLB home-page: /spoutpre.html). This strategy has led to an earlier recognition of favorable waterspout environments, often resulting in lead-time marine warnings.

e. Other Activities

NWSO MLB acquired a Warning Decision Support System (WDSS) during the summer of 1996. During a 1-year proof-of-concept test, MLB will work with NSSL scientists to determine needs for local algorithm improvements and begin to make necessary changes. The most likely candidates are the damaging downburst and hail algorithms. Aside from joint research with the NSSL, the WDSS will allow the MLB staff a unique opportunity to continue radar-based applied research.

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7. PITTSBURGH, PENNSYLVANIA

a. The Areal Mean Basin Estimated Rainfall (AMBER) Program

The Areal Mean Basin Estimated Rainfall (AMBER) technique (Davis and Jendrowski, 1996) uses high resolution radar reflectivity measurements to compute average basin rainfall (ABR) estimates for a multitude of hydrologic basins. Basin sizes range from large-scale Mean Areal Precipitation (MAP) areas used by NWS River Forecast Centers for river forecasting to very small basins covering small streams and urban areas, specifically defined for flash flood forecasting.

High-resolution stream basins, subdivisions of stream basins, and urban areas for study are determined from topographical maps and by subjective consideration of such hazards as roads that cross streams in flood prone areas. One degree by 1 km radar reflectivity data from the Digital Hybrid Scan WSR-88D product are then mapped to the defined basins and running totals of areal basin rainfalls are computed. The AMBER output consists of areal basin rainfall from each volume scan over the past 6 hours plotted graphically along with Flash Flood Guidance (FFG) to provide information on total and rate of accumulation and to facilitate easy comparison of radar rainfalls and FFG values. Alerts, based on the ratio of radar-indicated rainfalls and FFG values, are generated automatically. Raingauge observations are being incorporated to provide statistical confidence in the radar-based accumulation estimates. Comparison between radar rainfall estimates and observations from 520 raingauges within the radar umbrella illustrate the importance of adjusting WSR-88D estimates with information from a gauge network in order to more accurately depict flash flood potential and severity. Also, a Geographic Information System (GIS) database will be developed to improve the basin definition process and to develop FFG specifically for the AMBER stream basins.

AMBER is currently operational at the NWSFO in Pittsburgh. Plans call for installation during the 1996/1997 winter at the NWSFO in Honolulu.

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8. SALT LAKE CITY, UTAH

a. WSR-88D Algorithm-Related Activities

The Western Region Radar Project at the Salt Lake City, Utah Weather Forecast Office (SLC WFO) has been active for a year. The project includes the evaluation of NSSL's Warning Decision Support System (WDSS) and the installation of a network of snowgauges (Snow-net). Installation of the Snow-net is about 75% complete. A Z-S algorithm developed by NCAR, which incorporates real-time snowgauge data for "calibrating" the radar and produces snowfall liquid equivalent accumulations at 30 gauge sites, is being evaluated.

Five cases of marginally severe downbursts have been observed in the Salt Lake City area. Efforts have concentrated on searching for radar signatures that could be used as precursors to damaging surface winds. A Technical Attachment (TA) describing one of those cases is available on the Western Region homepage (http://www.wrh.noaa.gov). Information on other research projects at the SLC WFO can also be found on the Western Region homepage.

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9. TULSA, OKLAHOMA

a. VIL Density as a Hail Indicator for Severe Thunderstorms

For warning purposes, forecasters at the Tulsa NWSO frequently use the Vertically Integrated Liquid (VIL) product as an indicator of thunderstorm severity and hail size. Because VIL varies greatly according to air mass characteristics, forecasters determine a "critical VIL" value for each thunderstorm event to help identify storms that are likely to produce severe hail (greater than ¾ inch in diameter). But air mass characteristics can vary substantially within the umbrella of a single radar and alter the critical VIL. A product which is independent of air mass characteristics, i.e., independent of season and geographic location, would be desirable in an operational warning environment.

VIL and thunderstorm height are both air mass dependent. High-topped thunderstorms with high VIL are usually in warm, moist air masses; while low-topped low VIL thunderstorms are typically in cool, dry air masses. However, the maximum reflectivity in both environs may associate with similar-sized hail. From this, one can hypothesize that "normalizing" the VIL with the height of the thunderstorm may produce a value or range of values for thunderstorms producing large hail, that is independent of air mass characteristics. The ratio produced by dividing VIL by the echo top is referred to as "VIL Density".

To test the hypothesis, the VIL and echo top were recorded for a large number of thunderstorms in a variety of air masses and the VIL Density was calculated. Results revealed that a substantial increase in large hail reports occurred as VIL Density increased above 3.5 g m^{-3}. At values greater than 4.0, virtually every thunderstorm produced severe hail, regardless of VIL or thunderstorm height. In fact, as VIL Density increased, the size of the reported hail also increased on average. Hence, VIL Density may have potential for the issuance of operational warnings.

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10. WILMINGTON, OHIO

a. WSR-88D Algorithm-Related Activities

The NWSO at Wilmington, Ohio (ILN) has been evaluating the performance of the current Hail Detection Algorithm. Events from 1996 are being examined using the WSR-88D Algorithm Testing And Display System (WATADS) software package. Archive Level II data for a number of hail events have been acquired. The evaluation process is about to begin.

Another project involves the investigation of numerous damaging wind events that occurred in the Ohio River valley during 1995 and 1996. Plans call for an evaluation of the predictive properties of such parameters as the Vertically Integrated Liquid (VIL), Echo Tops (ET), and the height of the maximum radar reflectivity. A second part of this study involves the evaluation of various radar signatures such as low and middle-level cloud convergence and rotation. A third activity will be to evaluate the NSSL Damaging Downburst Prediction and Detection Algorithm. These projects are at a very preliminary stage; no results are available.

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K. NOAA/Atlantic Oceanographic and Meteorological Laboratory, Hurricane Research Division

1. EFFECTS OF VERTICAL DRAFTS ON RADAR RAINFALL RATES

The effects of strong vertical drafts on rainfall rate R and subsequently on Z-R relationships has been investigated in a recent study. When the updraft equals the fallspeed of the mass-weighted drop, a balance is attained in which the water mass is divided equally between rising and falling components. At or near such a condition, the drop-size spectrum tends toward an equilibrium distribution. When the average vertical velocity w exceeds 2 m s^{-1} the net rainfall rate is decreased while Z remains the same, substantially altering Z-R relationships. The research suggests the following: (1) for $|w| < 1$ m s^{-1} (e.g., stratiform rain) Z-

R relationships are well defined; (2) for w > +2 m s^{-1} (convective rain) Z-R relationships become meaningless; and (3) for w <-1 m s^{-1} and between +1 and 2 m s^{-1} Z-R relationships are poorly defined.

In any appreciable updraft a significant portion of the water rises and ultimately falls out elsewhere. However, in the absence of growth or evaporation the total mass remains constant and methods such as the Area Time Integral (ATI), which estimate rainfall over a sufficiently large space-time domain, may be employed. To account for growth or evaporation the Probability Matching Method (PMM) may be used, forcing the surface gauge measurements to equal those of the radar in a probabilistic fashion.

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L. NOAA/Techniques Development Laboratory

1. WSR-88D ALGORITHM-RELATED ACTIVITIES

The Techniques Development Laboratory's (TDL) Local Applications Branch develops automated techniques for interpreting radar and other data in terms of the threat of thunderstorms, severe local storms, and flash flooding. Three such algorithms are currently being refined and tested.

An algorithm that provides current information and short-range forecasts of the location and intensity of convective storms has been constructed and tested. This "AWIPS Thunderstorm Product", described by Smith and Churma (1996), simultaneously interprets volumetric radar, lightning information, and upper-air soundings to determine if radar echoes are likely to be convective. The algorithm also determines the convective weather threat at airport locations within the local radar umbrella. Individual products include current thunderstorm locations, general severe weather probability (large hail, damaging winds, or tornado), large hail probability, and heavy rainfall probability. Work is underway to enhance the predictive capabilities of the product by incorporating satellite infrared observations to detect developing storms (Li and Smith 1996; Smith 1996).

The 0-1 h extrapolative-statistical rainfall forecasting algorithm, described by Kitzmiller (1996), has been revised. The latest version incorporates WSR-88D Stage III gridded rainfall estimates as a predictand. The new version also provides a "heavy rainfall probability" product that gives the probability of 1-h rainfall in excess of one inch anywhere in the vicinity of intense showers and thunderstorms.

Both the AWIPS Thunderstorm Product and the 0-1 h rainfall algorithms are now being tested at National Weather Service Headquarters with real-time radar data from the Sterling, Virginia WSR-88D site. Finally, a 0-3 h quantitative rainfall forecasting algorithm is being tested. This algorithm utilizes upper-air data, and the 10-km national radar reflectivity mosaic produced from Radar Coded Messages (RCM's) by the Storm Prediction Center's Aviation Weather Unit in Kansas City, Missouri. It will forecast peak point rainfall amounts on a 40-km national grid.

For further information see TDL's World-Wide Web site (http://www.nws.noaa.gov/tdl/).

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Abstract for reference 1:
One-Hour Forecast of Radar-Estimated Rainfall by an Extrapolative-Statistical Method

A common approach to short-range precipitation forecasting involves the extrapolation of gridded radar reflectivity fields. In general, the future rainrate at any given point is forecasted by assuming that the current rainrate pattern inferred by radar will move at some known velocity, and that the rainrates within the echo region remain constant in time or decrease at an assumed rate. The echo velocity may be estimated by pattern correlation between the most recent radar image and earlier ones, or it is assumed to be equal to the environmental wind at some level between 850 and 500mb.

As a refinement of this basic technique, a large number of extrapolative rainfall amount forecasts were prepared and then statistically correlated with the observed rainfall, as estimated by radar. The relationship between the purely extrapolative forecasts and the observed amounts

can then be used in interpreting other extrapolative forecasts prepared operationally. The resulting extrapolative-statistical approach to rainfall forecasting implicitly accounts for echo decay and uncertainty in the extrapolation process, and is a form of the Model Output Statistics technique often used to produce forecasts of sensible weather from numerical weather prediction model output. Both low-level reflectivity and vertically-integrated liquid (VIL) are used as predictors of rainfall amount. In practice, the extrapolative-statistical algorithm produces probabilities that the radar-estimated rainfall will exceed 0.1, 0.25, 0.5, and 1 inch, within each box of a 4-km grid, during the next hour. A categorical rainfall forecast can then be derived from the probabilities. The operational WSR-88D Z-R relationship was used to convert reflectivity to rainrates.

Because it incorporates input from a variety of statistical predictors, the extrapolative-statistical approach yields improvements over a purely extrapolative one, at the expense of modest increase in computing time. This note shows that the use of multiple statistical predictors measurably improves forecasts of rainfall amounts of 0.5 inch and greater.

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M. U.S. Air Force Phillips Laboratory and Hughes STX

1. OVERVIEW OF NEXRAD ALGORITHM-RELATED RESEARCH

NEXRAD-related development efforts at Phillips Laboratory this past year have resulted in a number of advances. Individual focus areas continued to be: (1) elliptical mesocyclone characterization, (2) Bounded Weak Echo Region (BWER) detection, (3) frontal analysis, (4) lightning initiation, and (5) spectrum width evaluation. A small 6th task is associated with tropical storms. This past year has also seen the development of a 7th task, establishing a framework for integrating the various algorithm products into a single overall storm assessment algorithm. All but one of the various efforts described here are slated for termination on June 1, 1997. The mesocyclone algorithm development will terminate by September 30, 1997. This is a direct result of a mandated reduction in U.S. Air Force funding.

The quantification of mesocyclones with an elliptical model has required a more precise detection of the mesocyclone circulation. Specialized wavelet forms have been developed to provide better detection and to better discriminate the circulation from background flow. Initial results employing wavelets tuned to the velocity shear patterns are very promising.

The BWER detection algorithm now includes more robust two-dimensional pattern analysis techniques for extraction of some of the more difficult WER regions and vertical integration to construct a three-dimensional comprehensive BWER representation. Success in tracking BWER's for more than 1.5 hours has been achieved. Parameters characterizing the extent and significance of the BWER are being evaluated. The detection phase of this algorithm is expected to be sent to the OSF in 1997.

The frontal analysis project has expanded to include the use of nonuniform filters, fuzzy logic, and gradient direction estimates to detect a wide class of wind shift phenomena. The algorithm suite is now capable of identifying convective frontal zones, gust fronts, and thin lines. The addition of a two-dimensional wind estimation capability permits forecasts of line movement with a nonuniform line advection scheme. Case studies show that the technique is superior to uniform displacement methods.

Lightning initiation analysis has focused upon macroscale features of storms, with particular emphasis upon precipitation growth above the freezing level. Various parameters (e.g. storm maximum reflectivity, top, centroid, area, volume etc.) are monitored for clues regarding the onset of lightning. Sudden increases in storm mass and the height of the maximum reflectivity factor appear to be precursors of increased lightning activity. Marked increases in the echo top height precede the first cloud-to-ground lightning strikes, thereby providing a potential precursor, as well. Procedures are being improved for monitoring the trends of these and of other parameters in an attempt to produce a predictive tool.

Spectrum width analysis has shown that, routinely, there are preferential three-dimensional regions of very high spectrum width along the storm's inflow and rear flanks. Within the inflow region, the variation in mean spectrum width appears to mimic mesocyclone evolution. Behind the storm precipitation core, spectrum width appears to indicate the presence of large hail, even when the hail signature may be insufficient to extend beyond the radar storm boundary. Algorithms are under development to automatically extract the whole hail flare and to monitor mesocyclone evolution.

A conceptual model for integration of the various algorithmic outputs into a single storm hazard algorithm has been developed. At this point, a first representation of a simple, yet comprehensive three-dimensional image, has been developed. Work on this product is ongoing.

2. MESOCYCLONE ANALYSIS

The development of an elliptical mesocyclone model has been completed and is described in Desrochers and Harris (1996). Recent efforts have been directed towards the improvement of techniques to extract the mesocyclone signature from single-Doppler data for subsequent automatic fitting of the elliptical model. The present operational technique for extraction of the mesocyclone signature employs pattern vectors to identify trends in the Doppler data. The pattern vector technique has been shown to work reasonably well for extracting regions of high shear, but does not discriminate between mesocyclones and other high shear flows. In our investigations we have found that pattern vectors do not reliably extract the shape of the mesocyclone.

The search for a greater signal extraction technique has led us to investigate wavelets, special wave forms that decay quickly to zero and are described by relatively few coefficients. Wavelet analysis can be applied to detect shapes in a given dataset. A wavelet-based analysis technique has been created to extract the mesocyclone Doppler signature. The approach is very similar to the human visualization process and appears very promising.

A one-dimensional wavelet algorithm has been developed and applied to several mesocyclone cases. This technique is reported in Desrochers and Yee (1997). A two-dimensional version will apply several different wavelets to account for the radial and azimuthal mesocyclone velocity profiles. The algorithm will adaptively apply the optimal wavelets to characterize the data.

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3. STORM STRUCTURE

HSTX continues to test and enhance the Storm Structure Algorithm it developed for Phillips Laboratory. The algorithm analyzes the reflectivity factor structure of storms to determine the potential for severe weather. An integral part of the algorithm is the automated detection of the Weak Echo Region (WER) and the Bounded Weak Echo Region (BWER) which are the signature features of the supercell, the most severe of thunderstorms. The WER is typically found at low levels within a supercell and at times tapers to a BWER at middle levels. The algorithm forms a three-dimensional representation of the BWER from two-dimensional WER/BWER detections on individual elevation scans. Characteristics of the detected 3-D BWER (if any) and the overall thunderstorm reflectivity factor structure are monitored in time to evaluate the threat of severe weather phenomena.

Enhancements made to the algorithm in the past year have increased the detection of the three-dimensional BWER. These include improved feature extraction resulting in better probability of detection of 2-D WER's as well as vertical correlation checks to help reduce false detections and to improve the overall 3-D composite BWER. Automated estimates of mass, volume, and area are made for the BWER and total thunderstorm radar volume for trend monitoring and correlating with severe weather.

Limited testing has been performed using about 100 Archive Level II radar volumes comprising thunderstorms with and without BWER's and with and without associated severe weather. Initial results are encouraging. BWER detections have been noted in supercells as far as 100 km from the radar. In the Goodland, Kansas case of May 12, 1995, the BWER was detected for about 100 consecutive minutes during which there were roughly 50 consecutive minutes of a detectable BWER in a minimum of one scan plane per volume. The most exciting results indicate that, for two supercells, the initial BWER detections precede reports of the initial tornado occurrence by 20 minutes and coincide with the initial hail reports. The early detections occur prior to evidence of a hook in the low-level PPI reflectivity factor display.

The algorithm also appears to have some limitations. The 1 km NEXRAD reflectivity factor range resolution negatively impacts the performance of the algorithm because it degrades the structure resolution. This renders the pattern recognition and image processing methods used for the BWER detection ineffectual. The impact appears most pronounced in smaller supercells. It has also been observed that the BWER structure sometimes fills into a relatively uniform, formless mass of high reflectivity factor with severe weather continuing. One storm exhibited this formless mass without ever having a BWER and yet produced considerable hail.

The algorithm is now undergoing additional testing with a wide variety of storm events in order to assess its performance more thoroughly. Unfortunately, further enhancements to the algorithm after this phase of testing are unlikely to be implemented due to the loss of funding for this project as of May 31, 1997.

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4. FRONTAL STRUCTURAL ALGORITHM

An algorithm has been developed by Hughes STX for Phillips Laboratory to detect and forecast three-dimensional frontal structure, motion, precipitation, and wind hazards. A combination of visualization techniques and physically-based computational analysis are adopted that utilize the horizontal gradient structure of reflectivity factor and Doppler velocity to examine the three-dimensional frontal structure. Pattern recognition techniques are used to detect frontal fine lines and velocity discontinuities associated with the front. Three-dimensional processing techniques are subsequently used to analyze the frontal structure and to characterize associated kinematic and precipitation structures.

The algorithm has undergone further enhancement and testing this past year. Several new techniques have been added. New capabilities and results are summarized as follows:

a. Detecting and Monitoring Fronts, Gust Fronts, and Thin Lines

The two-dimensional frontal line detection procedure has been upgraded for monitoring precipitation-enhanced frontal lines, wind shear-enhanced gust fronts, and reflectivity thin lines. The basic methodology is based on two-dimensional gradient computations in spherical coordinates, feature extraction with binary-weighted fuzzy logic, and line identification using gradient vector directions. (Tung et al., 1996). The advantages of the 2-D gradient vector approach are that both radial and azimuthal shears are incorporated in the analysis and that the data are kept in the original spherical coordinates without any interpolation. The enhanced line detection logic uses varying binary weights dependent upon the line to be detected. To develop a more focused and meaningful fine line feature that is useful for tracking and forecasting, the directions of gradient vectors relative to frontal orientation are used to define regions of positive (low to high) and negative (high to low) changes. The boundary between the two regions is the desired fine line.

b. Forecasting Differential Motions of Features

The sector uniform wind method of Hermes et al. (1993) has been adapted and applied to estimate winds along and near fronts. To forecast frontal motions, it is assumed that the front simply advects with the local winds. The points along the thin line are advected to new positions by applying the estimated wind speed and direction at each point over the desired forecast time interval. The advantage of this technique is that no historical information is required to initiate a forecast and the shape of the forecast line is determined by the local winds. Results from the test cases are very promising; the correspondence between the forecast and actual detected lines is very good for periods up to one hour (Tung et al., 1996).

c. Estimated Local Winds in Vicinity of Fronts

The sector uniform wind method is also applied to estimate two-dimensional winds ahead of and behind fronts for wind shear and wind shifts. For the Dodge City cold front case, the velocities behind the cold front were found to have northerly components. While strong southerly component vectors occurred south of the gust front. The strongest wind shifts occurred along the detected gust front fine line and correspond well to the area with the largest gradients in the radial velocity field (Tung et al., 1996).

d. Depicted Frontal Features in Three-Dimensions

A new technique has been developed to determine the cold front wedge and to compute the frontal surface slope. The cold front wedge can be depicted as a volumetric display of radial velocities. The 2-D gradients of the frontal height on the upper surface of the wedge are computed via the 2-D gradient algorithm. The frontal surface slope is approximated by the median of the slope field. For the Dodge City case, the slope was found to be 0.02 - 0.03, which corresponds to a vertical-to-horizontal ratio of 1:50 - 1:33, reasonable values for a cold front (Tung et al., 1996). The advantages of this technique are that the wedge can be easily determined from the radial velocity distribution, and the surface slope can be defined regardless of the surface roughness and data sparseness. In addition to frontal surface slope, the 3-D convective precipitation boundary, length, orientation, and the motion of front are also computed and monitored in time for trends in the character of the frontal region.

e. Monitoring Precipitation Evolution

The area, volume, centroid, echo top, and mass of frontal-related precipitation are computed and examined over time. Parameter evolution can indicate the location and intensity of associated hazardous weather. The gradient intensity trends can be used to forecast convective development and strength (Tung et al., 1996).

A limited set of test cases were run this past year. The algorithm is automated for the detection of cold fronts and gust fronts. Currently, the algorithm is undergoing extensive testing and is being upgraded for automatic thin line detection. There are many enhancements and improvements planned for the algorithm, but the task will be terminated by May 31, 1997 due to the Air Force funding cuts.

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5. LIGHTNING PRECURSOR ALGORITHM

Lightning production is known to depend upon the presence of updrafts and mixed phase precipitation at sub-freezing temperatures. Techniques have been developed to monitor the temporal variations of bulk storm and profile parameters (Harris, et al, 1997) as determined from radar reflectivity. Parameters being evaluated include storm mass and volume, layer mass and area, storm and layer centroids, maximum reflectivity factor values and height, and echo tops. The height domain for parameter determinations can be specified both in terms of extent and resolution. In general, the computations are constrained to the sub-freezing portions of the cloud. Results to date indicate that the onset of lightning usually occurs after a sharp increase in storm mass, especially aloft, and a sharp increase in storm top. Monitoring the trends of these and the other storm properties appears to give strong indications of the onset and subsequent bursts of lightning.

Techniques for predicting lightning initiation by monitoring trends are expected to be in place by mid 1997. Future development involving algorithm automation and the inclusion of spectrum width patterns and low-level convergence are planned but are highly dependent upon continued funding.

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6. EVALUATION OF DOPPLER SPECTRUM WIDTH IN THE DETECTION AND FORECASTING OF SIGNIFICANT WEATHER EVENTS

This effort investigates whether the WSR-88D Doppler spectrum width (SW) can support existing or new methods for detecting and/or forecasting storm hazards. Although sensitive to a number of radar and meteorological factors, SW offers some advantages over other radar parameters in an operational setting. First, SW is a simple scalar quantity that is automatically provided by the WSR-88D. Second, the spatial "patterns" of high SW immediately identify regions where high turbulence or gradients of radial velocity (v_r) and reflectivity (Z) are likely to exist. Third, monitoring the temporal evolution of such regions may provide insight into storm structure and hazard development. To investigate these possibilities, three severe storms with associated tornadoes, hail, and gust fronts were analyzed using WSR-88D Archive Level II data. A simple methodology was applied to: (1) determine the relative strengths of contributors to SW, (2) associate regions of high SW with storm features, (3) monitor both these associations and various SW region characteristics over time, (4) evaluate the potential benefit to hazard detection and forecasting, and (5) determine guidelines for employing highly variable SW's in automated hazard analyses. The results suggest that spectrum width can play a strong supportive role in storm analysis.

Within severe storms the SW typically lies within the range 0 - 8 m s^{-1}, but significant three-dimensional concentrations (regions) of high SW (8 - 14 m s^{-1}) are often observed. In general, the proportion of SW contributed by the three-dimensional radial velocity shear is minor in comparison to that provided by turbulence. Only high SW and low Z (typically < 20 dBZ) show any significant correlation, and this occurs near three storm regions: (1) the inflow flank, (2) the rear flank, and (3) the anvil. Concentrations of high SW appear predictable, trackable, and tied to specific storm features. They are not artifacts of sidelobe contamination or of low signal-to-noise ratio (SNR), but may be enhanced (minor in these data) by such effects. Regions of high SW on the storm's inflow flank associate with the storm intensification cycle. Shear concentrates near the Weak Echo Region (WER) and at the tip of the hook echo and is spatially associated with the mesocyclone velocity maximum near the radar storm boundary (-5 to 20 dBZ). The mean SW, averaged over a layer on a storm's inflow flank, was investigated as a potential tracking parameter. Its variation clearly follows mesocyclone development, being about 4 m s^{-1} in quiescent periods and rising and falling (up to 10 m s^{-1}) with mesocyclone intensification and dissipation. This SW signature often extends to adjacent altitudes where reduced shear is found, perhaps indicative of a very weak and ill defined mesocyclone circulation at these locations.

Initial results suggest that the mean SW is more closely correlated with mesocyclone maximum velocity and degree of organization (visual detectability) than either the maximum mesocyclonic shear or the mesocyclone diameter. Even though the full association is unclear and the SW signature likely reflects a fortuitous blend of turbulence, velocity shear, and low SNR effects at the storm-environment interface, the use of SW for detecting weak or poorly organized mesocyclone events where automated detection may be difficult seems reasonable. Additional SW tracking parameters (e.g., volume per SW threshold, rate of change, etc.) and storm features (WER, storm maximum Z, volume, etc.) are being considered for linking SW to storm development.

The large volume of high SW at the rear flank region is primarily associated with a hail flare and storm environment interaction. As discussed by Zrnić (1987) and Wilson et. al. (1986) the hail flare "outside" the radar storm boundary is readily observed as a slender storm extension characterized by low Z, negative v_r, and high SW. The hail flare signatures "within" the storm boundary (low Z and strong negative v_r) are often overwhelmed by the signal from the precipitation located there. However, the SW is generally high, often clearly visible between the storm boundary and the 50 dBZ contour. Extraction of the "external" hail flare component was readily achieved through thresholding of v_r, Z, and SW data.

The large mean spectrum widths in the anvil region also appear connected with storm evolution. The primary regions of high SW lie above the updraft and along the inflow flank side of the spreading anvil, likely reflecting the updraft outflow into the anvil. However, due to the difficulty of maintaining thorough and continuous monitoring of the anvil region, this SW signature is not currently being investigated.

Other features readily detected through monitoring 3-D regions of high SW included two tornadoes and an emerging gust front. One tornado formed between the surface gust front and mesocyclone aloft. As the gust front propagated ahead of the storm, the tornado separated from the gust front and weakened. A new tornado formed with the gust front and a weak circulation aloft but was short lived.

This study clearly suggests that SW can aid storm hazard detection. Due to the variability of the SW estimate, however, some care must be exercised. Study shows that the identification of "patterns" of high SW is useful for focusing attention on those regions of the storm requiring more detailed analysis. The use of soft thresholds (derived from the data field) appears prudent, since the whole field of SW values throughout the storm may vary with storm development. Because of its simple scalar nature and relative independence from viewing angle effects, the generation of automated detection techniques seems very reasonable.

Funding for this task has been terminated. However, integration of SW information into a storm hazard appraisal algorithm (with WER, lightning initiation, mesocyclone, and wind shift detection capabilities) is continuing. In this support role, an algorithm to monitor the SW along the inflow flank is under consideration. The first phase, discrimination of the hail flare (external and internal) is currently under investigation.

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7. TROPICAL CYCLONE EVALUATION

Exploratory efforts have been directed toward evaluating wind field derivatives, as estimated from Doppler weather radar data, and toward the analysis of the circulation characteristics of tropical cyclones. Earlier work (Donaldson, 1991) indicated that a measure of cyclonic circulation vitality might be the degree to which the circulation approached a potential-vortex model. Later work (Donaldson et al., 1995) suggested a means of estimating radial wind speeds of the cyclone, and indirectly providing an assessment of environmental contamination of the cyclone circulation. The most recent report (Donaldson, 1996) summarized and organized all previous work related to wind field derivatives in hurricanes, corrected inconsistencies in notation, numerically tested the theory, and suggested possible directions for future studies.

Current work is aimed at objective Doppler radar techniques for estimating cyclone translational velocity even when the eye cannot be located with certainty owing to distortion in its structure or to resolution problems. At this early stage, the techniques appear to be promising pending numerical validation by theoretical models and exploration of case data.

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N. Illinois State Water Survey

1. ESTIMATION OF LAKE-EFFECT SNOWFALL RATES FROM NEW OBSERVATIONAL FACILITIES

a. Background

Lake-effect snowstorms are common features of winter-time weather in the Great Lakes region, affecting large numbers of communities and transportation systems. The National Weather Service is conducting a three-year lake-effect snow study to examine the impact of new technologies, such as WSR-88D and GOES 8/9, on monitoring and predicting lake-effect snowfalls in the Great Lakes region. The ability of these new observational facilities to monitor lake-effect events is not fully known and the most useful methods for their utilization are still under development. This study combines data available from the NWS WSR-88D radar network in the Great Lakes region and other sources (such as satellite, surface observations, and soundings) with the current understanding of lake-effect precipitation and boundary layer growth processes to determine methodologies for estimating lake-effect snowfall rates.

b. Radar-Related Research

The primary goal of this two-year project is to determine methods by which lake-effect snowfall rates can be estimated both close to and far away from WSR-88D sites. To achieve this goal, satellite images, surface data, Archive II WSR-88D radar observations (from GRR, LOT, and MKE), and atmospheric soundings were archived for twenty lake-effect snow events which occurred in the Lake Michigan area during the winter of 1995/1996. Data are also being archived for 1996/1997 events. Based on these data, preliminary relationships between radar-estimated snowfall rates, visibility, cloud patterns, and various other indicator variables were derived for cases with strong westerly-component winds and widespread lake-effect snow patterns over Michigan. Initial results appear in Laird et al. (1996). We are in the process of completing these investigations by continuing statistical analyses of all lake-effect cases with strong westerly-component winds during the past two winters and adding relationships with maximum rates of snowfall within intense shore-parallel bands of lake-effect convection over Lake Michigan.

Research toward achieving the primary research goals of this project has increased understanding of boundary-layer processes associated with lake-effect snowstorms and has enabled the determination of WSR-88D capability of the radars to observe the evolution of lake-effect snow structures. Kristovich and Laird (1995) investigates the relationships between lake surface temperature and upwind stability on the development of lake-effect cloudiness (and snow) in Lake Michigan lake-effect snowstorms. Other investigations involve radar observations and numerical modeling of the evolution of lake-effect snow bands over Lake Erie. One focus of this work is to understand the effects of air modified by Lake Michigan on the development of intense lake-effect snowbands over Lake Erie.

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0. Massachusetts Institute of Technology/Lincoln Laboratory

1. GROUND CLUTTER REMOVAL

A NEXRAD Clutter Editor (CE) was designed to detect range gates that are contaminated by ground clutter and anomalous propagation. The clutter algorithm makes use of the fact the clutter usually associates with (1) weak radial velocity, (2) small spectrum width, and (3) is most commonly found in low elevation scans. Based on the altitude and distance of the sampling volume corresponding to a given range gate, as well as the concurrent radial velocity and spectrum width of the sampled volume, the range gate is classified as representing either "weather" or "clutter". Range gates classified as containing clutter are ignored during the subsequent generation of NEXRAD precipitation products.

Studies of NEXRAD clutter performed by LL/MIT indicate that most clutter is found at low elevation angles and near the radar. The clutter editor therefore first defines regions of space around the radar and then applies a specific set of rules in each region.

Briefly, proceeding radially away from the radar, these zones and rules can be stated as (1) very close to the radar and below a relatively low altitude, all data are rejected as clutter (2) in the next zone, where clutter is most often found, data at low altitudes are assumed to be clutter unless proven other wise, and (3) in the final region, where clutter is not typically found, data are assumed to represent weather unless the velocity and spectrum width are representative of that expected from ground clutter. In cases where ground clutter has been identified based on velocity and spectrum width out to a certain range, but no velocity/spectrum width data exists at longer, adjacent ranges, editing continues if there is continuity in the reflectivity field. Finally, median filtering is applied to the composite reflectivity products that are derived from the edited data to remove speckles of "unedited ground clutter".

The operation can be divided into four distinct phases: registration, identification, dilation, and smoothing. The first phase is the registration of the velocity and reflectivity data from the low-level reflectivity only and velocity only scans. In addition, if the reflectivity and velocity data have different spatial resolutions, e.g., 1 km for reflectivity and 0.25 km for velocity, then a mechanism is activated to associate a single gate of the low resolution product with multiple gates of the higher resolution product. After this registration phase is complete, a second phase of range gate classification is performed wherein clutter is identified on a range gate by range gate basis. In the third phase, certain range gates in proximity to previously identified clutter-contaminated gates may also be declared as clutter if there are no velocity/spectrum data available to use as a discriminant. This is, in effect, an extension of the identification of clutter into neighboring range gates. The final processing phase applies a median filter to remove "speckles" of unedited ground clutter.

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2. IMPACT OF CLUTTER REMOVAL ON GUST FRONT DETECTIONS

Clutter removal should have a positive effect on the performance of most algorithms. The improvement with the Machine Intelligent Gust Front Algorithm (MIGFA) was determined for 5 gust front cases observed in Memphis, Tennessee during 1995. Gust fronts, defined as having convergent wind change of >5 m s^{-1}, were detected using both clutter contaminated and edited data. Results are presented in the following table.

	PLD	PFD	POD	PFA
NEXRAD (unedited)	46.8	23.3	47.8	26.0
NEXRAD (edited)	59.3	22.6	57.6	18.7

PLD is the percentage of the gust front length actually detected, PFD is the proportion of fronts lengths that were false, POD is the percentage of gust fronts detected at least somewhere, and

PFA is the percentage of gust front detections which are false. Ground truth was based on the analyses of meteorologists.

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P. National Center for Atmospheric Research

1. ATMOSPHERIC TECHNOLOGY DIVISION

a. Anomalous Propagation (AP) Clutter Mitigation

The Environmental Research Laboratory/Forecast Systems Laboratory (ERL/FSL) and the National Center for Atmospheric research/Atmospheric Technology Division (NCAR/ATD) are completing a technique for automatic AP clutter mitigation at the Radar Data Acquisition (RDA) level to improve the quality of the base data. The direct effort is to improve allocation of the WSR-88D clutter processing to minimize reflectivity losses while maintaining coverage of precipitation and clear air echoes. We have developed a reflectivity compensation technique based on a Gaussian spectrum model and its moments.

The FY-96 effort customized a recognition technique implemented from neural network and fuzzy logic structures. Many unusual Archive II cases of AP clutter were collected, with assistance from the OSF, on which to train and test the technique. The goal is to develop an AP clutter recognition algorithm, that can be implemented in Build 11 (or equivalent), which will identify areas of AP clutter and facilitate automatic suppression and reflectivity compensation.

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b. Enhanced Archive 1 Data Analyzer (A1DA) Recorder/Base Data Display

NCAR/ATD and ERL/FSL have designed and built an enhanced Archive 1 Data Analyzer (A1DA#2) which taps the digital samples, analyzes their spectral components, and writes the dataset to 8 mm tape for later detailed analysis. Storage capacity for one case study is 24 GBytes, suitable for recording a complete watershed precipitation event. The A1DA consists of a Unix client using a X windows server and a measurement server executing under a real-time operating system. The A1DA is transparent and totally isolated from the RDA, thereby allowing non-intrusive real-time digital data access and monitoring of the RDA data quality. The digital data allows evaluation of new RDA processing techniques and serves as a new hardware and/or software signal processor platform. Archive II data (reflectivity, velocity, and spectrum width) are also accessed and can be displayed in real time on a PPI color display for data monitoring, calibration, or diagnostic work. An LED antenna angle readout of azimuth and elevation is a part of the interface. The original A1DA#1 is being used at the NSSL testbed radar (KOUN1) for system qualification tests. The enhanced second unit (A1DA#2) will be transported to selected sites by ATD and FSL to obtain hydrology, clutter, and range-ambiguous datasets.

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c. Network Calibration Techniques

ERL/FSL and NCAR/ATD have reviewed the technical need for a network level reflectivity calibration procedure and identified an engineering strategy for initiating and performing this calibration over the system lifetime. Aids to calibration maintenance have been recommended.

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d. KOUN3 Testbed Radar Instrumentation

NCAR/ATD, ERL/FSL, and NWS/OSF have designed and implemented a prototype diagnostic and performance monitoring network for the new OSF testbed radar in Norman, Oklahoma. The first stage of installation (FY 97) will emphasize monitoring power and environmental variables. The instrumentation network uses on-screen, windowed control and reporting. The Archive 1 Data Analyzer (A1DA#1) will also be an important component of this radar instrumentation.

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e. Archive II Recording Extensions and Format

NCAR/ATD and ERL/FSL have proposed to the OSF to write additional messages to the Archive II tapes to allow more complete base data interpretation for off-line studies being performed by NWS and various research agencies. The existing tape format allows a variety of supplemental message types that can readily be written to tape that assist the off-line data recovery. Such message types could include transmitter, receiver, and calibration performance data, site adaptation parameters, clutter filter maps and filter parameters, and supplemental scan definition information.

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f. Reduction of Range/Velocity Ambiguities

NCAR, NSSL, and FSL have jointly submitted a proposal to the OSF to study "NEXRAD Range/Velocity Unfolding Problems and to Explore Selected Mitigation Techniques". The proposal was accepted by the OSF and is now funded. As of October 1996, work had begun by all three institutions. The initial three-year effort will lead to selecting one or more techniques that are able to improve the current ability of the WSR-88D system to resolve velocity and range ambiguities.

Range folded echoes are the cause of the well known "purple-haze" in the WSR-88D products and limit the performance of many of the meteorological algorithms. During the first year, we are exploring four techniques that we believe have merit in mitigating the present range/velocity ambiguity restrictions:

1) Spectrum decomposition techniques to identify and separate overlaid echoes in the Doppler spectrum.

2) Phase coding of the transmitted pulses to allow examination of echo coherence in different range intervals. This technique, combined with spectral processing, looks very promising.

3) Staggered Pulse Repetition Time (PRT) techniques to extend both the unambiguous velocity and range. These methods work best in the absence of ground clutter and other narrow-band signal contaminants.

4) Determination of the Nyquist interval of aliased velocities by using within-the-pulse Doppler processing (intra-pulse Doppler estimation). This method has never been considered useful by itself for measuring weather echo velocities, because the Doppler phase change that occurs in the microsecond time that the pulse is on is so minuscule that it can't be measured with much accuracy. Nevertheless, if enough of these low accuracy measurements can be made without bias, they can be averaged to obtain a velocity estimate with uncertainty that may be less than a Nyquist interval for the normally obtained Doppler estimates. Combining this technique with other methods may prove useful.

Other techniques will also be explored. The emphasis will be on identifying techniques that are readily adaptable to the WSR-88D for the short term and/or are cost effective to implement in the long term. Our efforts will compliment the work done by NSSL, FSL, and others to develop methods which use continuity of Doppler fields. These well-developed methods are currently used on the WSR-88D data to provide some level of ambiguity mitigation.

We will collect Archive I (I/Q) data from either the OSF testbed or other operational WSR-88D radars and analyze the spectra to determine whether the radar imposes any limitations on any of the techniques. The Denver, Colorado and the Memphis, Tennessee radars are specifically targeted. The ATD S-Pol 10 cm portable radar may also be used. It may be possible in 2nd or 3rd year efforts to acquire data taken using "advanced technique" transmitted waveforms that can be implemented on S-pol or a WSR-88D testbed, which couldn't be transmitted on the current operational network. These tests would allow the presumably greater performance potential of these advanced techniques to be evaluated in real weather situations.

Determination of Nyquist interval of aliased velocities is accomplished by analyzing and combining independent estimates from all pulses within a beam and from adjacent range and azimuthal bins.

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2. RESEARCH APPLICATIONS PROGRAM

a. In-Flight Icing Research

The In-Flight Icing Product Development Team formed the auspices of the FAA is including NEXRAD-related research in its activities. The purpose is to examine the use of existing NEXRAD capabilities or possible upgrades (i.e. changes in scan strategies, polarization capability) for unambiguous detection of in-flight icing. The program is just beginning.

1) Potential improvements to detection

NEXRAD has potential for supplying valuable information about the icing environment. However, a systematic study of this potential has not yet been conducted. Present capability is being explored through theoretical studies as well as with datasets from the Winter Icing and Storms Project and possibly from a number of WSR-88D's. Improvements to icing and Supercooled Liquid Droplet (SLD) detection through alterations in NEXRAD scanning strategy and added polarization capability are being examined and recommendations to the NEXRAD Steering Committee will be made.

2) Supercooled liquid detection

Several ideas exist for constructing an algorithm to detect SLD using operational radar data (NEXRAD, TDWR) in combination with other data (i.e. model generated temperature profiles, sounding data, etc.). An SLD algorithm that can be implemented using operational systems is being developed for testing during the winter of 1997/1998.

At this time, a specific algorithm has not been determined. Candidates include but are not limited to: (1) the radar PPI method proposed by Thomas and Marwitz; (2) a simple 1-D model combined with radar information as proposed by Czys; and (3) a combination of Baldwin's model-based precipitation diagnosis algorithm with radar data.

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b. Hail Detection

Polarimetric measurements, because they are sensitive to the physical properties of the illuminated particles, have distinct advantages in hail detection. Unlike reflectivity-based techniques, hail designations can be made as the data are collected rather than at end of a volumetric sampling sequence.

All weather radars transmit electromagnetic signals and measure the backscattered (reflected) energy. Returned signals received from a precipitation field are proportional to the sixth power of particle diameters. For radars transmitting and receiving polarized signals in orthogonal planes, e.g., in the horizontal (H) and vertical (V), two reflectivity measurements are made, i.e. Z_H and Z_V. Rain drops tend to flatten as they fall, increasing in flatness as their size increases; while hail, graupel, and aggregates tend to tumble and to fall with random orientation. Thus, for rain $Z_H > Z_V$ and for hail $Z_H \approx Z_V$. A differential reflectivity, Z_{DR}, is defined as the ratio of reflectivity at horizontal and vertical polarizations, i.e.,

$$Z_{DR} = 10 \text{ x } \log(Z_H/Z_V)$$

For intense rainfall rates, Z_{DR} values are typically 2 to 4 dB. For measurements with hail, Z_{DR} approaches 0 dB; and if the hail is large, Z_{DR} may even be slightly negative.

In practice, hail detection is facilitated by looking for departures from the expected relationship between Z_H and Z_{DR} pairs for the "rain-only" case. A simple algorithm has been proposed by Aydin et al. (1986) who defined a differential reflectivity hail signal

$$H_{DR} \equiv Z_H - f(Z_{DR})$$

where f is a function of Z_{DR} only. The empirically determined boundary $f(Z_{DR})$ delineates pure rain from mixed-phase precipitation. Regions with $H_{DR} > 0$ dB signify hail.

In a preliminary evaluation with 39 hail reports from two days, maximum hail sizes were plotted on maps of the geographical regions swept out by radar measurements of $H_{DR} > 0$ and $H_{DR} > 30$ dB. All hail reports resided in the region swept out by $H_{DR} > 0$ dB, and nearly all reports of large hail were within the region of $H_{DR} > 30$ dB.

To determine whether or not the H_{DR} parameter can be used to estimate maximum hail size, H_{DR} values at the time of the hailfall were tabulated. Although questions arise when point ground observations and areal radar measurements are compared, the linear correlation coefficient between H_{DR} and maximum hail size was 0.63. The correlation between hail size and radar reflectivity was only 0.33. Hence, H_{DR} may be a better indicator of hail size than the reflectivity factor itself. Possible reasons are that the larger hail may fall with its major axis aligned in the vertical or that the larger hail is in the Mie scattering range creating a resonance in the measured reflectivity which causes Z_{DR} to be negative and H_{DR} to be large.

Scattergrams of Z_H versus Z_{DR} show that the boundary between "rain only" and "hail contaminated" measurements wanders somewhat from storm to storm. Future work will attempt to delineate the two regimes by determining the boundary $f(Z_{DR})$ directly from the radar observations.

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c. Precipitation Estimation with Radar and Satellite

The National Center for Atmospheric Research has begun a comprehensive program to improve radar reflectivity-based techniques for estimating precipitation, to evaluate dual-polarimetric methods, and to improve satellite estimation techniques. Interest extends to all storm types (convective and stratiform, summer and winter, and orographic). Programmatic goals are to be met by conducting modest but highly-focused efforts in which polarimetric research radars are collocated with operational NEXRAD's. Ultimately this research will be coupled with efforts to improve quantitative precipitation forecasts.

The first phase of the program was conducted in northeastern Colorado during the summer of 1996. NCAR's S-pol (S-band dual-polarized) radar was placed within 2 km of the Denver, Colorado WSR-88D. Scanning strategies duplicated that of the WSR-88D; elevation angles were 0.5, 1.45, 2.4, and 3.35° and the sampling interval was slightly less than 6 min. Additional 0.5° scans were obtained to evaluate the impact of more frequent temporal sampling.

Rainfall algorithms being tested include 1) the NEXRAD Z-R relationship, 2) a relationship combining Z_H and differential reflectivity (Z_{DR}), and 3) a relationship based on the specific differential phase (K_{DP}). Rainfall measurements are available from 113 gauges operated by the Urban Drainage and Flood Control District in Denver, Colorado. The dataset comprises 12 major rainfall events including the Buffalo Creek flash flood of 12 July 1996. Analysis, with particular emphasis on the use of polarimetric measurements and estimating rainfall in complex terrain, has begun. Preliminary results confirm that rainfall rates computed from K_{DP} are relatively insensitive to beam blockage. Also for convective rainfalls, the mean radar bias is much reduced.

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Q. University of Alabama

1. MESOSCALE CONVECTIVE SYSTEMS IN THE SOUTHEAST: A SURVEY

A climatology of mesoscale convective systems (MCS's) in the southeastern U.S. is available. MCS's were identified and characterized with composite (multi-radar) WSR-88D reflectivity data. The data were interpolated to a 2x2km grid having 15 min resolution and 15 intensity levels by WSI Corporation. Although only one year of data is employed in the study, the month-to-month variability in the number of MCS's is small compared to the amplitude of the annual cycle. MCS's can occur at any time of the year but are about twice as frequent in summer than in winter. The most common lifetime and size (width) of MCS's is 5 hours and 250 km, respectively. In the summer months small, short-lived MCS's are relatively more common; whereas in winter larger and longer-lived systems occur more frequently. MCS's occur more commonly in the afternoon, but the amplitude of the diurnal cycle is small compared to that of thunderstorms in general. Clearly separated regions of convective and stratiform precipitation co-exist within some MCS's, usually in the form of a squall line with a trailing stratiform region. Other storms exhibit distinctive convective and stratiform stages. Both organizational types are rare in winter.

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2. NEAR REAL-TIME ESTIMATION OF THUNDERSTORM-INDUCED COOLING

In this study WSR-88D data are combined with satellite visible imagery to "finetune", in quasi-real time, the surface temperature forecast by a RAMS (Regional Atmospheric Modelling System) simulation initialized by an 1200 UTC objective analysis. The model domain is the southeastern U.S. Statistical data have been obtained for the period 15 May to 15 September 1995. During this period, daytime cooling is usually due to the outbreak of convection, the timing, intensity, and location of which is largely unpredictable. We use a "dry" run of RAMS to predict the evolution of surface temperature if the atmosphere were free of cloud and precipitation and then finetune the model with observed cloudiness (from visible imagery) and precipitation (from composite radar data). The tuning parameters are determined through statistical techniques. The resulting detailed surface temperature field is much more accurate than that currently available.

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R. Clemson University

1. STUDIES OF DROP-SIZE SPECTRA FOR TROPICAL RAIN

Analyses are performed of raindrop size spectra to explore the relationships among rainfall parameters for tropical rain. The data were acquired with an airborne 2-D optical precipitation probe in the TOGA COARE experiment during a 4 month period in 1992-93. It is assumed that the experimental size spectra can be described by a gamma drop-size distribution (DSD) of the form $N(D)=N_0D^\mu\exp(-\Lambda D)$ involving three parameters (N_0, μ, Λ) which are determined using a new method of truncated moments. It is found that spectra with small time and space scales involve considerable fluctuations in all three of the DSD parameters. However, with large-scale averaging the composite drop-size distribution is described by exponential form for drop diameters less than about 4 mm. At larger diameters the distribution is concave upward.

An examination has been made of the effects of changing the duration of the averaging interval on the DSD parameters. The parameters do not converge to limiting values even when the averaging interval is large enough to encompass the entire dataset. Nevertheless, the parameters display a tendency toward asymptotic behavior as the sample volume increases, and the limiting values of the DSD parameters are not greatly different from those for an exponential distribution. It is therefore concluded that the assumption of an exponential distribution is adequate for the interpretation of data acquired in tropical rain with remote sensing techniques.

The data have also been stratified separately into classes according to the DSD parameters D_0 (median volume diameter) and μ. The latter term is shown to be directly related to the width of the distribution. Empirical analyses between the reflectivity factor Z and rainfall rate R were performed for the data in each class. Results are consistent with that predicted by the assumption of a gamma DSD.

An investigation was made of the effects of changes in the shape of the drop-size distribution on the structure of the rain parameter diagram, i.e. the diagram of Z versus R on which isopleths of integral parameters (liquid water content M, median volume diameter D_0, etc.) are plotted. In this work, variations in DSD shape are assumed to be described by changes in the parameter μ. Results show that for reasonable deviations from exponentiality ($-1 \leq \mu \leq 2$), changes in the isopleths of integral parameters are about 10%. Hence, a rain parameter diagram for an exponential distribution may used for distributions of different shape with little error.

The well known correlation between the gamma DSD parameters N_0 and μ was investigated to determine whether other integral parameters are available which will provide more statistically independent behavior. It is concluded that there are alternatives which will reduce the magnitude of this correlation, but none of the parameters investigated completely eliminated it.

2. EFFECTS OF VARIATIONS IN Z-R RELATIONSHIP PARAMETERS

Studies (Ulbrich et al. 1996) show that differences between rainfall estimates made with the WSR-88D and raingauges are due in part to variations in the coefficient and exponent of the Z-R relationship that associate with rain type. The residual bias, which can often be large in gauge/radar comparisons, is attributed to errors in the measurement of radar reflectivity. The combination of these two error sources causes a significant underestimate of tropical rainfall and relative high accuracy of midlatitude convective rainfall estimates (reference is made to the study of Klazura and Kelly, see last year's report). Calculations indicate that if the coefficient A of the Z-R relationship is actually 200 (representative of stratiform precipitation) instead of 300 (the NEXRAD value), the current algorithm will give a rainrate value that is smaller than the actual value by 34%. If A is actually 450, the WSR-88D radar would overestimate the rainrate by 25%. These differences are only a small fraction of the discrepancies noted in radar/gauge comparisons. Calculations show that a systematic bias of -2 dB in Z and an actual coefficient value of 200 causes the error to be 85%. In another test, the use of an improper Z-R relationship is found to be small except for tropical rain where the rainfall rates are 65% smaller than actual values.

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S. Colorado State University

1. HAIL DETECTION WITH POLARIMETRIC RADAR

The use of dual-polarization radar data to identify hail (particularly large hail), has been a continuing research effort. Study has been made of three cases in which ground observers confirmed the existence of large (> 2 cm diameter) hail. The radar analyses were referenced to the times and locations of the large hail events. Time histories of the low elevation angle dual-polarization data associated with each hail event were constructed. As expected, it was found that natural variations in the precipitation characteristics (i.e. rain/hail ratio, significantly non-spherical hail shapes, etc.) affected the multiparameter hail signatures. All three events displayed fractionally negative differential reflectivity (Z_{DR}) values in the echo cores. Some degree of localized reduction in the copolar H, V correlation at zero time lag [$\rho_{HV}(0)$] was also present in each case. The Mie scattering-induced differential phase shift was only apparent in the storm that generated the most nonspherically shaped hailstones (maximum and minimum diameters of 3.5 and 1.0 cm respectively).

Reference

1. Kennedy, P. C., V. N. Bringi, S. Bolen, and S. A. Rutledge, 1995: An Examination of Dual Polarization Signatures Associated With Confirmed Occurrences of Large Hail. *Preprints, 27th Conference on Radar Meteorology,* Vail, Colorado, Amer. Meteor. Soc., 41-43.

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T. University of Iowa/Institute of Hydraulic Research

1. SUMMARY OF RESEARCH RELATED TO WSR-88D ALGORITHMS AND PRODUCTS

The focus of activity at the Institute of Hydraulic Research is directed toward the Precipitation Processing Subsystem (PPS). We have investigated the performance of the mean-field bias adjustment algorithm using a data-based Monte Carlo simulation. Several ways to improve the current algorithm were recommended and some are being implemented at the NWS

Office of Hydrology. We have also investigated optimal calibration of the PPS parameters. A global optimization algorithm which is capable of accounting for the parameter interactions has been implemented and used. Results show that considerable improvements can be achieved. Another topic of interest is radar data compression and database organization. The objective is to develop techniques that allow the conduct of studies on multiple year databases. With the current Archive II format this is practically impossible. Hence, procedures have been developed that make studies of large datasets feasible.

Reference

1. Anagnostou E.N., W.F. Krajewski, D.-J. Seo, and E. R. Johnson, Mean-Field Radar-Rainfall Bias Studies for NEXRAD, Submitted to the *ASCE Journal of Engineering Hydrology*, 1996.

Abstract

Real-time 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.

2. RADAR DATA BROWSER

The Iowa Institute of Hydraulic Research has developed a browser and display software for radar data. An efficient design and implementation allows random access to any volume scan data. The software is interfaced with an efficient data compression scheme developed for NEXRAD reflectivity data. The display provides Plan Position Indicator, Range-Height Indicator and Azimuth-Height Indicator (15°) modes of viewing the data.

Reference

1. Kruger, A., and W. F. Krajewski, 1995: VRAD: A radar data browser, *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 368-370.

3. TROPICAL PRECIPITATION MEASUREMENT

This task relates to NASA-supported studies on precipitation algorithm development for the Tropical Rainfall Measuring Mission. Data used include radar reflectivity observations from the WSR-88D in Melbourne, Florida. In addition to documenting the algorithm development and testing the study included issues related to anomalous propagation echo detection with the WSR-88D, the use of neural network-based rainfall estimation algorithms, examination of data compression schemes, study of the effects of the radar measurement process on inferred rainfall statistics, and statistical summarization of the several months worth of data.

Reference

1. Krajewski, W. F., J. A. Smith, V. Chandrasekar, E. N. Anagnostou, M. L. Baeck, G. J. Ciach, M. Grecu, A, Kruger, J. R. McCollum, M. Steiner, and R. Xiao, 1996: Radar-rainfall estimation studies for TRMM ground validation, IIHR Technical Report No. 379, Iowa Institute of Hydraulic Research, 210 pp.

4. RADAR DATA COMPRESSION

A radar data compression scheme based on the run length coding method has been developed. The procedure includes several features which make it very efficient in both storage and read time performance parameters. The performance of the scheme compares favorably with several other popular schemes of data compression.

Reference

1. Kruger, A. and W.F. Krajewski, 1996: Efficient Storage of Weather Radar Data, *Software Practice and Experience*. (In press).

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U. McGill University

1. BISTATIC RECEIVER SHAKEDOWN

In cooperation with the University of Oklahoma, a bistatic receiver developed by

Wurman et al. (1995) was installed 40 km southeast of the McGill radar site. This system, designed at NCAR, allows the direct measurement of two or three-dimensional winds in real time by the use of additional receivers at remote locations. The bistatic system supports wind field retrieval work, both for verification of single-radar wind retrievals or linear wind approximations, and will support future real-time thermodynamic retrievals. Furthermore, the geometry of the main radar site and the additional receiver allows accurate determination of dual-Doppler winds in the vicinity of Montreal's Dorval Airport.

The successful operation of the system depends on the perfect synchronization of the two receivers as well as the flawless operation of communications and software at the radar and the remote sites. Considerable effort was expended to transform this research instrument into a system that could be used in an operational environment and with minimum monitoring. System upgrades included changes in the hardware (e.g. GPS synchronization firmware), in the software (making it more robust to communication outages and system crashes), as well as dealing with breakdowns of varied causes (phone line problems, power surges, vandalism, etc.). At this point, the system has a mean time between failures on the order of weeks. Failures are mostly due to software crashes at the remote site.

In addition to the shakedown work, software was written to archive and play back the data. The results are very encouraging; comparisons between dual-Doppler winds and profiler data (collected 30 km east of the radar site in the coverage zone of the receiver) show excellent agreement at distances away from the ground. Near the ground, the differing ground clutter coverage of the system results in unreliable winds as one receiver sees zero velocity from clutter while the other observes Doppler velocities associated with weather. This problem should be reduced significantly when clutter filtering at the main radar site will be implemented next year.

Reference

1. 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.

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2. MEASUREMENT OF THE INDEX OF REFRACTION NEAR THE SURFACE

The speed at which electromagnetic waves travel is dependent on the index of refraction of the atmosphere. Small changes in the time it takes a radar signal to travel to a fixed target and back are related to small perturbations in the refractive index caused by changes in humidity, temperature, and pressure. The measurement of the refractive index therefore affords the possibility of extracting information of surface conditions (especially humidity) from radar.

Using the phase information from ground targets and its time evolution as a proxy for the travel time of radar waves, a procedure for measuring the near-surface index of refraction field near the radar was demonstrated and implemented. After a quick development period, the algorithm now runs operationally on the McGill radar system and was also tested on NCAR's S-Pol radar.

The result of this collaborative work between McGill and NCAR can be readily implemented on any Doppler radar, provided the transmitter's stable local oscillator (STALO) has accurate (below 0.25 ppm) frequency stability over very long periods and that the phase of the targets are measured. Accurate measurements of refractive index fields in a radius of a few tens of kilometers around the radar (where ground targets can be observed) are being made, and contrasts in refractivity associated with frontal passages and storm outflows have been observed.

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3. REFLECTIVITY-BASED PREDICTION OF DAMAGING WINDS

In order to detect damaging winds, a VIL and echo-top based "wind gust" algorithm (Emanuel 1981; Stewart 1991) has been used at McGill for several years. Although the algorithm was originally developed for isolated air mass-like thunderstorms, surprisingly high correlation has been reported by the local weather office between the prediction from the gust algorithm and damage on the ground for many types of convective weather. Using Doppler data, a more thorough evaluation of the gust algorithm was hence undertaken.

First, an algorithm computing peak radial velocity shear near the ground was developed for verification purposes. This algorithm computes the maximum radial wind shear (in $m\ s^{-1}\ km^{-1}$) over distances from 2 to 8 km. Then a comparison between the wind gust and shear algorithms was made. No significant Doppler signature was observed for predicted gusts smaller than 15 $m\ s^{-1}$. Beyond this threshold, most gusts detected using reflectivity data had an associated Doppler signature. Moderate correlation existed between the strength of the gusts and the magnitude of the Doppler shear. Most importantly, the echo-top gust algorithm was found to have a lead time on the order of 5 min over the Doppler signature.

References

1. Emanuel, K., 1981: A similarity theory for unsaturated downdrafts within clouds. *J. Atmos. Sci.*, **36**, 2462-2468.

2. Stewart, S. R., 1991: The prediction of pulse type thunderstorm gusts using vertically integrated liquid water content and cloud top penetrative downdraft mechanism. *NOAA Tech. Memo. NWS SR-136*, National Weather Service Office, FAA Academy, Oklahoma City Oklahoma.

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4. FINE TUNING OF THE MESOCYCLONE ALGORITHM

Evaluation and fine tuning of the mesocyclone detection algorithm was performed. The algorithm, based on the work of Zrnić et al. (1985), was first tuned to Montreal's less severe weather using the values found by the King City group in Toronto (Crozier et al. 1991) as guidance. In addition, a vertical continuity requirement was added to take advantage of our 24 elevation angles scanning program. To ensure mesocyclone detection, the signature must be found on at least three consecutive elevation angles or be found at five total angles. Furthermore, the signature must extend over 2 km in the vertical. A significant reduction in false alarms and an increase in the robustness of the algorithm was observed.

References

1. Crozier, C. L., P. I. Joe, J. W. Scott, H. N. Herscovitch, and T. R. Nichols, 1991: The King City operational Doppler radar: Development, all-season applications and forecasting. *Atmos.-Ocean*, **29**, 479-516.

2. Zrnić, D. S., D. W. Burgess, and L. D. Hennington, 1985: Automatic detection of mesocyclonic shear with Doppler radar. *J. Atmos. Ocean. Tech.*, **2**, 425-438.

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5. RIVER OUTFLOW PREDICTION OVER HILLY TERRAIN

In order to demonstrate the potential of radar for hydrology to the local hydroelectric power company (Hydro Quebec), three hour rainfall accumulations over a five month period were computed for input to Hydro Quebec's hydrological model of the Chateauguay River basin (2500 km^2). Because a large proportion of the Chateauguay basin is located in the Adirondacks where significant ground clutter is observed by the radar at low levels, a technique to infer near-surface rainfall using VIL was devised. On an hourly basis, the relationship between VIL and low-level reflectivity was computed in the ground-echo free areas near the problem region. If a minimum number of VIL-Z pairs was available, the relationship derived from this data was then used in the following hour to replace the contaminated reflectivity measurements based on the VIL. Otherwise, the nearest clutter-free neighbor was used.

The maps were then provided to Hydro Quebec who ran the hydrological model using both radar data and raingauges as input. Despite the clutter conditions, limited radar adjustments (one Z-R relationship, no gauge adjustment on a case-by-case basis), and the fact that the model had been tuned for raingauges, the model produced better outflow predictions in convective weather when radar data was used than when raingauges were used. In stratiform rain, the radar-based and gauge-based predictions were comparable.

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V. University of Oklahoma/Center for Analysis and Prediction of Storms

1. DESCRIPTION OF WSR-88D RELATED RESEARCH

Research and operational testing with WSR-88D data at the Center for Analysis and Prediction of Storms (CAPS) covers three topical areas: 1) analysis of winds over broad areas using WSR-88D data in combination with winds from forecast models, wind profilers and surface stations, 2) derivation of cross-beam wind components from a sequence of single-Doppler radar volumes, termed Single-Doppler Velocity Retrieval (SDVR), and 3) retrieval of thermodynamic variables from a sequence of wind analyses with the Doppler radar data as the primary data source.

Although not directly involved in research on algorithms within the WSR-88D system, CAPS uses the base radar data. Hence, CAPS is potentially affected by changes in quality control, scan strategies, clutter suppression, and implemented velocity/range unfolding algorithms. CAPS also has interest in developing and/or using schemes to compress the data for efficient real-time transmission.

2. COMBINING MESOSCALE DATA SOURCES, INCLUDING WSR-88D DATA, FOR MODEL INITIALIZATION

CAPS has developed a program to ingest real-time radar reflectivity and velocity information from the WSR-88D, Archive Level II, or NIDS data streams in concert 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) uses the Bratseth analysis technique and a Cartesian radar remapping program similar to that developed by the Forecast Systems Lab (FSL) for their Local Analysis and Prediction System (LAPS). 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, satellite, and the WSR-88D.

Analyses and forecasts have been made in real time and in case-study mode for events during the VORTEX field experiment in 1995 and the CAPS Spring Operational Period in 1996. Samples of real-time runs and preliminary results are documented in recent conference publications (e.g., Droegemeier et al., 1996, Xue et al., 1996).

References

1. Brewster, K., 1996: Application of a Bratseth analysis scheme including Doppler radar data. *Preprints, 15th Conf. on Wea. Analysis and Forecasting*, Norfolk, Virginia, Amer. Meteor. Soc., 92-95.

2. Droegemeier, K.K. et al., 1996: The 1996 CAPS spring operational test period: Real-time storm-scale NWP, Part I: Goals and Methodology. *Preprints, 11th Conf. on Num. Wea. Pred.*, Norfolk, Virginia, Amer. Meteor. Soc., 294-296.

3. Xue et al., 1996: The 1996 CAPS spring operational test period: Real-time storm-scale NWP, Part II: Operational summary and sample cases. *Preprints, 11th Conf. on Num. Wea. Pred.*, Norfolk, Virginia, Amer. Meteor. Soc., 297-300.

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3. SINGLE-DOPPLER VELOCITY RETRIEVAL

The SDVR research involves three different techniques developed at CAPS as well as a comparison project that includes two techniques developed elsewhere. All five schemes are summarized in Shapiro et al. (1996). Briefly, the CAPS-developed schemes include 1) a simple adjoint applied to radial winds (Xu et al. (1995), 2) the conservation of scalars (Shapiro et al. (1995), and 3) conservation in a moving reference frame (Gal-Chen and Zhang, 1993). Data from several field experiments have been used in development and testing. Case events include a microburst, a quiescent boundary layer, multicellular convection, and a severe thunderstorm (Shapiro et al., 1996). Using high temporal resolution data from a research radar, Xu et al. demonstrated that rapid scanning (frequent data availability) was essential to obtaining a successful single-Doppler velocity retrieval. The Shapiro et al. 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. 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.

References

1. Gal-Chen, T., and J. Zhang, 1993: On the optimal use of reflectivities and single-Doppler velocities to deduce 3-D motions. *Preprints, 26th Intl. Conf. on Radar Meteor.*, Norman, Oklahoma, Amer. Meteor. Soc., 414-416.

2. Shapiro, A., S. Ellis and J. Shaw, 1995: Single-Doppler velocity retrievals with Phoenix II data: Clear air and microburst wind retrievals in the planetary boundary layer. *J . Atmos Sci.*, **52**, 1265-1287.

3. Shapiro, A., L. Zhao, J Zhang, J. Tuttle, S. Laroche, I. Zawadski, Q. Xu, J. Gao, 1996: Single-Doppler velocity retrievals with hailstorm data from the North Dakota thunderstorm project. *Preprints, 18th Conf. on Severe Local Storms*, San Francisco, California, Amer. Meteor. Soc., 546-550.

4. Shapiro, A., L. Zhao, S. Weygandt, K. Brewster, S. Lazarus, and K. Droegemeier, 1996: Initial forecast fields created from single-Doppler wind retrieval, thermodynamic retrieval and ADAS. *Preprints, 11th Conf. on Num. Wea . Pred.*, Norfolk, Virginia,

Amer. Meteor. Soc., 119-121.

5. Xu, Q. C.J. Qiu, H.-D. Gu and J.-X. Yu, 1995: Simple adjoint retrievals of low-altitude wind fields from single-Doppler wind data. *J. Atmos. Oceanic Technol.*, **11**, 579-585.

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4. RETRIEVAL OF THERMODYNAMIC VARIABLES

The thermodynamic data retrieval involves applying the techniques originally described by Gal Chen (1978) to the ARPS model using a time sequence of SDVR wind analyses as input. 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.

Reference

1. Gal-Chen, T., 1978: A method for the initialization of the anelastic equations: Implications for matching models with observations. *Mon . Wea. Rev.*, **106**, 587-696.

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W. University of Oklahoma/Cooperative Institute for Mesoscale Meteorological Studies

1. WIND FIELD ANALYSES TECHNIQUES

For the past several years OU/CIMMS has been developing analysis packages that include:

1) A variational data analysis algorithm for interpolating raw radar data onto a model grid and for filtering data holes.

2) Simple adjoint (SA) algorithms for 2-D wind retrievals from single-Doppler wind and/or reflectivity data.

3) Least-square (LS) algorithms for 2-D wind retrievals from single-Doppler wind

and/or reflectivity measurements.

4) A simple adjoint (SA) algorithm for 3-D wind, perturbation pressure, and temperature retrievals from single-Doppler wind and/or reflectivity measurements.

This work is continuing as a joint effort between the Cooperative Institute for Mesoscale Meteorological Studies and the Naval Research Laboratory. The basic ideas and some of the detailed techniques used in the above algorithms are described in the listed publications.

References

1. Qiu, C. and Q. Xu, 1992: A simple adjoint method of wind analysis for single-Doppler data. *J. Atmos. Oceanic Tech.*, **9**, 588-598.

2. Xu, Q., C. Qiu, and J. Yu, 1994: Adjoint-method retrievals of low-altitude wind fields from single-Doppler reflectivity measured during Phoenix II. *J. Atmos. Oceanic Tech.*, **11**, 275-288.

3. Xu, Q., and C. J. Qiu, 1994: Simple adjoint methods for single-Doppler wind analysis with a strong constraint of mass conservation. *J. Atmos. Oceanic Tech.*, **11**, 289-298.

4. Xu, Q., C. Qiu, and J. Yu, 1994: Adjoint-method retrievals of low-altitude wind fields from single-Doppler wind data. *J. Atmos. Oceanic Tech.*, **11**, 579-585.

5. Qiu, C., and Q. Xu, 1994: A spectral simple adjoint method for retrieving low-altitude winds from single-Doppler data. *J. Atmos. Oceanic Tech.*, **11**, 927-936.

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7. Xu, Q., and C. Qiu, 1995: Adjoint-method retrievals of low-altitude wind fields from single-Doppler reflectivity and radial-wind data. *J. Atmos. Oceanic Tech.*, **12**, 1111-1119.

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10. Yang, S., and Q. Xu, 1996: Statistical errors in variational data assimilation – A theoretical one-dimensional analysis applied to Doppler wind retrieval. *J. Atmos. Sci.*, **53**, 2563-2577.

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3. Xu, Q., S. Yang and H. Gu, 1995: New simple adjoint method for three-dimensional wind and temperature retrievals from single-Doppler data. *Preprints, 27th Conf. on Radar Meteorology*, Vail, Colorado, Amer. Meteor. Soc., 806-807.

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X. Princeton University

1. SUMMARY OF RESEARCH ACTIVITIES AND RESULTS

A major focus of the research at Princeton University is the hydrometeorological assessment of the NEXRAD WSR-88D based rainfall estimation products. This includes detailed case studies of heavy rainfall and/or hail 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. These analyses focus on range effects, bright-band contamination, issues related to Z-R relationships, testing of different elements of the NEXRAD Precipitation Processing System, and the application of hail thresholds. The quality control of recorded 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 the hydrometeorological environment.

Principal results from the above studies may be summarized as:

1) The climatology of WSR-88D reflectivity observations at the lower four tilts for the Southern Plains and mid-Atlantic regions during the warm season is most strongly influenced by reflectivity enhancement in the melting layer. This translates into warm season reflectivity

peaks at approximately 50 km for the fourth tilt, 70 km for the third tilt, 100 km for the second tilt and 180 km for the first tilt.

2) The close range bias observed in hourly rainfall analyses is more appropriately termed a mid-range bias, centered at approximately 100 km during the warm season. The principal causes of the mid-range bias are amplification of second tilt reflectivity at the bright band combined with the use of biscan maximization. Amplification often involves reflectivity values close to the reflectivity hail threshold, consequently the mid-range bias is also linked to the reflectivity threshold.

3) Scan strategies which replace the third and fourth tilts with either second or first tilts have little effect on overall range-dependent biases.

4) Range dependent biases, as well as systematic biases, could be mitigated through elimination of biscan maximization and changing Z-R relations (for example, at Melbourne, Florida, to $Z = 200\ R^{1.4}$).

5) Flood and flash-flood producing storms typically produce rainfall rates exceeding the maximum imposed by a 53 dBZ threshold with $Z = 300\ R^{1.4}$. In numerous cases, large rainfall rates occur in conjunction with significant hail production. Increasing the reflectivity threshold to 55 dBZ should be considered.

6) Severe underestimation of rainfall occurs for catastrophic storms, like the Rapidan, Virginia (June 27, 1995) and Houston, texas (October 16-17, 1994) storms. An important characteristic of these storms is low-echo centroid suggesting the prominence of warm rain processes. Underestimation for the Rapidan and Houston storms resulted from a combination of a) an inappropriate Z-R relationship, b) low-level growth, and c) occurrence of reflectivity values in rain exceeding the reflectivity threshold for hail. The development of warm rain Z-R relations should be examined, along with the determination of criteria for applying these relations.

7) Severe thunderstorms, like the Orlando hailstorm (March 25, 1992), can produce large rainfall rates (exceeding 300 mm h^{-1}) with a severe underestimation by the WSR-88D algorithms, or moderate to low rainfall rates (like the May 29-30, 1995 New Jersey storm or the Oklahoma July 7-8, 1994 squall line) with severe overestimation by radar, or large rainfall rates with acceptable estimates from the WSR-88D rainfall algorithms (like the June 3-4, 1995 Oklahoma storm).

8) The relationship between Z-R parameters, $Z = AR^b$, and the storm environment was examined for Florida and the Southern Plains. Useful correlations between Z-R parameters and environmental factors such as pre-storm values of CAPE, precipitable water, and cloud base were not obtained for Florida. For the Southern Plains, the multiplicative parameter A decreases with increasing CAPE, likely due to a connection with the storm's vertical development. The parameter A decreases with increasing cloud base, reflecting the possible role of evaporation

below cloud base.

9) The climatology of refractive index variations in the boundary layer has been characterized through analyses of observations from the climatological radiosonde network. Geographic, seasonal, and diurnal variations in the potential for anomalous propagation contamination have been estimated.

10) A selection of algorithms to detect anomalous propagation signatures in radar echo patterns have been implemented and tested on selected Archive Level II datasets. None of the investigated algorithms (all reflectivity-based only) adequately eliminates signal contamination due to anomalous propagation. The problem is exacerbated during periods in which anomalous propagation echoes are embedded in rainfall.

References

Topics indicated refer to:

1. Radar-rainfall measurement/estimation
    a) range effects
    b) bright band
    c) Z-R relationships
    d) testing of the NEXRAD Precipitation Processing System (hybrid scan, biscan maximization, etc.)
    e) hail threshold
2) Radar data quality control
    a) anomalous propagation (algorithm development and intercomparison)
    b) sounding analysis to assess anomalous propagation potential
3) Case studies
    a) heavy rainfall
    b) hail/rain
    c) hydrometeorological environments of storms
    d) thunderstorm electrification and rainfall
4) Climatological studies

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1. WSR-88D DATA QUALITY CONTROL

The University of Washington Quality Control (UWQC) program was created to automatically remove non-precipitation echoes from NEXRAD Archive II data. The procedure removes clear air return, echo from insects, and most ground clutter and anomalous propagation (AP). Strong ground clutter and AP that exist in the second or third tilts are almost entirely removed in the general application.

For each tilt in the NEXRAD volume, the UWQC looks at the 18 km x 18 km neighborhood around every 2 km x 2 km pixel in the tilt. If any pixel in the neighborhood (excluding the center pixel) is greater than or equal to a specified dBZ threshold, the central pixel is kept. Otherwise, the pixel is set to a "bad value" flag. This method maintains weak reflectivity values at storm edges while removing other areas of weak non-precipitation echo and isolated intense ground clutter and AP.

The dBZ thresholds were determined by observing maximum dBZ values of non-precipitation echo at varying altitudes. Non-precipitation echo dBZ values were observed to decrease with increasing altitude and thresholds were set for three different layers: the boundary layer, below the boundary layer +1 km, and below the freezing level. No data are removed above the freezing level.

Since radars vary somewhat in calibration, dBZ thresholds must be adjusted for a specific radar. Layer heights are a function of climatology and change seasonally. Once these parameter adjustments are made, the automatic algorithm performs well for data collected throughout a season without further adjustment.

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Z. University of Western Ontario

1. STUDIES OF ATMOSPHERIC TURBULENCE USING DOPPLER SPECTRAL WIDTHS

The use of Doppler spectral widths to determine strengths of atmospheric turbulence has been discussed extensively by a number of authors (Atlas et al., 1969; Frisch and Clifford, 1974; Hocking, 1983a,b, 1985, 1986). The theory related to this process is well known and essentially involves measurement of the spectral width, extraction of contaminant contributions like spectral broadening due to the mean horizontal motion of the scatterers through the finite beam width, and conversion of the remaining contribution to an estimate of the turbulent energy dissipation rate. The extraction of "contaminant" effects is not trivial, but is fairly well understood. The importance of removing the effects of wind shears is also important, and it is important to recognize that wind shears can act in both a negative and a positive sense. For example, it is not always appreciated that when observing with tilted beams of a wind profiler radar it is sometimes possible that a wind shear can actually cause a narrowing of the spectrum relative to that which would be expected for a uniform wind when using wind profiler radars (Hocking, 1983a). It is also sometimes necessary to remove effects due to periodic motions like gravity waves. Hocking (1988) and Murphy et al. (1994) have discussed how temporal variations due to gravity waves may contaminate the spectral width even though the data length recorded may only be a small fraction of the period of the gravity waves.

Once gravity waves and beam broadening effects are deconvolved from the measured spectra, the remaining spectral width can be used to determine the energy dissipation rate. Almost all workers use an expression of the form $\epsilon = \beta \sigma^3 / L$ (possibly with second order corrections) where ϵ is the turbulent kinetic energy dissipation rate, β is a constant, σ is the root mean square velocity deduced from the spectral width of the signal, and L is a scale. However, there is some confusion about the appropriate scale L to use.

Radar meteorologists tend to use a value for L which relates to the scales of the radar volume (either the radar beam width or the pulse length, whichever is larger). Middle atmosphere dynamicists tend to use a value for L which relates to the largest scale of eddies in a turbulent regime (the so-called "outer scale"). It is important to determine which is the most appropriate scale.

The issue has been discussed extensively by Hocking, (1996). This work was most relevant to near-vertically pointing radars, such as wind profilers, but its relevance to the NEXRAD radars may also be significant. As long as the radar scales (beam width and pulse length) are less than one half of the buoyancy scale of the turbulence, the formulae presented by Atlas et al., (1996) and Frisch and Clifford (1974) (with corrections as discussed by Labitt, 1979; and Bohne, 1982) are appropriate. However, once either the radar beam width or the pulse length become comparable to the buoyancy scale of the turbulence, the scale L should be the buoyancy scale. Indirect experimental confirmation of this important result has been provided by Bohne (1981). Hocking (1996) gives detailed pictographs that can be used to determine which scale is most important in any circumstance, but the important point is that users must be aware that different expressions apply under different circumstances. Consideration of this point must be taken in determinations of energy dissipation rates using

Doppler spectral width methods.

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AA. University Space Research Association, Global Hydrology and Climate Center

1. HURRICANE-SPAWNED TORNADOES

Radar echo histories, tornado reports, and Cloud-to-Ground (CG) lightning data from Tropical Storm Beryl, which produced a major tornado outbreak in South Carolina on 16 August 1994, are being studied. Of particular interest are the observations that: (1) some of the tornadic cells (definitely miniature supercells) persisted as recognizable echo entities for as long as 9 or 10 hours (though not supercellular for that entire time), (2) CG lightning rates were not generally large, and (3) CD flashes were almost always of negative polarity. The Cammarata et al. (1996) paper showed that there were sometimes significant reductions in CD rates in cells when they were producing major tornadoes. As in other miniature supercell cases, it was often found that shear thresholds suitable for Great Plains supercells were too high to guarantee detection of the small mesocyclones associated with the tropical cyclone tornadic storms. While no single parameter seems to be a perfect indicator of the presence of these small mesocyclones, a compound approach using echo height and size, mesocyclone diameter, height and shear, and possibly CG lightning flash rate fluctuations might yield improvement in detection and warning for these storms.

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BB. Bureau of Meteorology, Australia

1. BACKGROUND

The Bureau of Meteorology (BOM) operates a network of 30 weather watch radars across Australia. They are a mixture of C (most) and S-band (few) conventional radars primarily based on EEC systems but with in-house modifications especially for display functions. The first BOM Doppler radar specifically for operational use is scheduled for installation in Sydney during 1997. The Bureau of Meteorology Research Centre (BMRC) also operates a C-band polarimetric/Doppler radar (linear horizontal and vertical polarization) in Darwin in support of its research activities.

The present BOM operational data system was primarily developed in-house and enables PPI looping, RHI reconstruction, CAPPI's, VIL computation, and 3-D rendering of 16 level volumetric reflectivity and Doppler data. Data from several sites can be composited. Development of algorithms for quantitative use of the radar data is also underway. Primary application areas include: 1) aviation support, 2) short-term forecasting and severe weather applications, and 3) rainfall estimation.

The work involves adaptation and testing of existing algorithms and their incorporation within the BOM operational framework. Currently 16 level data only are available in real time. Work is underway to provide 256 level intensity and Doppler data for implementation of future algorithms. Engineering and software steps necessary to achieve these ends are proceeding as part of the development of a new BOM Doppler radar system.

2. AVIATION AND STORM APPLICATIONS

Cell tracking and extrapolation applications have been developed employing the TITAN package provided by NCAR. Components of this system have been implemented on the BOM operational radar using the currently available 16 level reflectivity data. The operational utility of TITAN for aviation and severe storm applications is presently under evaluation.

To provide more diagnostic planetary boundary layer information, the NCAR TREC (Tracking Clear Air Echoes by Correlation) has been incorporated in the BOM radar real-time framework for evaluation. Currently, derived wind vectors are available for display on the existing radar system and in a database for a mesoscale analysis. A VAD technique has also been developed within the BMRC and will be available for operational use primarily in a time/height display mode.

A wind profiler display, which includes a capability to incorporate ACARS data, is also under development. It will designate high shear regions and provide diagnostics such as temperature gradient and advection based on the assumption of geostrophic balance.

The next phase of development will be to test and evaluate gust front/air mass boundary detection schemes for research and operational applications. Initial trials are underway with the NCAR COLIDE system. Plans are also proceeding to test the Lincoln Laboratory MIGFA package. Intercomparson of these algorithms will be made under Australian conditions using the operational radar configuration. These trials will determine if the algorithms are consistent with operational needs. It is planned to combine microburst detection algorithms with information available from LLWAS as part of the aviation program.

It is also proposed to investigate the NSSL Warning Decision Support System (WDSS) for severe weather applications including, cell identification and tracking as well as the detection of hail, mesocyclones, tornadoes, and microbursts.

3. RAINFALL AND HYDROLOGICAL APPLICATIONS

Based on the Tropical Rainfall Measuring Mission Ground Validation (TRMM GV) activities in Darwin, several quantitative radar rainfall estimation techniques are being investigated for hydrological applications. Conventional techniques being compared include traditional power law relationships, the Window Probability Matching Method (WPMM), and various Kriging techniques. Initial research work is directed toward evaluating these techniques at time and space scales suitable for hydrological applications. Their impact on hydrological run-off models is also being studied. This work is being undertaken using BMRC Darwin research quality radar and raingauge datasets. The next stage will involve operational extension of these techniques to other sites with hydrological significance. Radar data will be combined with satellite, raingauge, and NWP data in this application.

Polarimetric radar data collected during the MCTEX program is also being evaluated for rainfall estimation applications. The polarimetric variables under study include differential reflectivity, specific differential phase shift, and the zero lag cross-correlation coefficient. Initial results indicate that use of a simple specific differential phase shift approach overcomes many of the inherent weaknesses in traditional approaches and provides excellent agreement with gauges (especially in high rainfall regimes).

The above polarimetric and conventional approaches for estimating rainfall and combinations thereof will be trial tested in Darwin in real time as part of the on-going NASA TRMM GV program over the next few years. The aim will be to evaluate the operational utility of the polarimetric measurements.

4. SUMMARY

Extensive engineering work is underway to modernize the BOM radars to include

Doppler capabilities and algorithms for severe weather, aviation, and quantitative rainfall applications. Much of the algorithm work is being done with close co-operation and support from other agencies including Colorado State University, the National Severe Storms Laboratory (NSSL), the National Center for Atmospheric Research (NCAR), the Hebrew University of Israel, NASA, and Lincoln Laboratory.

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1. WIND FIELD RETRIEVAL FROM SINGLE-RADAR DATA

A method for retrieving two-dimensional wind fields from a single snapshot of Doppler velocity measurements from a single radar is being developed. The method is applicable to wind fields containing significant discontinuities such as mesocyclones, microbursts, and gust fronts. A two-dimensional field of wind vectors is produced. The method can be used not only as an analysis tool but also as an improved hazard detection algorithm.

The wind component tangent to the radar beam is not measurable with a single radar. Therefore, additional simplifying assumptions or information are needed to determine the two-dimensional winds from a single Doppler radar. An assumption used here is that a wind field with vorticity and divergence constraints is a good representation of the true wind field. This assumption is formulated as a non-linear variational minimizing problem which is solved with Ritz's method. The basis set used involves axisymmetric vortices and divergences and two constant vectors.

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DD. Swiss Federal Institute of Technology (ETH)

1. TRACKING RADAR ECHOES

The well-known Tracking Radar Echoes by Correlation (TREC) technique has been extended by using a variational constraint to smooth the individual motion vectors. The new technique, called COTREC, allows not only the retrieval of the motion of radar echo patterns but also objectively identifies regions where echo growth or decay are taking place (Li et al., 1995). Thus, potentially dangerous storms can be detected in a very early stage of their development. Comparisons of COTREC-derived motion vectors with Doppler velocities show good agreement. One big advantage of the new technique is that no contouring of the radar cells is necessary to obtain the motion of small-scale radar features. The method is applicable for nowcasting severe weather (floods, hail, and wind) over complex orography. Present research seeks to extend COTREC to three dimensions and to combine COTREC with other Doppler information.

2. NOWCASTING DAMAGING WINDS

Radar signatures of intense convective storms are being sought to detect severe weather (hail, wind) at the ground. It was found that a combination of three criteria (maximum height of the 45 dBZ volume, divergence in the echo tops, and azimuthal shear at midlevels) is very promising in the nowcasting (40-55 min in advance) of severe straight-line (i.e., non-tornadic) winds. The severe winds are not associated with an extension of a midlevel mesocyclone to the ground, but rather with explosive secondary cellular growth. This preliminary finding resulted from detailed case study analyses (Schmid et al. 1997). A statistical evaluation of a large data sample is progressing.

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EE. Swiss Meteorological Institute

1. ALGORITHMS FOR PRECIPITATION ACCUMULATION

A scan strategy was chosen to collect simultaneous reflectivity and Doppler information from network radars at 20 antenna elevation angles, every 5 min, to a range of 230 km (Joss and Lee, 1995). The procedure to deduce radar estimated precipitation rate at ground level, as implemented on the operational Swiss radars, requires four steps:

1) Calibration of the radar, elimination of ground clutter, and adjustment with rain gauges (Joss et al, 1996a,b).
2) Extrapolation of the reflectivity aloft to ground using the vertical profile of reflectivity measured by the radar itself in real time at close ranges.

3) Choosing a Z-R relationship based on past experience and the vertical profile of reflectivity.
4) Transformation of all extrapolated reflectivities at ground into the best estimate of rain-rate. For this task, a representative Z-R-relationship is needed (further analyses are required, Doelling et al 1997).

Note that for steps 2 and 3 the distribution of reflectivity with height (vertical profile) is needed. The procedure (extrapolation) makes it unnecessary to know the back-scattering cross-section of frozen particles and takes care of bright band phenomena (Fabry and Zawadzki, 1995).

Determining the profile becomes more difficult with increasing distance from the radar due to decreasing resolution of the radar beam and limitations imposed by the radar horizon (Andrieu et al., 1995). Therefore, at longer ranges it may be better to use (extrapolate) profiles determined at close ranges or to apply climatological profiles. One aim of future work is to optimize the selection of a representative profile and determine how well precipitation can be estimated using such information.

For step 4 the existing German drop-size and concurrent radar data should be further analyzed in order to allow the determination of Z-R relations at a point for a given weather situation (Doelling et al., 1997). This analyses should indicate the representativeness of the point-information for an area. Goals are to find the optimum Z-R relationship parameters and to define the errors in the full volume of the radar. It is hoped to estimate the errors from vertical profiles measured by the operational radar itself (Henrich (1997). To reach this goal precise case studies as well as rainfall climatology are needed.

2. RADAR PRODUCTS

Every 5 min the following products are made operationally:

1) Polar reflectivity and velocity information (1 km x 1 deg x 1 deg resolution, 20 elevations (up to a maximum height of 12.5 km or a maximum range of 230 km, whatever is reached first).
2) Full volume information (1 km x 1 km resolution, 12 CAPPI's (up to a maximum height of 12.5 km or a maximum range of 230 km, whatever is reached first).
3) Best estimate of rain rate at ground level (1 km x 1 km resolution, a running mean over 30 min).

At present the third product is experimental, the parameters need optimization, and the best way to determine the vertical profile as well as its representativeness has to be further developed. However, already with default parameters, the implemented procedure gives better results than previous methods.

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IV. BIBLIOGRAPHY OF RELATED RESEARCH ACTIVITY

As in previous reports, the bibliography section is based upon an extensive search of formal journals, bulletins, popular magazines, technical reports, and conference proceedings. 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 primarily of scientific interest. Case studies representing successful applications of WSR-88D data and products are also listed in the "low impact" 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 measurements are regarded as being in the latter category. "High impact" refers to closely related research activity.

Journals selected for review were determined largely 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
IEEE Transactions on Geoscience and Remote Sensing
Journal of Atmospheric and Oceanic Technology
Journal of Applied Meteorology
Journal of the Atmospheric Sciences
Journal of the Meteorological Society of Japan
Meteorological Applications
Monthly Weather Review
National Weather Digest
Water Resources Bulletin
Weather
Weather and Forecasting
Weatherwise
7th Conference on Aviation, Range and Aerospace Meteorology
15th Conference on Weather Analysis and Forecasting
18th Conference on Severe Local Storms

Papers Reviewed

Amburn, S., and P. Wolf, 1996: VIL density as a hail indicator. *Preprints, 18th Conf. on Severe Local Storms*, San Francisco, California, Amer. Meteor. Soc., 581-585.
[Moderate impact, could lead to improved hail detection and indications of maximum hail size. In an attempt to lessen the impact of the storm's environment, VIL densities (VIL divided by echo height) were computed for 221 thunderstorms and compared to surface reports from hail and rain-only storms. A threshold value of 3.5 g m^{-3} correctly identified over 90% of the severe hail events. There is some evidence that the parameter may be an indicator of hail stone size.]

Aydin, K., V. N. Bringi, and L. Liu, 1995: Rain-rate estimation in the presence of hail using S-band specific differential phase and other radar parameters. *J. Appl. Meteor.*, **34**, 404-410.
[Moderate impact. Rainfall estimates derived from measurements of radar reflectivity (Z_H), specific differential phase (K_{DP}), and attenuation at X-band (A_X) in a hail storm are compared to each other and to the temporal record at a single raingauge. Rainrate estimates from K_{DP} and A_X closely agreed with the gauge. Rates computed from Z_H agreed when a hail threshold of 55 dBZ was employed.]

Bankert, R. L., and D. W. Aha, 1996: Improvement to a neural network cloud classifier. *J. Appl. Meteor.*, **35**, 2036-2039.
[Low impact. An earlier paper discussed a probabilistic neural network (PNN) for classifying ten cloud types. Fifteen features were selected from an original listing of 200 spectral, textural, and physical features. In this paper an improved evaluation function pares the number of selected parameters to 11 and yields a 7% increase in the accuracy. The selection routine has three parts (a search algorithm, an evaluation function, and a classifier). The classifier (the PNN) uses the feature subset found by the search algorithm that maximizes the evaluation function. Search algorithms tested include those which start with one feature and sequentially add features until no additional improvement is found (forward sequential selection or FSS) and algorithms that begin with all possible features and eliminate those redundant and irrelevant features (backward sequential selection or BSS). Best results were found with a FSS approach that incorporated a "nearest neighbor" classifier.]

Bentley, M., 1996: A midsummers's nightmare. *Weatherwise*, **49**, No. 4, 13-19.
[Low impact, case study. The article gives an account of a severe derecho that struck the northeastern U.S. in the early morning hours of July 15, 1995. The storm formed over southern Ontario and moved southeastward at speeds up to 85 miles per hour. The event is well depicted in observations collected with the WSR-88D radar located at Berne, New York (about 20 miles west of Albany). A second storm from July 9, 1993 is also featured. This storm produced winds up to 125 miles per hour and spawned several tornadoes. The storm was probed by the WSR-88D near Hastings, Nebraska.]

Bieringer, P., and P. S. Ray, 1996: A comparison of tornado warning lead times with and without NEXRAD Doppler radar. *Wea. Forecasting*, **11**, 47-52.
[Low impact, performance report. Statistics regarding changes in tornado warning performance are tabulated for the pre-WSR-88D and WSR-88D eras. In general, improved detection statistics and greater lead times for warnings are found for the WSR-88D era. On average, POD's have

increased 10-15% and mean lead times have increased significantly for the first tornado occurrence on a particular day from 5 to 8 min and for all tornadoes from 9 to 11 min.]

Burlando, P., A. Montanari, R. Ranzi, 1996: Forecasting of storm rainfall by combined use of radar, raingauges and linear models. *Atmos. Res.*, **42**, 199-216.
[Moderate impact. A point rainfall prediction scheme based on radar and gauge observations is presented. Autocorrelation functions derived from radar data yield information on storm motion and are used to select nearby raingauges with predictive value. The combination of radar and gauges produced better forecasts than schemes based entirely on gauge measurements.]

Crosson, W. L., C. E. Duchon, R. Raghavan, and S. J. Goodman, 1996: Assessment of rainfall estimates using a standard Z-R relationship and the probability matching method applied to composite radar data in Central Florida. *J. Appl. Meteor.*, **35**, 1203-1219.
[Moderate impact. Problems associated with precipitation estimation using vendor supplied radar composites prepared from 15 min samples are addressed. The study found that the WSR-88D Z-R relationship produced precipitation estimates with considerable positive bias. The problem was due to the grid filling procedure employed by the vendor and to beam spreading at far ranges that resulted in echoes that did not contribute to surface rainfall. Neither Z-R technology nor the PMM worked very well for point rainfall estimates. However, for watershed averages, rainfall estimates by the PMM had smaller rms errors, slightly improved correlations with gauges, and significantly smaller bias.]

Davis, R. S., and P. Jendrowski, 1996: The operational areal mean basin estimated rainfall (AMBER) module. *Preprints, 15th Conf. on Wea. Analysis and Forecasting,* Amer. Meteor. Soc., 332-335.
[High impact. A nice study describing a flash flood detection procedure implemented by the NWS Weather Forecast Office in Pittsburgh. High resolution precipitation products are generated from the composite Hybrid Scan (1° by 1 km data). The routine monitors mean rainfalls for some 2427 basins and issues warnings whenever the estimated amounts exceed certain thresholds related to Flash Flood Guidance. The authors mention several successful detections.]

Gopal, S., and C. Woodcock, 1996: Remote sensing of forest change using artificial neural networks. *IEEE Transc. on Geosci. Remote Sensing*, **34**, 398-404.
[Low impact, applied technique. The paper describes a neural network application whereby changes in tree mortality during drought conditions are monitored with a Multilayer Feedforward Network. The paper provides a detailed description of the method. The authors conclude that the neural network yields improved results over other change detection techniques such as the Gramm-Schmidt orthogonalization scheme of image decomposition. The advantage comes from the handling of non-linearities. The internal structure of the network provides insight concerning the physical relationships between input and output.]

Gorgucci, E., G. Scarchilli, and V. Chandrasekar, 1996: Operational monitoring of rainfall over the Arno River basin using dual-polarized radar and rain gauges. *J. Appl. Meteor.*, **35**, 1221-

1230.
[Moderate impact. The authors compare rainfall estimates made from radar reflectivity (Z_H) and differential reflectivity (Z_{DR}) at C-band with rain gauge observations. The study presents results of point comparisons and for experiments with the probability matching method (PMM). In spite of ground clutter contamination and attenuation, Z_{DR}-based rainfall estimates were superior for both point rainfall estimates and for estimates made with the PMM method. Of the algorithms studied the best performer was an Z_{DR}-based algorithm that had been fine tuned using a cumulative distribution function.]

Hand, W. H., 1996: An object-oriented technique for nowcasting heavy showers and thunderstorms. *Meteor. Applications*, **3**, 31-41.
[High impact. The paper describes an automated procedure for forecasting convective storms that is being developed by the Meteorological Office in the United Kingdom. The goal is to provide warning of heavy rain and to forecast accumulations for watersheds. An object-oriented nowcasting procedure is used that incorporates vertical profiles of radar data to characterize convective cells. A conceptual model and information from a numerical weather prediction model are then used to produce forecasts of movement and subsequent cell development for periods of up to three hours. CSI scores for rainfall rate forecasts of 1, 2, and 3 hours revealed that the object-oriented technique out performed the current operational nowcasting system (FRONTIERS).]

Hand, W. H., and B. J. Conway, 1995: An object-oriented approach to nowcasting showers. *Wea. and Forecasting*, **10**, 327-341.
[High impact. The paper, an earlier version of Hand (1996), describes a simple conceptual model depicting the life cyclone of convective storms. The model is combined with radar and satellite observations to make short-term forecasts. The model consists of a sequence of 6 distinct developmental stages: 1) young developing, 2) developing, 3) young mature, 4) fully mature, 5) early dissipating, and 6) dissipating. (The paper gives a detailed description of the distinguishing characteristics for each stage.) All storms pass through each stage; hence, recognition of the specific stage of storm development enables prediction of later stages. An important factor in storm longevity is the production of "daughter" cells. The object-oriented technique is based on a set of attributes that describe a cell, define its current state, and change quantitatively during its lifetime. Examples are the age of the cell, height of the storm base, its top, area, and precipitation rate. The observed attributes are compared to those normally associated with each stage. Forecasts are made for 30 min steps out to 3 h with the notion that developing storms will mature, mature storms will dissipate, and dissipating storms will disappear. Storms are advected with numerical model winds. The difference between storm motion and upper-level outflow gives an indication of the likelihood that new cells will generate. New cells advect according to low-level winds. Two case studies are presented and evaluated qualitatively.]

Hardaker, P. J., and A. H. Auer Jr., 1994: The separation of rain and hail using single polarisation radar echoes and IR cloud-top temperatures. *Meteor. Applications*, **1**, 201-204.
[Moderate impact, important for hydrology. The paper proposes a solution to the problem of

rainfall overestimation when hail is present. A nomogram of cloud-top temperatures plotted versus reflectivity discriminates between rain and hail situations. Combining an analytical expression of the separation boundary with a Z-R relationship, permits estimates of surface rainfall rates when hail is present. Unfortunately, testing on an independent dataset and comparison with other methods attempting to mitigate hail contamination, such as establishing a maximum reflectivity value for rainfall rate calculation, were not performed.]

Holmes, R. T., D. A. Imy, 1995: Using new technology to enhance the warning process for a deadly wet microburst in eastern Colorado. *National Wea. Digest*, **20**, 18-29.
[Low impact. Diagnosis of WSR-88D products and local forecasts from the LAPS model of the NOAA Forecast Systems Laboratory resulted in an excellent warning of damaging winds. The model indicated a potential for severe downdrafts. The radar data revealed a significant echo overhang and rapidly increasing VIL values. The downburst was triggered by a sudden decrease in VIL as the reflectivity core began to descend.]

Hudak, D. R., and R. Nissen, 1996: Doppler radar applications in major winter snowstorms. *Atmos. Res.*, **40**, 109-130.
[Low impact, could be important for improving radar estimates of snowfall. Characteristics of snowstorms were monitored with mesoscale wind information derived from the Extended Velocity Azimuth Display (EVAD) method and from precipitation terminal velocities and spectral width data obtained from vertically pointing data. Deduced flow properties were compared to particle types observed at ground. The analysis suggests that storm regions with terminal velocities > 1.75 m s^{-1} and spectrum widths > 0.60 m s^{-1} were associated with accretion. Terminal velocities > 1.25 m s^{-1} associated with aggregation and those < 1.00 m s^{-1} represented diffusion processes. Knowing which processes dominate within storms could be important for estimating the density of particles.]

Jameson, A. R., and S. L. Durden, 1996: A possible origin of linear depolarization observed at vertical incidence in rain. *J. Appl. Meteor.*, **35**, 271-277.
[Low impact, findings need to be confirmed. Measurements taken with airborne, vertically pointing polarimetric radars show large linear depolarization ratios. This suggests that precipitation growth processes of coalescence, collision, and breakup cause the drops to be tilted. An ensemble of distorted drops produces a depolarization. If this effect is also present at other viewing angles, adjustments may need to be applied when estimating precipitation amounts with polarimetric data.]

Jameson, A. R., and A. B. Kostinski, 1996: Non-Rayleigh signal statistics caused by the relative motion during measurements. *J. Appl. Meteor.*, **10**, 1846-1859.
[Low impact. When mean values are fixed during radar sampling, fluctuations in amplitudes and intensities obey the same probability density function (pdf) as those for each sample contributing to the estimate. The paper shows, however, that when the mean values change from pulse to pulse, as with a scanning radar in the presence of gradients, the probability density function of the amplitudes and intensities differ from that of the samples. The radar estimates are formed by sampling a sequence of random variables from different pdf's with the result that

the pdf's of the amplitudes and intensities are no longer Rayleigh nor exponential. In the net, biases and variances increase.]

Jameson, A. R., M. J. Murphy, and E. P. Krider, 1996: Multiple-parameter radar observations of isolated Florida thunderstorms during the onset of electrification. *J. Appl. Meteor.*, **35**, 343-354.
[Low impact, application of polarimetric radars. The paper begins with a nice summary of charging mechanisms and findings of recent research in storm electrification. The differential reflectivity parameter is used to detect supercooled water in the upper regions of developing storms. The electrification process coincides with the freezing of drops and the growth of graupel. This transition is heralded by an increase in depolarization of the radar signals as measured by the linear depolarization ratio (LDR).]

Kusunoki, K., O. Suzuki, and H. Ohno 1997: Hybrid algorithm for Doppler velocity dealiasing with dual PRF data. *Preprints, 7th Conf. on Aviation, Range and Aerospace Meteor.*, Long Beach, California, Amer. Meteor. Soc., 346-349.
[Moderate impact. Most current dealiasing algorithms rely on reference wind information (environmental soundings) and assumptions of time and space continuity. The paper presents a scheme based on a dual-PRF measurements. In a first step the data are dealiased according to velocity differences at the two PRF's. The dealiased data are edited to remove strong residual azimuthal shears (regions where the difference in velocities is $\geq \Delta V_o/2$, where V_o is a positive minimum of difference velocities for the PRF combination), data points that exist only at one PRF, and velocities that exist on echo edges. The resulting "valid dataset" and original data are compared and checked for continuity. Data points removed from the original dataset are dealiased and in a final step compared to surrounding points.]

Laird, N. B., D. A. R. Kristovich, K. Labas, and S. A. R. Kristovich, 1996: Relationship between lake-effect snowfall rate and operationally observed boundary layer characteristics. *Preprints, 15th Conf. on Wea. Anal. and Forecasting*, Norfolk, Virginia, Amer. Meteor. Soc., 586-587.
[Low impact. Lake-effect snow storms are monitored with measurements taken from WSR-88D's. The shallow nature of the storms and beam filling problems aggravate the measurement problem. The authors hypothesize that the rate of boundary layer growth across the lake, the distance that the clouds and snow develop from the upwind shore, and conditions at downwind locations all influence snowfall rates. Bivariate linear regression was applied to characterize relationships between snowfall rate and a set of predictors. Statistically significant parameters related to radar-estimated snowfall rates were visibility, strong winds, the difference between the surface and 850 mb temperatures, differences between lake water and 850 mb temperatures, and surface dew-point temperature. Visibility is suggested as a parameter for estimating snowfall rates at locations that are distant from the radar.]

Liu, C., and W. F. Krajewski, 1996: A comparison of methods for calculation of radar-rainfall hourly accumulations. *Water Res. Bull.*, **32**, 305-315.
[High impact. A comparison of the advection method and the space-time Kriging method for calculating hourly accumulated rainfalls is presented. A stochastic model was used to produce

simulated radar fields which varied in time and space. Results showed that the Kriging method worked best for low wind cases while the advection method had the smallest error for high wind situations. The authors recommend the advection technique be used for flash flood situations.]

Makihara, Y., 1996: A method for improving radar estimates of precipitation by comparing data from radars and raingauges. *J. Meteor. Soc. Japan*, **74**, 459-480.
[High impact. A procedure for estimating rainfall with multiple radars and raingauges is presented. The method seeks to correct for system calibration bias, errors associated with the vertical profile of reflectivity, and radar beam height. Correction factors are computed at each grid point by comparing estimates from more than one radar. The procedure mitigates discontinuities between rainfall estimates made with different radars and from different elevation angles when constructing CAPPI's.]

Martiner, B., 1996: An intimate look at clouds. *Weatherwise*, **49**, No. 3, 20-23.
[Low impact, information only. This popular article gives a detailed look at cloud structures with a millimeter-wavelength radar. Cloud water droplets and ice crystals are readily detected because the radar beam is narrow and the reflected energy is large at 8.7 millimeter wavelength. Vertical cross sections are shown through Kelvin-Helmholtz instability billows, a small convective snow shower, and region of mammatus beneath a thunderstorm anvil.]

Marzban, C., and G. J. Stumpf, 1996: A neural network for tornado prediction based on Doppler radar-derived attributes. *J. Appl. Meteor.*, **35**, 617-626.
[High impact, relates directly to algorithm enhancements. The paper describes a neural network application for the detection of tornadoes. The network examines mesocyclones to determine which are likely to produce tornadoes. Twenty-three output parameters from the NSSL mesocyclone detection algorithm constitute the database. The network outperformed the MDA rule-based detection system, a discriminant analysis procedure, and a logistic regression scheme. Critical success indices for a series of tests with the neural network averaged 34.4% versus 26.0 for the MDA and 28.7% for the discriminant analysis.]

Matrosov, S. Y., R. F. Reinking, R. A. Kropfli, and B. W. Bartram, 1996: Estimation of ice hydrometeor types and shapes from radar polarization measurements. *J. Atmos. Oceanic Tech.*, **13**, 85-96.
[Low impact, application at K_a-band (8.6 mm). Polarization measurements are used to discriminate between planar crystals, columnar crystals, and aggregates in stratiform clouds. The radar features a phase-retarding plate that permits horizontal, vertical, left-hand and right-hand circular, and different states of elliptical polarization. The paper extends earlier theoretical studies for differentiating ice hydrometeor types and estimating their shapes. The authors argue that elliptical polarization provides an increase in the intensity and signal-to-noise ratio of the "weak" channel. A description of the theoretical basis for particle discrimination follows. Concepts are illustrated with observations.]

McFarquhar, G. M., R. List, D. R. Hudar, R. P. Nissen, J. S. Dobbie, N. P. Tung, and T. S. Kang, 1996: Flux measurements of pulsating rain with a disdrometer and Doppler radar during

Phase II of the Joint Tropical Rain experiment in Malaysia. *J. Appl. Meteor.*, **35**, 859-874. [Low impact, implications for precipitation estimation. Measurements from a Doppler weather radar revealed temporal pulses in precipitation with a period of 8 min. Pulses, confirmed by drop-size spectra, began with concentrations of large drops followed by high concentrations of successively smaller drops. The progression seems largely dictated by gravitational size sorting. The cause of the fluctuations seems related to the "seeder-feeder" process whereby new cells are generated within storms.]

Murphy, A. H., 1996: General decompositions of MSE-based skill scores: Measures of some basic aspects of forecast quality. *Mon. Wea. Rev.*, **124**, 2353-2369.
[Low impact. Simple skill scores for evaluating the accuracy of forecasts, e.g., against climatology or persistence, while providing information on overall accuracy, may not be adequate for judging forecasting performance. The author argues that decompositions of the skill score may be important because they measure specific aspects of quality and contributions to overall skill. Decompositions of the mean square error, one term derived by conditioning on the forecasts and another term derived from conditioning on the observations are described. The properties of the various terms are examined and interpreted.]

Pankiewicz, G. S., 1995: Pattern recognition techniques for the identification of cloud and cloud systems. *Meteorological Applications,* **2**, 257-271.
[Moderate impact, could be important for recognizing changes in storm character. The paper describes the fundamentals of pattern recognition and summarizes a large number of pattern recognition schemes. Numerous references are given.]

Peters, J. C., and D. J. Easton, 1996: Runoff simulation using radar rainfall data. *Water Resources Bull.*, **32**, 753-760.
[Low impact, application. In anticipation of mosaic radar information from the network of WSR-88D's, a procedure was developed that permits runoff simulations with distributed rainfall amounts. Radar grid cells are superimposed on the basin and rainfall amounts are tracked for each cell. Runoff is then routed in time to the basin outlet. For other tests, Stage III hourly precipitation data were acquired from the River Forecast Center in Tulsa, Oklahoma. An elaborate hydrologic procedure is then described for routing the water toward the basin outlet. An adjustment was made to ensure that the total volumes were nearly identical. The time histories for the observed and simulated flow agreed nicely.]

Petersen, W. A., and S. A. Rutledge, 1996: Cloud-to-ground lightning observations from TOGA COARE: Selected results and lightning location algorithms. *Mon. Wea. Rev.*, **124**, 602-620.
[Low impact, lightning flash rates are related to reflectivity trends. In several tropical cases a peak in cloud-to-ground lightning activity corresponded with the lowering of the precipitation mass enclosed by the 30 dBZ contour. Echo cores tended to reach peak heights 0 to 10 min before the peak in cloud-to-ground activity. Also, heavy rainfall began at the ocean surface before any lightning activity. This suggests that a warm rain coalescence process was occurring--at least initially.]

Pfost, R. L., 1995: Disastrous Mississippi ice storm of 1994. *National Wea. Digest*, **20**, 15-33.
[Low impact, WSR-88D application. The event took place largely in the overlap region between the Little Rock, Arkansas and Jackson, Mississippi radars. The radar depicted the stratiform rain that produced most of the rain as well as the bright band that existed in the elevated warm air. The Little Rock soundings showed a deep cold layer at the surface. Precipitation products generated by the Jackson radar substantially underestimated the precipitation in spite of bright band reflectivity enhancement, while products from the Little Rock radar grossly overestimated the rainfall. The author attributes this result either to the fact that the Little Rock radar was in a better position to observe the bright band or to system calibration errors.]

Pierce, C. E., C. G. Collier, and P. J. Hardaker, 1995: Forecasts of heavy convective rain for use within a flash flood warning system. BHS 5th National Hydrology Symposium, Edinburgh, Scotland, 4.17-4.23.
[Moderate impact. GANDOLF (Generating Advanced Nowcasts for Deployment in Operational Land-based Flood forecasts) is a project of the Meteorological Office in the United Kingdom to help forecasters by automatically assessing flash flood potential through an object-oriented approach. Monitor, Alert, and Action represent three levels of response. Assimilated information comes from mesoscale models, earth satellite infrared images, and radar. Once radar echoes are detected, the object-oriented technique described by Hand and Conway (1995) generates forecasts for periods up to 3 h. New cells are conceptually modeled according to the relationship between winds at the storm's steering level and the upper level outflow. For an illustrative example the object-oriented approach out performed the extrapolative "Frontiers" procedure for 2 and 3 hour forecasts. Results were mixed for shorter forecast periods. In general, the authors feel that advantage of object-oriented approach will increase in convective situations.]

Qiu, C.-J., and Q. Xu, 1996: Least squares retrieval of microburst winds from single-Doppler radar data. *Mon. Wea. Rev.*, **124**, 1132-1144.
[High impact. A least square method of retrieving winds from single-Doppler radar data is developed and compared with a previously developed simple adjoint method. The model uses a form of the radial momentum equation and a smoothing constraint with divergence and vorticity terms. A number of experiments are run in which different terms are neglected and with different time levels between data insertions. The least squares method fared best except in tests where the smoothing constraint was omitted and for tests in which the interval between data insertions was increased from 60 to 120 s.]

Russchenberg, H. W. J., and L. P. Ligthart, 1996: Backscattering by propagation through the melting layer of precipitation: A new polarimetric model. *IEEE Trans. Geosci. and Remote Sens.*, **34**, 3-14.
[Low impact. A simple physical model for the melting layer, with rain intensity and snow density (before melting) as inputs, is described. The model creates vertical profiles of radar reflectivity, radial velocity, differential reflectivity, and linear depolarization ratio. For two examples given, good agreement was found with observations.]

Ryzhkov, A. V., and D. S. Zrnić, 1996a: Rain in shallow and deep convection measured with a polarimetric radar. *J. Atmos. Sci.*, **53**, 2989-2995.
[Moderate impact. Rainfall estimates are made from radar reflectivity and specific differential phase measurements for two squall line events that passed through a dense network of 42 raingauges. The Marshall-Palmer Z-R relationship worked well for a summer case but not for a winter storm. The authors attribute this outcome to a narrow distribution of ice particles aloft that did not come to an equilibrium (exponential) distribution prior to deposition at the earth's surface. In contrast, rainfall estimates made from K_{DP} agreed with raingauges for both storms. Unlike simple power relationships between Z and R, K_{DP} is insensitive to variations in the drop-size distribution.]

Ryzhkov, A., and D. Zrnić, 1996b: Assessment of rainfall measurement that uses specific differential phase. *J. Appl. Meteor.*, **35**, 2080-2090.
[Moderate impact. The paper begins with a review of the advantages of using K_{DP} for rainfall measurement. A description of a simulation to determine the effects of the drop-size distribution on the rainfall estimates, particularly at low rainfall rates, on K_{DP} follows. Disdrometer measurements show the utility of K_{DP} estimates at rainfall rates well below 20 mm h^{-1}. When properly filtered in time and space, the radar measurements also gave excellent rainfall estimates. An experiment with K_{DP} rainfall rate estimates made from data obtained at 0 and 0.5° antenna elevation revealed that the data from 0° elevation angle gave higher rainrates despite beam blockage.]

Scarchilli, G., E. Gorgucci, V. Chandrasekar, and A. Dobaie, 1996: Self-consistency of polarization diversity measurement of rainfall. *IEEE Trans. Geosci. and Remote Sens.*, **34**, 22-26.
[Moderate impact. The self-consistency among radar reflectivity, differential reflectivity, and specific differential propagation phase is examined. The authors retrieve K_{DP} from Z_H and Z_{DR} and compare the result with the measured value. When measurement errors and physical processes are considered, the fractional standard error is found to be ~20% for $K_{DP} > 2^\circ$ km^{-1} (a rainfall rate of roughly 40 mm h^{-1}). Similar comparisons between estimated and measured K_{DP} values in operational settings could be important for detecting hail, ground clutter contamination, and system bias.]

Schulz, T. J., and A. B. Kostinski, 1996: Variance bounds on the estimation of reflectivity and polarization parameters in radar meteorology. *IEEE Trans. Geosci. and Remote Sens.* (accepted for publication)
[Low impact. Taking the autocorrelation function into account, the number of independent samples is usually used to estimate measurement variance. Because the number of independent samples may be considerably less than the total number of samples, the authors assert that much information could be lost in the process. The paper presents a search for variance estimators which extract the maximum information from correlated samples. The assumptions are that the horizontal and vertical polarized echoes are obtained simultaneously, that the autocorrelation function is known, and that the signal-to-noise ratios are high. The notion is that if the autocorrelation function is known it can be used to devise a better estimator whose structure

depends on the autocorrelation function. It is shown that the lower bounds of the estimation accuracy are independent of the autocorrelation function and that the effective number of independent samples is equal to the total number of samples as long as no two samples are perfectly correlated. This is accomplished by "whitening" the original data with a linear filter whose coefficients are determined by the autocorrelation function.]

Seed, A. W., J. Nicol, G. L. Austin, C.D. Stow, and S. G. Bradley, 1996: The impact of radar and raingage sampling errors when calibrating weather radar. *Meteorol. Appl.*, **3**, 43-52.
[High impact. Using simulated drop-size distributions, the least squares method (whereby the coefficient and exponent of the Z-R relationship are computed) and probability matching method of computing radar rainfall rates are compared. Findings suggest that 100 gauge and radar observations are required to estimate the coefficient of the relationship to within a value of 50 or the exponent to within 0.1. The models tended to converge with errors of 10-20% for rainfall rates < 15 mm h^{-1}. At high rainfall rates errors were sensitive to the exponent of the Z-R relationship with increasing overestimates of rainfall as the exponent increases. The authors argue that real-time detection of shifts in Z-R relationships based on a small number of comparisons will be virtually impossible. The suggestion is made that "the best that can be done operationally is to have a limited number of climatological relationships for convective and stratiform events".]

Shewell, H. M., 1996: The design and construction of a simple rate-of-rainfall gauge. *Weather*, **51**, 249-251.
[Low impact. An proposal for a rain rate measurement device is presented. The instrument receives the runoff from a known area and funnels it into a holding tank. The tank is drained with a series of vertical holes of known size. The rainfall rate is related to the "head" of water within the tank. Algae growth at the lowest hole proved to be the only difficulty with the device. The problem was alleviated somewhat by allowing the tank to drain very slowly between rain events.]

Stewart, S. R., and S. W. Lyons, 1996: A WSR-88D radar view of Tropical Cyclone Ed. *Wea. and Forecasting*, **11**, 115-135.
[Moderate impact, makes recommendations concerning the mesocyclone algorithm. Radar reflectivity and radial velocity measurements from Tropical cyclone Ed enabled close monitoring of trends in storm intensity. Maximum surface winds correlated well with radial winds at 1500 m but were 80% of their intensity. The storm's reflectivity and circulation centers were not coincident. Also, several small embedded circulations were detected by the mesocyclone algorithm. The authors caution against using output from the algorithm to locate the larger circulation center. To ensure the detection of small vortices to authors recommend that the number of pattern vectors needed to define a shear region be reduced.]

Strangeways, I. C., 1996a: Back to basics: The 'met. enclosure': Part 2(a) - Raingauges. *Weather,* **51**, 274-279.
[Low impact. The paper begins with brief history of precipitation measurement with gauges. (The first self-recording tipping-bucket raingauge was apparently invented by Sir Christopher

Wren in 1662.) A description of the various gauge types follows. Tipping-bucket gauges are described as being quite efficient and giving a reasonable representation of the rainfall when the bucket is small (0.1 mm per tip) and each tip is time stamped when recorded. The total rain volume can be stored and later measured as a backup and as a calibration check. (Part 2(b) of this series discusses wind effects on measurement errors.)]

Strangeways, I. C., 1996b: Back to basics: The 'met. enclosure': Part 2(b) - Raingauges, their errors. *Weather,* **51**, 298-303.
[Low impact, measurement errors can influence gauge/radar comparisons. The author argues that non-level gauges, manufacture precision (the lack there of), evaporation, and splashing are minor problems causing errors on the order of 1 to 2%. Large errors arise whenever the gauge interferes with the wind flow. The wind speeds up as it rises over the gauge top and carries some of the precipitation with it. Compared to a gauge at ground level, a gauge with an orifice at 1 foot height measures 5% less on average. A gauge at 20 feet measures 15% less. Errors increase with wind speed and for small droplets and snow. Shielding helps to mitigate wind effects by driving the air flow downward. Optimal installations employ pits with gratings to reduce wind eddies and splashing.]

Sun, J., and N. A. Crook, 1996: Comparison of thermodynamic retrieval by the adjoint method with the traditional retrieval method. *Mon. Wea. Rev.*, **124**, 308-324.
[High impact. A series of tests are performed in which thermodynamic fields are retrieved from a radar dataset with a gust front and from simulated data of a collapsing cold pool. Sensitivity to temporal sampling frequency, random measurement error, spatially correlated error, and errors in the divergence and vorticity forcing terms of the adjoint method are examined. The paper begins with a review of previous retrieval work by the authors and others. A discussion of the traditional retrieval method, i.e., from the continuity, momentum, and thermodynamic equations, and an adjoint method with one or two cost functions, depending on whether the input data are horizontal or radial velocity components, follows. The advantage of the adjoint method is thought to be the direct insertion of radar observations rather than the preprocessing needed by the traditional method to derive u and v. Retrievals with radar data having a temporal resolution of ~2 min differed considerably. The adjoint method had a considerably smoother potential temperature field while preserving the sharp temperature gradients at the front. In contrast, the traditional method exhibited a number of suspicious small-scale features. An rms error of 113% occurred when time differences were computed with a backward time step rather than a centered difference. The traditional method also degraded more rapidly as the time interval between data insertions increased. Errors ranged from ~0.02% at 1 min sampling to 0.21% at 10 min sampling. For the adjoint method the errors were generally < 0.5% for 1 to 10 min sampling intervals. (The traditional method was slightly better at 1 min sampling. Because the adjoint method solves a three-dimensional Poisson equation while the traditional method solves a two-dimensional Poisson equation, the adjoint method is less susceptible to random errors.]

Suzuki, O., 1997: A new method to retrieve 2-dimensional wind field from single Doppler data with local axisymmetric basis. Preprints, 7th Conf. on Aviation, Range and Aerospace Meteorology, Amer. Meteor. Soc., 336-339.

[Low impact. Two-dimensional wind fields are retrieved with a variational model that includes in a cost function consisting of the difference between the observed (Doppler) and derived wind field and as well as information of divergence and vorticity (assumed to be axisymmetric). The procedure involves three steps: (1) partition of the analysis domain, (2) solving the minimization problem in each subdomain, and (3) minimizing the problem over the entire domain. The influence of divergence and vorticity is kept small. The partitioning processes seeks to minimize the impact of vorticity and divergence sources near boundaries. Tests with a rankine vortex revealed a rms error of 0.4 m s^{-1}. Wind field recovery is good provided that the analysis domain contains the vortex core and the radar is outside the core.]

Tokay, A., and D. A. Short, 1996: Evidence from tropical raindrop spectra of the origin of rain from stratiform versus convective clouds. *J. Appl. Meteor.*, **35**, 355-371.
[Low impact, could help classify precipitation type but findings should be confirmed. The paper presents empirical evidence from raindrop spectra indicating dramatic changes in N_o (the intercept of the drop-size distribution) during the transition from convective to stratiform rain. (Such shifts are also marked by changes in the coefficient of Z-R relations ($A_{conv} < A_{strat}$). Note that this change is opposite that found by others. The authors assert that stratiform rain has a larger number of large drops and a smaller number of small drop than convective rains at the same rainrate. The transition occurs without a significant change in rainfall rate, at least initially. For a large storm sample, results indicated that stratiform rain was observed 74% of the time but in total rainfall only 32% of the rainfall was stratiform. This partitioning of rainfall was roughly reproduced by assuming that radar reflectivities > 40 dBZ represented convective rainfall.]

Toracinta, E. R., and K. I. Mohr, 1996: A comparison of WSR-88D reflectivites, SSM/I brightness temperatures, and lightning for mesoscale convective systems in Texas. Part I: Radar reflectivity and lightning. *J. Appl. Meteor.*, **35**, 902-918.
[Low impact, WSR-88D application. The paper begins with a detailed summary of previous research relating convective storms and lightning activity. As an aside, the authors mention the difficulty in producing elevated CAPPI's and in estimating echo tops with the nine elevation angles available to them. Comparison of reflectivity and lightning locations and polarity were made mostly at the 6 km level. Lightning data were summed over 5 min intervals and compared to closely timed reflectivity observations interpolated to a 2 km grid. Reflectivity values were stratified in 5 dB steps and flash densities were tabulated after normalizing by the total area covered by each reflectivity interval. In a case described in detail, the majority of negative flashes (those lowering negative charge to ground) concentrated along the convective line while few positive flashes occurred in the trailing stratiform rain region. Most negative flashes were found in the 30 to 35 dBZ intensity category; all positive flashes associated with reflectivities < 40 dBZ. In general, higher reflectivity values were observed nearby negative flashes. However, considerable variability was found among storms. Some of the variability is undoubtedly related to different stages of storm development. A regenerating MCS exhibited a declining flash rate. Negative flashes concentrated near particular convective cells, while positive flashes occurred across a broad range of reflectivities but usually below 30 dBZ. In other storms, both positive and negative flashes were clustered about intense convective cells.

Storms with low lapse rates of reflectivity produced higher numbers of negative flashes than MCS's which decreased rapidly with height.]

Ulbrich, C. W., J. M. Pelissler, and L. G. Lee, 1996: Effects of variations in Z-R law parameters and the radar constant on rainfall rates measured by WSR 88D radars. *Preprints, 15th Conf. on Weather Analysis and Forecasting,* Norfolk, Virginia, Amer. Meteor. Soc., 316-319.
[Moderate impact. The authors show that observed variations in the parameters A and b of a Z-R relationship account for only a portion of the discrepancies between observed and estimated rainrates. The large residual error often found in gauge/radar comparisons is attributed to bias in the reflectivity measurement itself.]

Wagenmaker, R., 1995: Environmental normalization of the WSR-88D Vertically Integrated Liquid Product for the detection of hail in southeast Michigan. Postprints, 1st Symposium on Michigan Weather and Forecasting, Michigan University, Ann Arbor, Michigan, 1-11.
[Moderate impact. Environmental parameters (height of the melting level, 500 mb temperature, and 500 mb geopotential) are used to determine threshold values of VIL for hail detection. For 94 storms (49 hailstorms) the POD was 0.91 and the FAR was 0.09.]

Wakimoto, R. M., and N. T. Atkins, 1996: Observations on the origin of rotation: The Newcastle tornado during VORTEX 94. *Mon. Wea. Rev.*, **124**, 384-407.
[Low impact, relates to tornado detection. The article begins with a short review of theories for how tornadoes form. This is followed by a lengthy documentation of the damage produced by a tornado observed with research radar. (Essentially no Archive II base data are available for this case.) The interesting feature about the tornado is that it did not develop within a pre-existing supercell but rather with a separate convective cell that formed along a flanking line to the supercell's northwest. While the original storm had a well defined mid-level circulation, the cell which spawned the tornado did not. Instead, the tornado was associated with a small-scale shear feature that first appeared near ground. Tornadogenesis took place as the shear zone became collocated with the strong updraft that fed the new cell. The cause of the low-level shear zone was not known.]

White, A. B., C. W. Fairall, A. S. Frisch, B. W. Orr, and J. B. Snider, 1996: Recent radar measurements of turbulence and microphysical parameters in marine boundary layer clouds. *Atmos. Res.*, **40**, 177-221.
[Low impact. Observations from radars operating at frequencies from 404 MHz to 34.6 GHz are examined in a "review" paper to determine turbulence and microphysical properties of marine clouds. Discussion details the contribution of Bragg and Rayleigh scatter to radar reflectivity. Modeled droplet distributions were then used to illustrate relationships between radar reflectivity and cloud water concentrations for various radar frequencies. A interesting plot shows K_a-band reflectivity versus 404-MHz radar reflectivity factor. The scatter increased markedly below 0 dBZ due to the domination of Bragg scattering over Rayleigh scattering at 404-MHz. An example of clouds sampled at S and X-band found much higher reflectivities at S-band, again due to Bragg scattering. High returns at S-band concentrated at the edges of the cloud, while largest X-band reflectivities came from near the middle of the cloud. A discussion of turbulence

follows. The authors note that all three radar moments (reflectivity, velocity, and spectrum width) contain information on turbulence. Unfortunately, the spectrum width is broadened by such factors as large-scale shear across the pulse volume, beam broadening with range, and, if the antenna is elevated, particle terminal velocities. Corrections are described. Profiles of C_n^2 illustrate the retrieval of turbulence within cloud layers. Other sections describe techniques for retrieving microphysical properties of clouds including the recovery of drop-size distributions when the ambient vertical motion is small.]

Zarader, J.-L., G. Ancellet, A. Dabas, N. K. M'Sirdi, and P. H. Flamant, 1996: Performance of an adaptive notch filter for spectral analysis of coherent lidar signals. *J. Atmos. Oceanic Technol.*, **13**, 16-28.
[Low impact. Signal processing with Doppler lidar systems is more difficult than with weather radars. Decorrelation times that are shorter than the pulse duration cause spectral widths to be relatively large. Generally, coherent lidar signal processing is accomplished with pulse-pair or poly-pulse-pair frequency estimators. The authors argue that availability of fast-floating point processors permits a new generation of algorithms that operate at low signal-to-noise ratios. A discussion of linear filtering techniques and adaptive notch filtering follows. The notch filter employs a finite-impulse-response filter to remove one frequency of the sampled signal without changing the others. To prevent the filtering of other spectral components, the filter is fine tuned with the "poles" and "zeros". Compared to the poly-pulse-pair method, the adaptive filter had a significantly lower standard deviation at low signal-to-noise ratios, an insignificantly higher standard deviation at high signal-to-noise ratios, and approximately the same bias. The adaptive notch filter approach had a distinct advantage in outlier removal.]

Zrnić, D. S., and A. Ryzhkov, 1996: Advantages of rain measurements using specific differential phase. *J. Atmos. Oceanic Technol.*, **13**, 454-464.
[Moderate impact. Advantages that accrue with the specific differential phase measurement for estimating rainfall include an insensitivity to beam blockage, an insensitivity to the effects ground clutter cancelers, and an inherent ability to detect anomalous propagation. In an example, beam blockage having an average radar horizon of 0.2° resulted in average reflectivity values that were 6.4 dB less than those at 0.5° antenna elevation. The average K_{DP} values for the two elevation angles differed by only 0.01° km^{-1}. The paper also examines the influence of ground clutter cancels on the K_{DP} measurement and illustrates how the differential phase can be used to detect anomalous propagation.]

APPENDIX A: LIST OF ACRONYMS AND SYMBOLS

ACARS	Aircraft Communication and Reporting System
AP	anomalous propagation
ARPS	advanced regional prediction system
AWIPS	Automated Weather Interactive Processing System
BWER	bounded weak echo region
CAPE	convective available potential energy
CAPPI	constant altitude plan-position indicator
CAPS	Center for the Analysis and Prediction of Storms
COLIDE	convergent line detection
CSI	critical success index
CWA	county warning area
DSD	drop-size distribution
FAR	false alarm ratio
FSL	Forecast Systems Laboratory
GIS	geographic information system
K_{DP}	specific differential phase
LAPS	Local Analysis and Prediction System
LLWAS	Low-level Windshear Alert System
MAPS	Mesoscale Analysis and Prediction System
MCS	mesoscale convective system
MCTEX	Maritime Continental Thunderstorm Experiment
MDA	mesocyclone detection algorithm
MIGFA	Machine Intelligent Gust Front Algorithm
NASA	National Atmospheric and Space Administration
NCDC	National Climatic Data Center
NCEP	National Center for Environmental Prediction
NIDS	NEXRAD information dissemination service
NWS	National Weather Service
NCAR	National Center for Atmospheric Research
NSSL	National Severe Storms Laboratory
NWSFO	National Weather Service Forecast Office
NWSO	National Weather Service Office
PMM	probability matching method
POD	probability of detection
PPS	precipitation processing subsystem
PRF	pulse repetition frequency
PRT	pulse repetition time
R	rainfall rate
RIDDS	radar ingest and data distribution system
rms	root mean square
SCIT	storm cell identification and tracking
SDVR	single Doppler velocity retrieval

SNR	signal-to-noise ratio
TOGA COARE	Tropical Ocean-Global Atmosphere Coupled Ocean-Atmosphere Response Experiment
TREC	tracking radar echoes by correlation
TRMM	tropical rainfall measuring mission
TVS	tornado vortex signature
UCP	unit control position
UTC	universal time constant
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
WFO	Weather Forecast Office
WPMM	window probability matching method
WSFO	Weather Service Forecast Office
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

B. SURVEY ANNOUNCEMENT

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

Request for Information

The Next Generation Weather Radar (NEXRAD) program is developing plans to improve the initial 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 developments and to become aware of possible future NEXRAD technical development participants.

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 address, 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. [A limited number of reports from last years survey are still available.] The deadline for submissions is December 6, 1996. For further information contact:

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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.

C. LIST OF RESPONDING ORGANIZATIONS AND INDIVIDUAL CONTRIBUTORS

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Environmental Technology Laboratory
Forecast Systems Laboratory
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