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

25 March 1996

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I. INTRODUCTION

A certain excitement is apparent when reading of the many successful applications and the demonstrations of improved weather monitoring capability with the WSR-88D. In many ways, a new phase of implementation and utilization has begun. The sensitivity of the WSR-88D reveals meteorological details and features not seen previously. The observations often suggest new techniques and applications. Users clamor for higher resolution in time (for low-level wind phenomena such as microbursts and waterspouts) and in space (particularly with precipitation products, VAD analyses, and the echo tops product). Many studies stress the need to integrate the radar data and products with other sources of information, such as environmental conditions, storm history, and spotter reports. Proper diagnosis of precursor synoptic and mesoscale meteorological conditions improves the warning function.

Perusal of the operational studies readily reveals which algorithms work and where the problems lie. Most frequently noted is the problem of precipitation product corruption by Anomalous Propagation (AP), bright band, and hail. Generally, current precipitation products significantly underestimate amounts. At short ranges the bias stems from the application of a hybrid scan composed of the lower four elevation angles and excessive ground-clutter suppression. At far ranges, beam elevation and broadening dominate. Provision for routinely adjusting rainfall estimates with raingage information exists within the WSR-88D Precipitation Processing Subsystem (PPS) but is not activated. Interestingly, the WSR-88D processing scheme builds rainfall estimates from observations nearly 1 km above the radar while techniques employed in other countries extrapolate the radar information to ground.

Because of their close association with severe weather, there is considerable interest in improved detection techniques for thunderstorm mesocyclones. The operational community wrestles with adaptable parameters and product thresholds, often seeking to detect mesocyclones in regions of the country where severe weather events are not archetypal. Archives of storm phenomena being assembled at several organizations should facilitate this effort.

The number of research studies utilizing dual-polarization measurements for precipitation estimation, particle type discrimination, and hail detection continues to grow. Also, there is considerable activity in the retrieval of two and three-dimensional wind fields from the observations of a single-Doppler radar. Whenever there is a multitude of viable techniques that could be implemented, such as for wind field retrieval or precipitation estimation, a systematic means for evaluation and comparison must be found.

The National Weather Service (NWS) long recognized a continuing need for incorporating software refinements and new technology into the WSR-88D system. Consequently, the NWS Office of System Operations (OSO) is planning a major upgrading of the NEXRAD Radar Product Generator and Radar Data Acquisition subsystems. The OSO conducted a survey of research institutions regarding potential algorithms which could be implemented on an upgraded WSR-88D. A summary report entitled "NEXRAD Product Improvement Program Information Resource Management (IRM) Report" (31 October 1995) has been prepared. For further information contact Robert E. Saffle [telephone: (301) 713 0304 x111)].

This survey of research draws heavily upon recent conferences and workshops, e.g., the First WSR-88D User's Conference (11-14 October 1994), the 27th International Radar Conference (9-13 October 1995), the III International Symposium on Hydrological Applications of Weather

Radars (São Paulo, Brazil; 20-23 August 1995), and the 6th Aviation Conference (15-20 January 1995). A large number of papers appearing in the formal literature are also included. The papers describe a broad spectrum of activity that will form the basis for future algorithms and techniques.

The format of this report closely follows that of last year. The Topical Activities Summary in Section II roughly conforms with the technical needs identified by the NEXRAD Technical Advisory Committee (see Appendix A). "Data quality assessment" and "data acquisition rate strategies" are not explicit research activities and hence do not appear as separate topics. New contributors to this year's survey are the Bureau of Reclamation, Brookhaven National Laboratory, Florida State University, Jackson State University, McGill University, and the South Dakota School of Mines and Technology. UNISYS, a contributor in the past, is now called Loral Defense Systems, East.

II. TOPICAL ACTIVITIES SUMMARY

A. Archive of Storm Phenomena

An archive of severe weather events, consisting of Level II radar data (base radar reflectivity, mean radial velocity, and spectrum width in polar format) and verification reports, is being assembled by the National Severe Storms Laboratory (NSSL) (see Section III.F.3.e). These data are an important resource for case studies, for fine tuning algorithm parameters in different geographic areas, and for testing algorithm enhancements. In addition, local data bases are being developed by regional offices within the National Weather Service (NWS) (e.g., Kuhl 1994) and by Florida State University (Section III.M.7). [The National Climatic Data Center WSR-88D routinely archives base data (Level II) from all radar sites and products (Level III) from NWS radar sites. For further information see "An update on WSR-88D Level II data availability" a letter to the editor by T. Crum in the December 1995 issue of the Bulletin of the American Meteorological Society.]

B. Velocity Dealiasing and Range Unfolding

The current WSR-88D velocity dealiasing algorithm may fail in regions of strong shear, may remove important data, and often performs poorly at low Nyquist velocities. Alternate dealiasing algorithms have been developed by the Forecast Systems Laboratory (FSL) and the National Severe Storms Laboratory (for details see Zittel 1994). Briefly, the FSL technique operates on a two-dimensional (horizontal) array of radial velocity data. "Missing" data bins are filled if valid velocities exist in adjacent data gates. The replacement value used is that of the range bin closest to the radar. The algorithm removes small isolated echoes which do not have at least 5 neighboring valid bins. The edited data set is then filtered prior to dealiasing. Regions with similar velocities are grouped accordingly and differences between groups are minimized by adding or subtracting multiples of the Nyquist co-interval. Environmental soundings aid in the determination of the proper interval. The NSSL method extends that currently used on the WSR-88D and is based upon gate-to-gate shears along radials. A confidence factor, derived from information in the previous five azimuths, is computed. If the confidence is low, the environmental sounding becomes the basis for co-interval selection.

Zittel evaluated the FSL and NSSL techniques using computer code supplied by the algorithm-producing organizations. Manually unfolded velocity fields provided "ground truth". These fields where then re-aliased using different Nyquist velocities. Test results were mixed. The NSSL method had the highest Critical Success Index (CSI) for full radar scans and for sub-areas (windows) of high interest. The percent correct for the window areas was the lowest. The FSL algorithm had the lowest CSI scores for the full scans but out performed the existing algorithm for the window areas. Its percent correct scores on the window areas were the highest. When missing data, i.e., velocities removed from the data field by the algorithm, were deleted from the comparison, the existing algorithm had the highest CSI and percent correct. The study concludes that the existing WSR-88D algorithm should be retained but modified to reduce the number of data discards.

Conway et al. (1995) also addressed the dealiasing issue. They note that although the current dealiasing scheme is fast and that only a small percent (~2%) of the data are dealiased incorrectly, problems generally occur in areas where it matters the most, e.g., with tornadoes, mesocyclones, and in regions of strong radial convergence. They attribute most failures to incorrect dealiasing when comparing individual data gates to a nine point average, re-dealiasing of previously dealiased velocities, incorrect dealiasing of the first radial in a tilt or a storm, the removal of data designated as noise, and the use of an environmental wind profile that is not representative of the storm flow pattern. Potential improvements tested in the study included velocity filtering before dealiasing and greater use of adaptable parameters. Setting the number of contiguous gates deemed as noise (and hence removed) to 1 improved the preservation of tornado vortex signatures. At this threshold, the algorithm is forced to either unfold the velocity measurement or accept it. The downside of this approach is an increase in the number of errors due to noise. The use of data from the previous radial and environmental wind information to fill data gaps alleviates the problem somewhat. Organizations activity engaged in dealiasing technique development include NSSL (Sections III.F.4.b and c) and the NEXRAD Operational Support Facility (Section III.C.2).

C. Anomalous Propagation and Clutter Removal

Radar measurements contaminated by ground clutter arising from Anomalous Propagation (AP) causes havoc when the measurements are used for quantitative precipitation measurement or inserted into severe weather hazard detection algorithms. Reflectivity measurements contaminated by clutter typically cause precipitation to be overestimated. Ground clutter may cause spurious gradients in the radial velocity that greatly affect velocity dealiasing algorithms and potential algorithms designed to detect gust fronts and microbursts. Precipitation accumulation products involve on-site pre-processing of the data; hence, corrections must be applied at the point of data acquisition. The clutter removal problem is exacerbated when precipitation and ground echoes are mixed and when precipitation forms close to the ground (i.e., for orographically generated precipitation).

The article by Chrisman et al. (1994) describes the current clutter suppression techniques used with the WSR-88D. Three layers of suppression are available. A Default Notch Width Map operates under the assumption that ground targets have near zero radial velocity. The filter reduces returned power for radial velocities near zero and is applied in up to three concentric regions in range. The method can cause a severe loss of meteorological signal wherever the flow is perpendicular to the radar beam. A Bypass Map attempts to identify normal regions of ground clutter. Finally, Operator-Defined Clutter Suppression Regions control the application of the notch filter or Bypass Map in specific regions. The article stresses that each situation must be monitored closely as it evolves to prevent the loss of meteorological information.

Moszkowicz et al. (1994) used radar reflectivity data from an X-band radar to develop a statistical approach for detecting anomalous propagation (AP). Radar measurements were interpolated to 4 x 4 km CAPPI's at 0.7, 1, 2,3, 4, and 5 km elevation. The dataset consisted of approximately 15% AP echoes and 85% precipitation echoes. The technique determines the probability that the radar echoes fall into either the AP or precipitation classifications and assumes that the conditional probabilities within each class are Gaussian distributed. Radar parameters considered were (1) a term relating to the sine of the elevation angle that corresponds to the highest elevation of non-noise reflectivity, (2) the elevation angle of the maximum reflectivity, (3) the maximum reflectivity, (4) a reflectivity gradient term, and (5) the echo top. Various combinations of the variables were then tested. Five and four parameter systems (the latter in which the maximum reflectivity was omitted) performed equally well. The effectiveness of the scheme was checked against an expert who manually determined which radar images contained precipitation or AP echoes. Tests revealed a general classification error of ~6%. Largest errors were in the detection of AP alone (12 to 33% error). AP elimination greatly reduced the bias in precipitation estimates.

A neural network technique for detecting AP was applied by Tsintikidis et al. (1995) to the X-band radar data of Moszkowicz et al. (1994). Twenty descriptors characterized the radar patterns. One half were empirically determined from echo patterns (e.g., the number of pixels in each radar image, average rainfall, average reflectivity, and moments of the reflectivity distribution). The remaining parameters represented the spectral and textural nature of the radar images (e.g., gray-level average and variance, image energy and inertia, prominence, and correlation). [References are provided.] Results with an independent dataset show that 95% of the precipitation images and 72% of the AP images were correctly identified. The suggestion is made that additional descriptors which characterize the vertical distribution of echoes might substantially improve algorithm performance.

A scheme for ground clutter removal during conditions of anomalous propagation is discussed by Pratte et al. (1995). The approach identifies regions of contamination, separates the meteorological and clutter signals, and then compensates for losses incurred during separation. Clutter identification is enabled by the observations that mean radial velocities in clutter areas are biased toward zero and that the width of the velocity spectrum is narrow. Signal separation is accomplished by implementing high-pass filters which remove a narrow band of targets near zero radial velocity. The procedure results in a reflectivity bias (a loss, usually < 10 dBZ). To compensate for this loss a family of curves is constructed from a Gaussian model that utilizes estimates of Doppler velocity, spectrum width, and the band-pass profile.

D. Severe Weather Detection

1. Mesocyclones

Procedures for detecting mesocyclones have evolved over the years, but detection at far ranges remains elusive because of radar sampling problems (Glass and Przybylinski 1994). At an elevation angle of 0.5° and a range of 124 nm, the radar beam rises to 18,000 ft above ground. In summer, only the middle and upper regions of mesocyclones are likely to be sampled; while in winter, mesocyclones may be contained wholly in the layer below the lowest elevation angle. At excessive distances the radar beam broadens and a large fraction of the mesocyclone may fall into one beam volume. The averaging of both outbound and inbound velocities may result in significant degradation of estimated mesocyclone velocities. Trends in rotational velocities may show large fluctuations which can be erroneously interpreted as weakening of the circulation but, in fact, are artifacts caused by sampling, i.e., the location of the mesocyclone relative to the radar beam. The suggestion is made that a new Volume Coverage Pattern (VCP) with additional low-level scans may alleviate the problem. In the meantime, forecasters should not overact to changes in storm trends but also consider the storm's reflectivity structure, prior history, and environmental conditions.

Wood et al. (1996) present a statistical summary of thunderstorm mesocyclone tracks. Mesocyclones were defined as persistent regions of tangential shear having a vertical extent that exceeded their horizontal diameter. Findings indicate that mesocyclones which spawn tornadoes typically travel farther than those that do not (70 versus 43 km). Tornadic circulations also live longer (97 versus 60 min). Curiously, the tornadic circulations moved on average 9° to the left of the nontornadic circulations.

The National Severe Storms Laboratory has been working on an enhanced mesocyclone detection algorithm that incorporates mean rotational strength, a convergence parameter, and neural network determined functions (Section III.F.2.b). This potential upgrade is being evaluated by the NEXRAD Operating Support Facility (OSF) (Section III.C.3). The OSF has conducted efforts to improve the detection capabilities of the current mesocyclone detection algorithm through the optimization of adaptable parameters and by integrating new variables such as mean rotational strength. Phillips Laboratory continues to develop its elliptical mesocyclone model (Section III.I.2). The McGill University report (Section III.O.2) mentions that they have a mesocyclone algorithm but no details are provided.

2. Tornadoes

In an operational study, Murphy et al. (1994) examined trends in Vertically Integrated Liquid (VIL) water and rotational velocity as related to tornadic activity in Alabama thunderstorms. An earlier study uncovered a tendency for VIL values to decrease and for rotational values to increase during storm collapse. This implies that excessive water loading within the storm leads to a collapse of the reflectivity profile and results in increased low-level outflow that triggers tornadogenesis. This scenario, a possible indicator of impending severe weather, also occurred in two storms described in the paper. However, the authors caution that the cause and effect relationship was not observed in two other cases and hence further investigation is needed to determine if the relationship between VIL and the rotational velocity is sensitive to the sampling (VCP) mode and the radar range.

The number of verifiable tornado warnings issued by the Wichita, Kansas office of the National Weather Service during its first season with a WSR-88D turned out to be very low (Stewart and Hedges 1994). The authors attribute the poor performance to an over reaction to the new technology. Reexamination of the nonverifying warnings showed that, although the storms contained mesocyclones, rotation was weak, lacked vertical continuity, or fell short of established guidelines for tornadic mesocyclones.

Experience indicates that thresholds for mesocyclone and tornado detection, as spelled out by the Operations Training Branch Tornado Warning guidelines, may be too high for the Eastern Region of the United States. An article by Kuhl (1994) stresses the importance of establishing an archive of storm cases for further fine tuning of threshold parameters.

An interesting case study of a tornadic storm was presented by Parker and Keighton (1994). A 1800 UTC prestorm environmental sounding revealed that the atmosphere was unstable and conducive for intense thunderstorms, but the storm-relative helicity (SRH) value of 102 $m^2 s^{-2}$ was well below suggested threshold values for tornadic activity. A poststorm sounding at 0000 UTC showed a SRH of 308 $m^2 s^{-2}$. The increase, due to an intensification of the wind speeds and a backing of the wind direction in the lowest 3 km of the atmosphere, was depicted in the VAD wind profile. Hence, in rapidly evolving severe weather situations, updating the helicity calculation with a more recent VAD wind profile is desirable. After 2237 UTC, the radar showed a strong mesocyclone and associated hook echo. The tornado formed at ~2304 UTC on the northwest flank of the storm (the right rear flank in the storm-relative frame) but was several miles from the mesocyclone. A small reflectivity protrusion and weak three-dimensional correlated shear coincided with the tornado. Initially, data dropouts that resulted when the dealiasing algorithm could not resolve the velocity of the few data gates that depicted the tornado made detection difficult. The spectrum width field contained a region of large widths which apparently represented the tornado. The study is a reminder that severe storms can be a veritable tea cup of vortices and the most dangerous circulations are not always the most obvious.

A storm that did not have a detected mesocyclone prior to tornado touchdown is being studied by the Little Rock WSFO (Section III.G.2). Investigation uncovered a subtle precursor circulation in the Combined Shear product.

3. Waterspouts

Waterspouts are widely regarded as being less hazardous than tornadoes. However, when waterspouts move inland, significant damage often occurs. Golden and Goodall-Gosnell (1995) report on a large, long-lived waterspout, 200 feet in diameter, that was not evident in measurements obtained with a WSR-88D just 15 miles away. No mesocyclone or velocity couplet was detected in an archived 1.5° elevation scan. The authors speculate that either the circulation was either too small to be detected or its signature was obscured by ground clutter. The waterspout resided within a bounded weak echo region of a 60 dBZ storm. The radial velocity field was weakly convergent. A sea breeze and several cloud lines were seen in satellite images but apparently were not evident in the 1.5° data. Nevertheless, the authors conclude that detection of waterspouts requires close monitoring of outflow boundaries and shear zones.

Collins (1995) described an outbreak of waterspouts in the Tampa Bay area of Florida.

Large increases in VIL occurred 0 to 10 min before the sightings. The waterspouts appeared to develop in storms that were associated with lines of convection.

A system for predicting waterspouts that incorporates local climatology, environmental soundings, and WSR-88D data has been developed by Spratt and Choy (1994) and Choy and Spratt (1995). As in other studies, the radar data readily portrayed the motion of boundary-layer convergence lines and the development of convective cells. (An interesting aside: The number of reported events in the study region--Melbourne, Florida--increased more than 4 fold after the installation of the WSR-88D. The issuance of waterspout warnings apparently led to greater public awareness and feedback concerning occurrences.)

4. Microbursts

A cautionary note presented by Huckabee (1994) asserts that the rapidity with which microbursts develop and their small size will cause them to go largely undetected unless reliable precursors are found. Two microburst events occurring within 20 nm of a WSR-88D, one affecting an area only 0.75 nm wide and several miles long and the other causing damage over an area 0.25 nm wide and 1 nm long, were shown. The radar beams were 1000 to 1200 feet above ground. Divergence signatures were present but weak. Huckabee posits that to detect microbursts the highest possible resolution data from the radar must be examined. Further, he feels that a rapid update cycle which includes a base angle below 0.5° would facilitate detection.

Microbursts are a common phenomenon in Arizona where dry adiabatic lapse rates in the lower atmosphere and elevated moisture layers frequently occur (Green 1994). By monitoring microburst precursors, such as strong and deep middle-level convergence and the rapid descent of reflectivity cores, warning times of ~10 min are thought possible.

5. Hail

Examples of the "three-body" scattering signature for large hail appear in papers by Lemon (1994) and Eyerman-Torgerson and Brown (1995) . The signature arises when energy is scattered by strongly reflecting hydrometeors toward the ground, some of this energy is backscattered to the same region of hydrometeors, and finally scattered a third time back to the radar. Lemon asserts that the signature frequently occurs with hail ≥ 1 inch in diameter. Eyerman-Torgerson and Brown describe a hail spike observed with a C-band radar. Non-Rayleigh scattering caused the spike to extend some 25 km beyond the storm core. The spike persisted with maximum reflectivities as low as 50-53 DBZ, but its length was much shorter.

An evaluation of the current WSR-88D hail algorithm and upgrades proposed by NSSL has been conducted at the National Center for Atmospheric Research (Section III.K.1.c). On going hail detection efforts at NSSL are described in Section III.F.2.d. A simple detection scheme with dual-polarization measurements is described in the article by Kennedy et al. (1995) and in Section III.L.1.

6. Turbulence

Johnson (1995a) studied a low-level turbulence incident involving an outflow boundary from a mesoscale convective system. The outflow generated a radar "thin line" at its leading edge and a trailing series of distinctly separated parallel reflectivity bands. The fine line moved south of the Dodge City WSR-88D. The lowest level from the VAD profile showed northerly winds but local surface winds remained southerly at 6-12 mph. At a nearby airport surface winds did become northerly at 15 mph. Forecasters reasoned that the outflow was shallow and would "mix out" with solar heating. A crop duster operating within and parallel to the reflectivity bands experienced large fluctuations in air speed and rolled unexpectedly. Post analysis suggests that the aircraft most likely encountered turbulence caused by Kelvin-Helmholtz instabilities that developed on the leading edge of the outflow. The author laments that although the radar data could be used to warn pilots of turbulent conditions there is no way to disseminate the information.

Lee and Crane (1995) examined the utility of spectrum width for detecting turbulence within precipitating storms. Attempting to calibrate the WSR-88D's, they compared spectrum width measurements from NSSL's Cimarron radar and the nearby Twin Lakes WSR-88D. While the same structural features appeared in the measurements from both radars, spectral width estimates from the Twin Lakes radar were about one half that of the Cimarron radar.

A preliminary examination of the NEXRAD turbulence algorithm was described by Cornman et al. (1995). The paper gives a short discussion of the turbulent spatial scales sensed by aircraft and the issues related to estimating turbulence with radar. The usual simplifying assumptions are that the turbulence is homogeneous and stationary, that the radial velocity measurements in adjacent azimuths are essentially parallel, that the inertial subrange extends to scales at least as large as the radar pulse volume, and that an outer scale can be prescribed. The spectral width method of estimating turbulence assumes that the turbulent wind field proportionately perturbs the velocities in the radar pulse volume. The assumptions clearly are violated in convective situations where observational evidence suggests the turbulence is more strongly influenced by vertical drafts. The paper compares Doppler radar-derived turbulence (eddy dissipation rates) estimates and aircraft measurements of turbulence from 8 penetrations of convective storm cells. The current WSR-88D algorithm (the Layer Composite Turbulence Maximum), simulated with measurements from a research radar, greatly overestimated the observed turbulence. Improvement was found (in terms of scatter) when NEXRAD turbulence values were interpolated to the aircraft's location. However, a significant bias remained. There is other information provided by the radar that could be useful for delineating areas of suspected turbulence. As an example, a turbulence metric composed of spectral width measurements and local variances in the radial velocity (as an estimate of the nonstationary portion of the wind field) is illustrated. Additional information appears in Section III.K.1.d.

One of the variables in the current WSR-88D turbulence algorithm is the outer scale (maximum eddy size). A method for objectively determining the scale for homogeneous wind fields has been suggested by Melnikov (1995). The contribution of turbulence to the radar-measured spectrum width (w_t) is estimated after applying corrections for radial, azimuthal, and vertical wind shears. A simple expression relating w_t to the eddy dissipation rate is then given. Melnikov hypothesizes that $w_t/r^{1/3}$ (where r is the radar range) depends only on the dissipation rate if the maximum size of the radar bin is less than the outer scale. Assuming a constant dissipation rate at a given level in the atmosphere, $w_t/r^{1/3}$ decreases when the radar bins become greater in size than the outer scale. The width of the radar beam at the range where the decrease begins defines the outer scale.

7. Flash Floods

The synoptic situation and radar data for two flash flood situations in Oklahoma were discussed by Sohl (1994). Both events were small in areal coverage and had rainfall totals of 3 to 5 in. In each case, heavier precipitation occurred nearby causing the regions of flooding to be overlooked. To aid in the detection of future events of this type the author suggests that displays be upgraded to provide detailed map backgrounds of basin margins and terrain contours, that rainfall accumulations be available at the basic measurement resolution of the radar (1° by 1 km), and that software be developed to automatically alert forecasters to potential problems.

Garza (1994) studied WSR-88D performance regarding wintertime flash floods in the Hawaiian Islands. A comparison of storm total radar rainfalls and rain gages for one event lasting several days revealed general precipitation underestimates of approximately 25 to 50% but one gage site where the precipitation was overestimated by 25%. The author mentions that the composite reflectivity product, constructed from maximum reflectivity values at any elevation, is useful for identifying areas of heavy rainfall.

Flash floods create hazards in Arizona where recreation areas are largely in mountainous regions and the rugged terrain causes rapid runoff (Green 1994). Convection is often tied to the topography. Steering winds are usually weak. Consequently, storms move slowly or not at all and precipitation depths can be significant even in the dry Arizona climate. The WSR-88D precipitation products prove most reliable during the summer monsoon (July through September). Experience shows that the reliability of radar rainfall estimates decreases for precipitating storms with high cloud bases, for storms with cloud tops below 6 km MSL, during upslope conditions where precipitation develops toward ground, and whenever bright bands exist. The author states that a flash flood algorithm would be beneficial for warning purposes.

8. Tropical Cyclones

Tuttle and Gall (1995) conducted a nice study in which the Tracking Radar Echoes by Correlation (TREC) method provided the wind fields in two hurricanes. The method determined the circulation center and gave an estimate of maximum wind speeds. The agreement with aircraft measurements was good.

Hurricane winds were also measured by McAdie and Sandrik (1994) who found excellent agreement between radial wind measurements made with a WSR-88D and wind velocities measured with a reconnaissance aircraft. Individual storm tracks and animation helped locate the circulation center of a poorly-defined tropical storm.

Mauro (1994) presented a case study of the remnants of tropical storm Alberto that used observations from a WSR-88D. A banded radar reflectivity structure persisted several days after landfall. On occasion, embedded convective cells can be difficult to differentiate from background reflectivity values in large-scale precipitating storms. In this study, the VIL product, because of vertical integration, proved more useful than base reflectivity products for detecting and tracking individual convective cells. A comparison of the Storm Total Precipitation product with gage reports indicated that maximum rainfall amounts were generally underestimated with the radar data.

9. Boundary-Layer Phenomena

A number of studies utilize the high sensitivity of the WSR-88D to investigate boundary-layer phenomena. Ruscher et al. (1995) studied sea, bay, and river breeze circulations and their interactions on days without significant convection. Earth satellite and mesonetwork information supplemented the radar data. The implication is that the boundary-layer phenomena and resultant convection often respond to local topography, i.e., coastline shape, the presence of rivers, and other bodies of water. Moreover, the monitoring of boundary-layer phenomena will lead to improved nowcasting of convective storms. The latter theme was also suggested by Spratt and Choy (1994), Choy and Spratt (1995), and Golden and Goodall-Gosnell (1995) in studies of waterspouts whose formation was tied to boundary-layer convergence zones.

Wallenfang and Korotky (1994) present a case study in which the interaction of an outflow boundary and a sea breeze was observed and the information used to issue short-term forecasts of thunderstorms. The problem of where thunderstorms initiate is clearly multiscale. Solution requires answers to several questions. Are large-scale environmental factors favorable for deep convection? Is there sufficient moisture on the large scale? Are there small-scale features such as outflow boundaries and sea breezes to focus boundary-layer forcing? In the case described, forecasts of thunderstorm initiation concentrated on the region where the outflow boundary and sea breeze interacted. The area behind the sea breeze could confidently be excluded from the forecast region because of the subsidence occurring there.

Ray et al. (1995) studied boundary-layer convergence lines in North Carolina with observations from a WSR-88D and encountered several problems. The 10 kt resolution of the velocity display (Level IV data) rendered the data useless when the synoptic forcing (wind) was weak. Another problem concerned the automatic switch from Clear Air Mode to Precipitation Mode whenever showers were detected. Although the switch can be manually over-ridden, hours passed before the command was recognized. The radar data revealed numerous boundaries associated with sea breezes, outflows, thermal and moisture discontinuities, orographical features, and horizontal rolls. Interactions between certain boundary-layer phenomena triggered increased convective activity in 94% of the cases. Thunderstorm outflows initiated new storms which eventually produced reflectivity > 40 dBZ, 96% of the time.

10. Icing

Meteorologists at Center Weather Service Units combine a number of WSR-88D products to identify icing layers (Strager and Kowaleski 1994). Bright-band information gathered from base reflectivity products and vertical cross sections determine the lower limits of the layers. Although the 18 dBZ minimum threshold more closely matches the edge of precipitation rather than the cloud boundary, the Echo Tops (ET) product is used to set the upper limit to the layer of icing threat.

11. Snowfall

Several papers presented at the WSR-88D User's Conference described snow events. Most combined WSR-88D products with other observations and numerical modeling data to better understand the meteorological situation. Such studies will undoubtedly increase our understanding of snow storms and inevitably lead to better short-term forecasts of snowfalls. For example, the paper by Grumm et al. (1994) combined reflectivity data, vertical wind profiles, and sounding data to predict the formation and orientation of snowbands. The bands associated with conditional symmetric instability which locally enhanced the precipitation. Band alignment roughly coincided with the shear vector in the 1.5 to 5.5 km layer, the 850 mb isotherms, and the 1000 to 500 mb thickness contours. Numerical forecasts were used by Dankers (1994) to detect conditional convective instability in the formation of snowbands observed in Colorado.

A situation in which multiple snowbands over Lake Erie evolved into an intense single band was described by LaPlante (1994). The transformation was attributed to a wind which backed with time becoming parallel to the elongated axis of the lake. The increased resolution and enhanced display capabilities of the WSR-88D were preeminent in revealing the mesoscale structure of the storm. The study of Cannon (1994), who summarized the experiences gained from a winter's use of WSR-88D information at Albany, New York, reached a similar conclusion. In particular, Cannon gives examples of snowfall enhancement under upslope conditions, snowfall suppression under downslope conditions, the influence of gravity waves, and lake effects on snowfalls.

For a summary of the Bureau of Reclamation effort to develop an algorithm to quantitatively estimate snowfall accumulation with radar see Section III.B.1. Testing of a prototype algorithm began during the winter of 1995-1996. Polarimetric radar techniques to discriminate among snow types and to locate rain/snow lines are being developed by the National Severe Storms Laboratory (Section III.F.4.a). Jackson State University (Section III.N.1) is beginning a program for studying and nowcasting rain/snow lines. Primary emphasis will be on the physical characteristics of the lines and the utility of bright-band information for nowcasting rain and snow events. A program to objectively determine the motion of snow echoes, which are often weak, have a strong range dependency, and generally lack internal structure, is in progress at the National Center for Atmospheric Research (Section III.K.1.a).

E. Feature Detection, Tracking, and Forecasting

Jackson and Jesuroga (1995) produce short-term forecasts of convective activity with a cross-correlation tracking algorithm. A series of national radar mosaic images are converted to binary patterns ("1" for echo above some dBZ threshold or "0") and filtered in time to ensure consistency. Forecasts for convective activity 15 and 30 min into the future are then produced by simple advection of radar echoes. Each segment constituting a radar echo moves according to the motion vector nearest the center of the segment. The technique preserves much of the echo's shape yet yields a conservative estimate of the differential motion within the storm complex. Results for 15 min forecasts of echo $\geq$ 30 dBZ show a Probability Of Detection (POD) of 0.63, a Critical Success Index (CSI) of 0.45, and a False Alarm Rate of 0.38.

A rule-based automated system for forecasting the initiation and evolution of thunderstorms, being developed at the National Center for Atmospheric Research (NCAR), was described by Henry (1995). Accuracy depends upon the ability to detect clouds (defined as regions with radar reflectivities $\geq$ 10 dBZ). [For additional discussion and references see Section III.K.1.b.]

Conceptual models of convective cells and an object-oriented approach are the primary components in the technique developed by Collier et al. (1995) for automatically identifying precipitation systems and for forecasting their evolution. An key element in the scheme is an ability to forecast new growth. Radar data from four low antenna elevation angles, having 250 m range resolution and 4 min temporal resolution, are used. First, ground clutter is removed in a stepwise process that includes (1) removing radar reflectivities that are less than those in a clutter map, (2) removing pixels with rain rates < 1/32 mm h^{-1}, (3) removing echoes $\leq$ 2.25 km^2 in total area, and (4) comparing the lowest three elevation angles and removing echoes in the lower beam which do not have a corresponding echo at the next higher elevation angle. Vertical profiles of reflectivity are used to stratify echoes as developing (precipitation aloft), growing but with precipitation reaching the ground, fully matured, weakening, and dissipating. Factors influencing forecasts are derived echo motions, changes in areal coverage, and environmental stability parameters.

Numerous studies involving the detection, tracking, and forecasting of specific phenomena appear in Section III. The Table of Contents lists specific applications.

F. Precipitation Analysis Techniques

A nice review of radar rainfall estimation techniques has been given by Sauvageot (1994). Topics include the merits of precipitation measurement with a single parameter (Z-R) relationship, techniques for combining radar and raingage observations, a method for correcting range bias errors, and a discussion of the Area-Time Integral (ATI) method of producing areal average rainfall estimates. Sections on multi-parameter methods include the estimation of rainfall at single and dual-wavelengths as well as a description of rainfall estimation with a combination of differential reflectivity and radar reflectivity measurements.

Experience with WSR-88D precipitation accumulation products proves to be mixed. [See Seo et al. (1995) for a recent description of the WSR-88D Precipitation Processing Subsystem (PPS). Planned improvements are discussed in Section III.E.] Klazura and Kelly (1995) compared radar estimates of rainfall from 23 storms with 418 gage measurements and determined that nearly two thirds of the comparisons agreed quite well. There was a tendency to overestimate convective rainfalls and underestimate stratiform rains. [For additional information on radar/raingage comparisons conducted by the NEXRAD OSF see Section III.C.5.]

A systematic comparison between high-resolution rainfall estimates with the WSR-88D and rain gages was made by Kelly (1994). The study involved three storm events in central Oklahoma and a large number of raingage measurements. A 3 x 3 matrix of radar bins (with 2 km by 1° bin resolution) that centered on each gage was defined. Precipitation estimates for each bin were then quantified at 0.01 in intervals rather than the coarse quantization of the WSR-88D products. The bin that most closely matched the gage was used to form a gage/radar pair. The selection process is thought to account for the horizontal displacement of rainfall and uncertainty in gage locations relative to the radar. Bias estimates were determined by summing all gage amounts and dividing by the radar estimates at the gages and by averaging the ratios determined at individual gage sites.

Large differences between the mean bias estimates resulted, and large storm-to-storm variations occurred. Although the range distribution of rain gages for each event was not described, the radar tended, as in the Klazura and Kelly study, to overestimate heavy convective precipitation and to underestimate stratiform events.

Generally, the WSR-88D analysis package underestimates precipitation. Marosi and Grumm (1994) computed mean bias errors in a large watershed after subjectively combining precipitation estimates from three radars. Despite using the maximum radar value in areas of overlap, the radar derived rainfalls underestimated the observed runoffs. The authors conclude that the WSR-88D consistently underestimated the rainfalls and suggest that a need exists for adjusting Z-R relationships for different meteorological situations. An investigation of rainfalls in Hawaii (Garza 1994) came to a similar conclusion.

Several studies reviewed in the Bibliography Section address issues related to precipitation type discrimination (stratiform versus convective) and the objective determination of Z-R relationships based on radar echo characteristics. Steiner et al. (1995) argue that bright bands are often indistinct and poorly sampled by operational radars and hence are not good discriminators of precipitation type. They suggest a scheme based on reflectivity magnitude and gradients. Convective precipitation is defined by reflectivity values > 40 dBZ and the presence of local reflectivity maxima. Compared to other techniques, the method reduced the proportion of rainfall amount classified as convective. The scheme classified 90% of the bright-band situations as stratiform precipitation.

An automated procedure to characterize precipitation echoes was presented by Rosenfeld et al. (1995a). Parameters examined in the study were an effective efficiency (the ratio of cloud-top to cloud-base water vapor mixing ratios), bright-band fraction (the fraction of maximum radar echo area in proximity to the 0°C level), and the strength of radial reflectivity gradients. Findings indicate that the effective efficiency when applied to areas of ~100 km^2 is useful for determining the distribution of rainfall intensity; and hence, the parameter can be used with ATI rainfall estimation techniques. The study found that reflectivity gradients can be used for precipitation type discrimination and for detecting problems associated with partial beam filling. Apparently, characteristic bright-band fractions for different precipitation regimes exist; but the parameter is thought limited with volume scanning, particularly at far ranges (Rosenfeld et al. 1995b). A series of tests with the window probability matching method and rain gages showed a modest increase in the correlation between radar and raingage estimates of rainfall from 0.78 to 0.84 when reflectivity gradients were used to determine Z-R relationships. The standard deviation in errors decreased. Further division of precipitation type according to effective efficiency showed only minimal additional improvement.

Fulton et al. (1995) evaluated the WSR-88D precipitation adjustment algorithm (see also Section III.E). Hourly precipitation totals from 50 rain gages within the radar umbrella were used with a Kalman filter to determine the mean difference (bias). The radar data had a resolution of 2 km in range by 1° in azimuth. To account for possible gage location errors, the numerically-closest radar rainfall estimate in the 9 radar bins surrounding the gage location was used for pairing radar and gage amounts. The bias, computed from 6 or more gage observations with rainfalls ≥ 0.6 mm, was assumed valid for the next hour and applied to the polar grid of radar estimated rainfall. Tests show that the method reduced the mean bias in radar rainfall estimates and that radar estimates at the majority of gage sites improved. The correction did not account for the range distribution of the gages and hence would seem most applicable for determining bias resulting from radar calibration errors. The method may detect systematic changes in precipitation character (in a catch up mode) as storm systems evolve, e.g., convective systems generally becoming increasingly stratiform in their late stages.

Valeria and Paolo (1995) describe efforts in Italy to adjust radar estimates of rainfall with raingage information. The radar data from a 500 m CAPPI are averaged over a 5 x 5 km area centered on a gage site. First, reflectivity values are corrected by subtracting a clutter map; and then the Marshall-Palmer Z-R relationship is applied. Findings suggest that a single correction factor based on a mean gage/radar comparison is less effective than techniques that weigh gage information according to the distance from a particular location. [A comprehensive summary of research activity in Europe concerning rainfall estimation with radar and earth satellite observations is given by Fattorelli et al. (1995).]

Radar and raingage data collected over a watershed in Portugal were combined with a Kalman filter in a study by Saramago (1995). The watershed was 225 km^2 in area and contained 5 gages. Radar measurements were obtained at 5 min intervals for 20 events. At hourly intervals the Kalman filter algorithm evaluated a set of calibration factors, determined from two telemetering raingages, and applied an adjustment to radar grids of 2 and 5 km spacing. The average watershed rainfall was computed from Thiessen polygons constructed with the 5 gages. The Root Mean Square (RMS) error of radar precipitation estimates before and after calibration was 1.41 and 0.52 mm respectively. The corresponding relative errors were 167 and 69%.

Radar rainfall estimates and raingage measurements were integrated in the study of Pereira and Crawford (1995). A statistical objective analysis scheme combined the datasets while reducing the error variance in the analysis. It was assumed that the radar and gage errors are uncorrelated. Less certain are the assumptions that the errors are unbiased and that the correlation functions are isotropic. The accuracy of the interpolation procedure stabilized when three gage observations were used in the accumulation analysis. Error variances decreased for longer integration times but the radar bias (an underestimate with a WSR-88D) was unaffected. The authors argue that combined analysis (with the radar providing the covariance structure of the precipitation field and the gages providing accurate local estimates of mean rainfall) effectively results in significantly smaller error levels than possible with the individual measurement systems.

Borga et al. (1995) conducted an intercomparison of rainfall estimates made by rain gages, radar, and a combination of radar and raingage information for a single event lasting several days over a small watershed (77 km^2) in mountainous terrain. The radar update rate was a coarse 15 min. The comparison is based on hourly areal precipitation accumulations using 19 rain gages. The radar data are "corrected" for attenuation, beam blockage, and the variability of the vertical profile of reflectivity. Rainfall estimates were then made with uncorrected and corrected radar data and by radar measurements adjusted by one to nine gage observations. Results suggest that radar underestimates, due to attenuation, beam blockage, and the vertical lapse of reflectivity, improve if the radar data are corrected at the outset rather than attempting to mitigate these losses using raingage information. Expectedly, the corrected radar data when combined with all nine gages gave the best results.

The effects of radar range, area, and integration time on radar rainfall estimates were examined by Antonio (1995). The relative ratio (G/R) between gage measurements and radar estimates of rainfall was a minimum not at the radar but at 50 km. This finding is similar to that reported in a number of WSR-88D studies where clutter and AP removal is often identified as the culprit. Also, G/R ratios decreased as the watershed area and the accumulation interval increased.

Several recent studies compare different techniques for estimating rainfall. Atlas et al. (1995) estimated rainfall in a small watershed using the Marshall-Palmer relationship, Area-Time Integrals (ATI's) using the Marshall-Palmer relationship, ATI's based upon a Probability Matching Method (PMM), and a polarimetric method. The latter method combined specific differential phase (K_{DP}) with the Marshall-Palmer relation for low rain rates. Four storms sampled by ~40 gages are examined. For point and areal rainfalls, best results were obtained using specific differential phase. The ATI method worked well in two cases but poorly in two others. Results with the probability matching method were inconclusive because of assumptions required to determine probability density functions (PDF's) of R and Z. The authors conclude that such methods are better suited to climatological measurements of precipitation.

Costa et al. (1995) present a radar-raingage adjustment technique, developed in Portugal, whereby raingage amounts are regressed (through a random-walk process and a Kalman filter) against radar estimates of rainfall and the relative vorticity at 500 hPa. Radar estimates of areal rainfall in 5 x 5 km data bins, gage observations, and hourly values of relative vorticity are used to derive radar adjustment factors at the gage sites. A quadratic surface is then fit to the distributed adjustment factors to yield calibration factors at each radar bin. The regression coefficients can be used to classify the events as non-frontal, cold frontal, or warm frontal and assign Z-R relationships to particular situations.

The range bias problem when making quantitative estimation of precipitation with radar was addressed in the study by Divjak (1995). Low-elevation reflectivity data and parameterized vertical reflectivity profiles were used to develop a rainfall estimation algorithm which was then applied to an independent dataset. Mean reflectivity profiles were determined by averaging volumetric data within 60 km of the radar. In a test in which the bright band was not a factor (i.e., at short ranges where the beam diameter was < 0.25 km, the beam axis was more than 1 km below the melting layer, and the mean reflectivity gradient above the melting layer was < -3 dB km^{-1}), the correlation between radar and gage estimates of rainfall was 0.84. For all gage/radar comparisons including those with bright-band contamination the correlation was 0.53.[1] Stratification by range revealed overestimates of rainfall for bright-band contaminated observations (equivalent to 3 dB) at middle ranges and large underestimates of rainfall at far ranges (~6 dB). The vertical gradient correction scheme developed in France and the United Kingdom (references provided) was then applied to elevated measurements in order to estimate the reflectivity at ground. The corrected data show smaller scatter about the mean than the uncorrected data. The correlation between radar and gage amounts increased from 0.53 to 0.63. Overestimates at middle ranges due to bright-band effects were reduced, and the percentage of actual rainfalls detected for distances greater than 100 km increased from 40 to 80%.

A similar study (Kitchen et al. 1995) describes a method for real-time, operational adjustment of precipitation estimates proposed for use in the United Kingdom. Specific corrections are applied for bright-band effects, range bias, and the orographic growth of stratiform precipitation.

[1]The use of the correlation coefficient a basis for comparing radar estimates and gage observations of precipitation was investigated by Kessler and Neas (1994). They argue that the coefficient is sensitive to the range of numbers compared and suggest that the range be normalized, perhaps by taking logarithms.

A special set of Range Height Indicator (RHI) scans were used to determine idealized reflectivity profiles which were compared to actual measurements at each radar pixel and matched within certain tolerances to observed profiles. Using high-resolution data from a second radar as truth, the methodology resulted in a 63% reduction in the RMS error of precipitation rate estimates.

Attempts to parameterize vertical profiles of radar reflectivity by precipitation type are reported by Fabry (1995). He found that, in general, profiles below the melting level in rain and convective situations are similar but that the thickness of the bright band increases with precipitation intensity.

Experiences gained in Switzerland using radar to estimate precipitation in mountainous regions are detailed in Joss and Lee (1995). They suggest that the primary sources of error in surface precipitation estimates are the decrease in reflectivity with height, ground clutter, beam blocking, and beam broadening with range. Procedures for constructing a radar visibility map (specifically the minimum height at which a storm is unobstructed when viewed by a radar) and for the vertical extrapolation of unaffected observed or climatological precipitation rate profiles to the surface are given.

Because a multitude of factors can influence the utility of radar rainfall estimates, it is not surprising that some investigators look to simulations to optimize the retrieval of information from radar (Giuli et al. 1994). These authors modeled the entire radar/raingage process and are able to investigate complex situations where the radar estimates are contaminated by beam blockage and attenuation.

G. Wind Analysis Techniques

One of the most used WSR-88D products is the VAD Wind Profile (Lee 1994). Quality control measures show that, in general, the VAD wind directions are within 10° of those from soundings 85% of the time (Lee et al. 1994). Wind speeds agree within 5 kt more than 75% of the time. Differences can usually be explained by beam ducting in the presence of nocturnal temperature inversions or by inversions associated with boundary-layer wind shift lines. Large systematic discrepancies between VAD and rawinsonde winds of 20 kt or more have been noted on a number of occasions. Differences of this magnitude may be due to migrating birds (O'Bannon 1994). The problem seems to be prevalent at night and may be aggravated by nocturnal inversions.

A number of studies appearing in the literature describe techniques for deriving two and three-dimensional wind fields from single-Doppler radar data. Large-scale meteorological systems, such as mesoscale convective systems, often move at near constant speed. If the storm (or a portion thereof) passes through a significant angular displacement (relative to a radar) in a time interval that is small compared to the total lifetime of the storm's larger features, a synthetic dual-Doppler (SDD) analysis can be performed by treating observations spaced in time as simultaneous measurements from two different radars (Bluestein et al. 1994). For mesoscale convective systems the advective time scale over which the system is thought to be approximately steady is ~3 h. In the Bluestein et al. study, a comparison was made against a conventional dual-Doppler analysis. The SDD method resolved the large-scale cyclonic circulations that often accompany mesoscale convective systems and the general convergence that characterizes the low-level convective portions of these storms. Minimal mean square errors were found for an advective speed that corresponded with the observed motion of the storm's larger scale features.

Laroche and Zawadzki (1995) performed a number of experiments in which horizontal wind fields were reconstructed from time sequences of radar observations. The tests included tracking echoes by correlation (TREC) and diagnoses incorporating reflectivity and radial velocity constraints. The clear-air reflectivity patterns in the test case showed considerable variation over the several minutes between observations and for a convective cell within the analysis domain. A series of tests revealed that wind field analyses improved when three time levels were used and as the retrieval grid interval increased from 2 to 4 km. The authors remark that the reflectivity patterns with the 2 km grid were simply too incoherent to be tracked. Even for clear-air signals, the sources and sinks of the echo patterns are thought important, i.e., the changes in the reflectivity patterns between consecutive data periods represents a severe test for the steady-state assumption. Methods assuming reflectivity or radial velocity conservation would seem most applicable to the retrieval of larger-scale flow features and less applicable to individual convective storms. Additional references for this and related wind retrieval work accomplished at McGill University can be found in Section III.O of this report.

The adjoint method was used by Sun and Crook (1994) to retrieve the three-dimensional wind and thermodynamic fields in a gust front case. The diagnostic model consisted of the Boussinesq set of prognostic equations for wind velocity, temperature, and reflectivity, the continuity equation, and a Poisson equation for pressure. A cost function measured the difference between the observations and the model solution. Penalty functions which dictated smoothing in time and space were added to the cost function to speed a solution. A series of experiments was performed in which the wind, perturbation potential temperature, and perturbation pressure fields were retrieved. Other tests investigated sensitivity to radar orientation, the effect of time interval on data insertions, and the influence of various analysis terms. Comparison was made with a wind field derived by dual-Doppler analysis. The thermodynamic fields were evaluated by comparing analyses derived from the measurements of one radar with that from a second radar. Optimum results were obtained with a test using two time levels of radial velocity measurements from a radar looking roughly in the direction of the mean flow. For a radar looking normal to the mean wind, results improved when reflectivity measurements were added to the analysis. Other findings were that additional volumes improve the retrievals and that the thermodynamic information requires a longer assimilation period than the wind field. Plans for future work include making the model anelastic and upgrading the parameterization for turbulent mixing.

Simple adjoint retrievals of microburst winds from single-Doppler radar data are described by Xu et al. (1995). [The paper is part of a continuing series by the lead author at the University of Oklahoma/Center for the Analysis and Prediction of Storms (CAPS) in which boundary-layer wind fields are derived from simple adjoint methods. The paper's introduction summarizes several methods which appear in the literature.] Previous methods applied by the lead author to relatively uniform wind fields on non-storm days were found to be unsatisfactory. The problem was solved in a series of experiments by adding a weak vorticity constraint, a first-guess field derived from previous analyses, and by including available surface wind measurements. Root mean square errors in the retrieved wind fields for the latter test were reduced to 2.55 m s^{-1} and had a correlation coefficient of 0.96 when compared to a dual-Doppler analysis. Retrievals were most accurate when the mean wind advection was strong and when local tendencies and mean advection terms were correlated in time.

The addition of two and three-dimensional wind field retrievals to the NEXRAD product suite would have great impact on hazard warning and short-term forecasting (nowcasting). Although this research field is evolving rapidly, it would seem desirable to begin a systematic and independent testing of proposed techniques. A preliminary intercomparison of several of the techniques is being conducted by Shapiro et al. (1995). Techniques studied so far include the cross-correlation method for tracking radar reflectivity features, adjoint formulations of the equations of motion, and constraints with conservation equations. Tests on several additional data sets are planned; but only results for a microburst case, using a dual-Doppler analysis as truth, were presented. Comparison is difficult because the regions of retrieved winds differ. However, based upon the total area of retrieved winds and the accuracy of the wind vectors produced, minimum errors were obtained with a simple adjoint approach (developed by Qin Xu and associates) that applies least squares fits to conservation equations for radar reflectivity and radial velocity. Further discussion of single-radar wind field retrieval techniques being conducted at the University of Oklahoma/Center for the Analysis and Prediction of Storms by Xu, Shapiro and others can be found in Section III.P.

Principals of velocity-azimuth display (VAD) and volume velocity processing (VVP) techniques of wind field retrieval are reviewed in the paper by Boccippio (1995). The discussion is directed toward operational application and includes recommendations for data preprocessing. Retrieval errors introduced by meteorological phenomena that have spatial scales which are smaller or larger than the analysis domain are also described. A nice discussion of collinearity problems with the VVP method, i.e., poorly conditioned matrices of independent variables and cross products, follows. [With the VVP method the wind field parameters to be retrieved are selected and then used to determine the basis (geometric) functions that determine the regression model. With the VAD method, the basis functions are selected and wind field components are derived from the regressed parameters.] Synthetic wind fields are used to show that an optimal set of parameters for the VVP technique is u_0, v_0, u_x, v_y, and $u_y + v_x$ and that this set is relatively insensitive to data gaps of up to 270°. Hence, the method is more robust than VAD methods. Neglecting parameters such as the vertical shear of wind components and higher order non-linear terms reduces the size of data gaps that can be tolerated.

Scialom and Leaître (1994) have developed a Quadratic Velocity Azimuth Display (QVAD) retrieval technique that uses observations from two simultaneously scanning radars or from a time series of observations from a single radar. The advantage of the scheme would seem to be that the higher order solution permits the retrieval of more detailed wind fields. A cold front situation is presented as an example. Using a dual-Doppler analysis as truth, the QVAD was shown to out perform a double VAD analysis scheme.

H. Data Acquisition Strategies

A number of observational studies express concern that the minimum elevation angle of 0.5° with the current VCP's may hamper the detection of low-level storm phenomena such as gust fronts and microbursts. Smith (1995) examines the effect of reducing the minimum angle on the detection of thin surface-based reflectivity layers. A Gaussian beam is assumed. His analysis suggests that maximum sensitivity to low-level echo features is attained at 0° elevation angle but that the 6 dB increase in sensitivity is not likely to uncover features missed at the 0.5° angle. Further, the increase in the strength of ground echoes would more than offset the gain in sensitivity. The analysis suggests that a reduction in the minimum elevation angle to 0.25° will result in 20% of the weighted beam volume intersecting the earth's surface and a 1 dB potential precipitation echo loss. The added benefit in detectability for such a small change, when weighed against the cost of implementation, is not known.

I. Interpretive Techniques/Human Interface Techniques

A number of software packages for displaying radar data and algorithm outputs are in development at several laboratories. These efforts seek to synthesize the large volume of radar information and to reduce the amount of interpretation required by radar data users. A storm cell display (Dasey et al. 1995) has been developed by Lincoln Laboratory for the aviation community as part of their Integrated Terminal Weather System (ITWS) Storm Cell Information algorithm. [See Section III.J.2 for more details.] By clicking with a mouse, users can display textual information regarding storm properties such as maximum reflectivity, maximum echo top, maximum probability of severe hail, and lightning flash rate. Because not all data sources are available at the same time, locations of some features are adjusted for mean storm motion.

Enhanced algorithms for storm identification and tracking, hail detection, mesocyclone detection, and tornado detection are being developed at NSSL (Johnson 1995b). The primary improvements are the detection of individual cells within large-scale storm clusters, greater specificity of hail events (including probability of occurrence and size), greater mesocyclone detectability at far ranges and decreased false alarm rates, and the detection of weak tornadoes and tornadoes not associated with mesocyclones. Comparison with the existing WSR-88D algorithms show marked improvement in the detection of individual storm cells (100 versus 43% for 50 dBZ cells), greater probability of hail detection (92 versus 66%) with a reduced false alarm rate (21 versus 38%), a marked reduction in the FAR for mesocyclone detections (13 versus 62%), and much greater POD for tornadoes (60 versus 10%).

A multimedia weather information display for non-meteorologists has been developed by Kelsch and Subramaniam (1995). This interactive product allows users to tailor the display for specific weather needs. Data sources include numerical models, WSR-88D products, special weather messages, and lightning data. Color coding and tone alerts are used to flag urgent information. The product is disseminated to emergency preparedness groups. McGill University (Section III.O.2) and the South Dakota School of Mines and Technology (Section III.Q.1) also have unique radar displays.

J. Analysis Techniques

Wavelet analysis is proving to be a powerful analysis tool. Recent applications include that of Hagelberg and Helland (1995) who applied the technique to radar fine lines. Fuzzy logic was then used to remap the scale images for input into expert systems for further analysis.

Another application is that of Tuttle and Gall (1995) who used a wavelet analysis to show the finestructure of a hurricane. Numerous coherent band-like features, many not apparent from cursory inspection of the reflectivity field, were detected.

Neural networks provide a method of solving complex problems where the physical processes are non-linear and not well understood. An application for rainfall estimation using radar data is described by Xiao and Chandrasekar (1995). No a priori assumptions were made concerning either the shape of the drop size distribution or the utility of a particular Z-R relationship. Instead, polarimetric measurements (Z_H and Z_{DR}) were mapped directly to gage measurements using a neural network. The network approximates the Z-R relationship methodology by updating the connectional weights between radar parameters and gage measurements. Once trained, the neural network is applied to independent datasets. Full PPI volume scan data at 5 min intervals was compared to 5 min raingage observations. By all measures, the neural network estimates were more accurate than rainfall estimates made with Z-R and Z-Z_{DR}-R relationships. (This work is also discussed in Section III.L.)

Moriyama and Muneo (1995) applied an Elman recurrent neural network and a multilayer network [references are given] to radar data in order to forecast rainfall intensities 10, 20 and 30 min into the future. A key difference between the two schemes seems to be that the Elman recurrent network provides a measure of the system chaos. For a series of tests with varying input and output meshes, the correlation between predicted and observed rainfall rates was slightly higher with the Elman recurrent network.

In yet another study, Tsintikidis et al. (1995) applied a neural network for the detection of anomalous propagation (see also Section II.D).

K. Polarimetric Radars

The considerable activity in the research community with dual-wavelength and dual-polarization radars is manifest by the large number of sessions and papers on these topics presented at the 27th Conference on Radar Meteorology. [A review of techniques for rainrate estimation with polarimetric radars was given by Carbone (1995). Discussion relevant to the use of specific differential phase (K_{DP}) for precipitation measurement is given by Kostinski (1994). While dual-wavelength radars are often suggested for rainfall estimation and rain/hail discrimination, such systems are not specifically treated this report.]

In a study comparing the utility of dual-polarimetric observations with Z-R relationship technology, Gorgucci et al. (1995) combined the reflectivity at horizontal polarization (Z_H) and differential reflectivity (Z_{DR}) measurements to give better rainfall estimates than that produced by Z-R relationships alone. When the probability densities of radar-derived estimates and the raingage observations were matched, the technique incorporating the differential reflectivity still fared best.

A clear advantage of dual-polarization measurements over singularly polarized measurements is in the detection of hail. Brandes et al. (1995) found excellent agreement between hail signatures and in situ measurements made by an armored aircraft. The study also shows that dual-polarization measurements can be used to remove the hail contribution to Z_H. Kennedy and Rutledge (1995) propose a hail detection technique based upon Z_H, Z_{DR} and the correlation between horizontally and vertically polarized signals at zero lag (ρ_{HV}). Hail is designated for $Z_H > 45$ dBZ, $Z_{DR} < -0.5$ dB, and $\rho_{HV} < 0.92$. Normally hail is assumed to tumble as it falls and, hence, to associate with a Z_{DR} value close to 0 dB. The use of a -0.5 dB threshold is thought to restrict detections to hail greater than 2 cm in diameter. The method produced maps of inferred hail locations.

A workshop addressing research and operational issues regarding polarimetric techniques was held on 22-23 February 1994 (Illingworth and Zrnić 1995). Research activities were reviewed, and the needs of the atmospheric science and operational communities were assessed. Based on the discussions, it was recommended that an S-band polarimetric radar be collocated with a WSR-88D and that a long-term statistical study be performed to quantify the benefits of the polarimetric measurements for rainfall estimation. A second test would seek to distinguish between those high reflectivity measurements which contain hail and those due to rain alone and hence having high potential for flash floods.

Yet another feature of polarimetric radars is a capacity to discriminate particle types. For example, Aubagnac and Zrnić (1995) combined measurements of Z_H, Z_{DR}, and K_{DP} to delineate regions of rain, solid hail, spongy hail, and graupel. The signatures for each particle type were clarified with simulations. Groups engaged in research with polarimetric radars and providing specific information for this survey include the National Severe Storms Laboratory (Section III.F.4.a) and Colorado State University (Section III.L).

L. Data Quality Assessment

An important indicator of algorithm quality is its utilization by users. Lee (1994) conducted a survey of National Weather Service (NWS) Forecast Offices, Center Weather Service Units (CWSU's), and Department of Defense sites to subjectively evaluate the performance of the current WSR-88D products. The Vertically Integrated Liquid, VAD Wind Profile, One Hour Precipitation, Three Hour Precipitation, Velocity Azimuth Display, and Layer Composite Reflectivity products were all highly regarded. Lowest rated products included Echo Top Contour, Hail, Severe Weather Potential, and Combined Shear. Of particular import in the Lee study are suggested improvements to the current algorithms. Most frequently received comments mention contamination of the precipitation products and deficiencies with the Storm Tracking Information algorithm regarding the detection of individual cells within large precipitation areas.

Data quality begins with the radar acquisition system. In that light, a portable client/server system is being developed for acquiring, recording, displaying, and analyzing real-time inphase and quadrature information (Gagnon et al. 1995). The system is designed to access data ports on the WSR-88D on a noninterference basis. Data collection is controlled by specifying range and azimuth limits through a graphical user interface. Real-time displays of reflectivity, velocity, and spectrum width and several options for storing data are available. Additional information can be found in Section III.K.2.b.

M. Data Compaction and Transmission Techniques

Because of the large volume of radar data that can be generated (much of it zeroes or noise even in storm situations) there is considerable interest in algorithms which compress the data for storage and reduce the time needed to transfer real-time data. Hipólito and Rodrigues (1995) compare the Run Length Encoding and the Lempel-Ziv-Welsh methods of data compaction. The Run Length Encoding algorithm replaces strings of bytes with two bytes (one which declares the number of bytes in the run and another which declares their value). The problem with the method in some applications is that for non-repeating sequences each byte is replaced by two bytes. In practice with floating point coding, there are generally some bytes that are not used and can be used to indicate strings. Several variations are described in the paper. The Lempel-Ziv-Welsh algorithm replaces strings of bytes with codes. Every observed string is assigned a code that is stored and used again when the string is repeated. A test was conducted on 20 radar data files. Both methods had large compression ratios (80-85%) with a slight edge to the Run Length Encoding method. In terms of processing times, the Run Length Encoding method was about a factor of three faster.

N. Human Factors

The survey of Lee (1994) presents feedback concerning the utility of current WSR-88D algorithms and products. With some exceptions, high product use, as with VIL and VWP, implies user satisfaction and confidence. Some products may not be well understood, hard to use (e.g., the Combined Shear product), or other products may work better. For example, comments of those surveyed indicate that VIL may be a better indicator of hail than the Hail Index and a better indicator of severe weather than the Severe Weather Probability.

Sanger et al. (1994) conducted a study to determine how interactive displays of radar information should be configured. In particular, they evaluate the Radar Analysis and Display System (RADS) being developed by NSSL. A multidisciplinary design team was assembled to study user interface issues in accordance with human factors principles. The philosophy adopted was that if RADS was difficult to use it would not be used regardless of the available features. By having human factors specialists design the user interface and by monitoring the reaction of "guest" operators, the team was able to make a number of improvements to the display system by reducing repetitive operations and by logically grouping display features.

An important component of the RADS design program was the evaluation of the training provided to display users (Jarboe et al. 1994). Video tape was used to record the activity (use and comments) of 12 operators during training and actual weather situations. Training consisted of providing participants with a manual explaining the features of RADS, a 1.5 to 2 hour one-on-one interactive demonstration of display features, a period in which operators used RADS while under supervision, and a concluding session in which operators demonstrated their proficiency. The initial training proved valuable for uncovering poorly designed interface features. An interesting conclusion was that participants utilized attribute tables and trend graphs more frequently than the raw reflectivity and velocity data in formulating warning decisions.

III. ACTIVITIES ACCORDING TO ORGANIZATION

A. Brookhaven National Laboratory

1. An Evaluation of the WSR-88D Radar for the Remote Sensing of Cloud Properties

The objectives of this two-year project are:

1) To demonstrate the capabilities of the National Weather Service WSR-88D radar to detect cumulus, stratocumulus, and cirrus clouds.
2) To develop and test retrieval algorithms for cloud coverage, vertical distribution, and thickness over large spatial domains.

It is generally accepted that the impact of changes in cloudiness on the radiation budget is a major unsolved problem in atmospheric research. Satellite images show that clouds cover a very large fraction of the earth's surface at any given time and, because of their high albedo, that they have a large effect on the shortwave radiation budget. In contrast, they have varying effects on the longwave budget depending on their location in the troposphere, i.e., high clouds have a large influence on the outgoing longwave flux and low clouds have a minimal influence. The net thermal response of the earth's surface to overlying clouds is dependent upon cloud type (with high clouds warming the surface and low clouds cooling it).

Studies that help decipher the mesoscale processes that regulate fractional cloudiness, cloud thickness, and cloud liquid water content are critical for the development of cloud parameterizations in forecast models. In order to develop these parameterizations, the relationship between the cloud structure and the thermodynamic environment must be established. Satellites can provide estimates of the top-of-atmosphere radiative flux over cloudy areas, but they cannot routinely distinguish between multiple cloud layers or unravel the complicated mix of physical processes that are modulating cloud structure. In contrast to passive sensors like satellites, active sensors such as radar can provide these details and relate them to the existing thermodynamic environment enabling the development of cloud parameterizations.

Non-precipitating clouds present a particular problem for radar detection due to the small signal-to-noise ratio that often characterizes their echo. Sophisticated short-wavelength cloud radars (< 9 mm) have been constructed and deployed during the last decade to provide a scientific data base from which cloud parameterizations could be formulated. Unfortunately, these short wavelength radars have limited areal coverage (~400 km^2) and are extremely expensive to construct and operate. They are available for temporary deployments during field programs and are not available on an operational basis. This means that they have very limited capabilities for short-term forecasting or for the development of regional cloud parameterizations. When parameterizations are formulated from data collected during these temporary deployments, they carry uncertainty created by extrapolation of the data to longer time and distance scales. Thus, there is a basic need for a measurement system that can continuously measure cloud structural parameters over large spatial domains.

With new state-of-the-art technology, the longer wavelength WSR-88D systems possess minimum detectability limits that may allow routine cloud detection over large areas. These radars can perform complete volume scans measuring reflectivity, radial velocity, and spectral width over an area exceeding 160,000 km^2 in a 5-10 minute period. In a subset of this volume, encompassing at least 4500 km^2, the sensitivity of the radar when operated in its clear-air mode permits detection of non-precipitating clouds. In addition, there are 169 WSR-88D radar locations planned worldwide -- 150 sites in the United States and 19 abroad -- providing unprecedented areal coverage. Because the WSR-88D radar is an operational system, the data are always collected and the system maintained, which makes it one of the most potentially cost effective tools for cloud research.

In order to use the WSR-88D radar for cloud studies, basic research is being conducted at Brookhaven National Laboratory to demonstrate system capabilities. The goals of this research are clearly defined: determine the detectability limits of the WSR-88D radar, develop algorithms to retrieve cloud structural parameters, and compare retrieved fields with in situ measurements to validate the technique. This approach has been used in the past to validate prototype radars for cloud studies (Clothiaux et al., 1995; Miller and Albrecht, 1995). Once capabilities have been demonstrated, they can be exploited to produce highly desirable measures of cloud structure with which important cloud research can be conducted.

References

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B. Bureau of Reclamation

1. Snowfall Accumulation Algorithm

The Bureau of Reclamation, U.S. Dept. of the Interior, has begun a three year effort toward the development of a snowfall accumulation algorithm. The algorithm will be designed for dry snow. Algorithms for mixed rain and snow or melting snow may be the subjects of future investigations.

A simplified prototype algorithm for estimating snowfall water equivalent (SWE) from WSR-88D observations is scheduled for completion by June 1996. The first refinement to the algorithm, to include the estimation of snow depth (SD), is expected to be available for testing at selected WSR-88D sites by November 1996. Further refinements will be made as additional datasets are obtained and will include recommendations on adaptable parameters or other means of algorithm adjustment for all major snow regimes within the United States (e.g., Northeast, Midwest, Intermountain West, etc.). It is planned to eventually adjust radar-estimated snowfall amounts by incorporating real-time surface observations.

As part of the algorithm development effort, observations of SWE and SD are being made during the winter of 1995-96 in collaboration with National Weather Service offices at Albany, New York; Cleveland, Ohio; and Denver, Colorado. Special attention is being given to the collection of high-quality SWE and SD measurements in protected locations because of the difficulties of collecting reliable snowfall depth information in the presence of even moderate wind speeds.

Datasets from other climatic regimes will be obtained in future winters.

The final algorithm, to be completed by May 1998, should be able to estimate SWE and SD from WSR-88D measurements under different winter storm conditions and for different climatic regimes. Attempts will be made to partition Z-SWE and Z-SD relationships by observations of temperature, moisture and stability, by storm type (e.g., closed low, cold front, upslope, lake effect), by storm phase (e.g., prefrontal, frontal passage, postfrontal), by radar cloud top heights, and by ice particle types and fall speeds.

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C. NEXRAD Operational Support Facility

1. New Storm Cell Identification and Tracking Algorithm and Hail Core Aloft Algorithm

Operational Support Facility (OSF) meteorologists and software engineers have incorporated the Storm Cell Identification and Tracking (SCIT) Algorithm and the Hail Core Aloft Algorithm (HCAA), developed by the National Severe Storms Laboratory, into the next WSR-88D software version, Build 9, due to be fielded in fall of 1996. The SCIT replaces the Storm Series algorithms (Segments, Centroids, Tracking and Forecasting, and Structure). The most significant difference is that the SCIT Algorithm identifies cells using multiple (7) reflectivity thresholds; whereas, the Storm Series identifies entire storms using one reflectivity threshold. The advantage is that individual cells within multicellular areas of significant reflectivity (e.g. squall lines) can be identified and tracked. Testing has shown that the SCIT identifies cells with near perfect skill. Another major change is that SCIT is able to track storm cells which are moving in directions opposite to the average storm motion. Included in the SCIT Algorithm is the computation of a new attribute, cell-based VIL. This parameter is based on the maximum (3 bin average) reflectivity. When storm cells are highly tilted, the cell-based VIL should be more accurate than the regular (columnar) VIL. Another change is that up to 100 cells per volume scan can be detected with SCIT.

The HCAA replaces the old Hail Algorithm in the WSR-88D. The HCAA searches for high reflectivities above the freezing level in each storm cell; whereas the old Hail Algorithm uses seven structural characteristics (e.g., storm tilt and storm orientation) to determine the hail potential for each storm. The output of the new algorithm also includes estimates of the Probability of Hail (POH), the Probability of Severe Hail (POSH), and the Maximum Expected Hail Size (MEHS). In general, the higher the height of the strong reflectivities and the greater the reflectivity magnitude, the greater the POH, POSH, and MEHS. The algorithm must be provided with the 0 and -20°C altitudes from an appropriate sounding. Studies which include geographically diverse cases have shown that the HCAA has significantly higher statistical performance than the old Hail Algorithm.

Also new will be the capability to display Cell Trends Data. When selected, the following attributes will be displayed at the PUP in four panels: (1) height of the maximum reflectivity, height of the storm cell mass-weighted centroid, height of the storm top, and height of the storm base; (2) Probability of Hail and Probability of Severe Hail; (3) maximum reflectivity; and (4) cell-based VIL. Trend information consists of plotting particular attributes in time for the cell's lifetime, up to the last 10 volume scans. The trend display includes a miniature graphical representation of the storm's location relative to the radar. For reference, the past 10 volume scan times are listed, and the volume scans for which the cell existed are highlighted.

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2. Velocity Dealiasing

During 1995, the Applications Branch of the OSF examined the improvement in the performance of the WSR-88D Velocity Dealiasing Algorithm (VDA) when it is forced to retain all data bins. Previously, an increase in the number of mesocyclone and TVS detections had been found when all the velocity bins were retained. In new version, the VDA is allowed to set up to four radially contiguous bins to the background "below threshold" value whenever it cannot resolve the correct Nyquist co-interval in which to place a velocity measurement. To force the VDA to retain all points, branch scientists reset the adaptable parameter that controls the number of contiguous bins set to "below threshold" from a value of 5 to 1. They adjusted other parameters to increase the algorithm's reliance on the Environmental Wind Table and to increase the tolerance for regions of high azimuthal shears (2.5 km to 5 km). While these changes improved the number of velocity bins that were correctly dealiased and the number of TVS's reported, they also produced incorrectly dealiased artifacts propagating from ground clutter near the radar. Branch scientists then modified the VDA code to use different adaptable parameters settings for regions near the radar than those used beyond the ground clutter contaminated regions. They also added a call to the Environmental Wind Table whenever radially continuity failed. The table below shows the results obtained for Run A (the default code and adaptable parameter settings), Run B (the initial adjustments to the adaptable parameters), and Run C (the modified VDA with the optimized settings). The data consisted of 36 elevation scans, 31 of which are storm events and 5 are from a low-level jet case (Zittel et al. 1994).

	Run A	Run B	Run C
Ratio Correct	0.9882	0.9954	0.9972
Prob. of Detection	0.8859	0.9825	0.9824
False Alarm Rate	0.0293	0.0415	0.0191
Critical Success Index	0.8629	0.9424	0.9640

Branch scientists also tabulated the types of dealiasing errors seen in the velocity field for each run and elevation scan. The categories were wedges, patches, spots, spikes, and specks. Wedges have sharply defined radial boundaries, patches have no sharply defined boundaries, spots are small patches, spikes are very narrow wedges, and specks are small spots visible only with 0.25 km resolution. Wedges were subdivided into three categories--small, large, and area; patches were subdivided into a small and large category; and spikes were subdivided into a long and short category. The errors were weighted by size from 100 for an area wedge to 1 for spots and specks. Weights were summed for all 36 elevation scans with each of the three runs. Run A had a combined total of 576 points, Run B had a combined total of 799 points, and Run C had a combined total of 762 points.

The table shows that Run C represented an improvement over Runs A or B. However, there was a substantial increase in the number of dealiasing errors the user would see in a velocity product using the procedures of Runs B and C. In particular, Run C only showed slight improvement in the visual problems despite the code changes. We believe the visible problems would be unacceptable to users and are continuing efforts to reduce their occurrence.

Reference

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3. Mesocyclone Algorithm

Several studies have shown that the current WSR-88D Mesocyclone Algorithm can be improved by employing additional logic to classify circulation strength via an Integrated Rotational Strength (IRS) Index and by increasing algorithm sensitivity through the optimization of adaptable parameters. The algorithm can also be improved by simply reducing the Threshold Pattern Vector adaptable parameter from 10 to 6.

A comparison between the NSSL second generation algorithm (named MDA2) and the enhanced WSR-88D Algorithm with the IRS Index incorporated (Enhanced MESO) revealed that MDA2 outperformed Enhanced MESO when all data were combined. However, on some days the Enhanced MESO performed better. Using the Critical Success Index (CSI), MDA2 outperformed the enhanced WSR-88D Meso algorithm by 5.5% or less. Using the Heidke Skill Score (HSS), MDA2 outperformed the enhanced WSR-88D Meso algorithm by 11.9% or less. However, there are uncertainties with the HSS regarding the definition of correct nonoccurrences which raise questions concerning its use as a comparative parameter. The performance of both the Enhanced MESO (with IRS Index) and MDA2 was higher than the currently fielded WSR-88D Mesocyclone Algorithm.

Algorithm Performance Scores for various Mesocyclone Algorithms

	Current 88D	Enhanced 88D	MDA2
CSI(Tornado Only)	12.3	18.0	23.5
HSS(Tornado Only)	-21.9	23.8	35.7
CSI(Tornado and Severe Wind)	16.9	22.0	26.1
HSS(Tornado and Severe Wind)	-25.4	27.0	37.5

The MDA2 Neural Network performed best for the combined dataset but did not stand out as the highest performer on every day. The Neural Network performed best on isolated supercells, the same type of weather event for which it was trained. (This was also true of the WSR-88D algorithm which employed no special training.) When the different classification parameters were maximized using CSI instead of HSS, lower values emerged for mini-supercells storm types.

One goal of this effort was to reduce the relatively high numbers of false alarms that occur with both MDA2 and the enhanced WSR-88D Mesocyclone Algorithms. Attempts are underway to reduce the number of false alarms without decreasing the number of hits. (A big improvement in algorithm performance could be realized by solving this problem.)

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4. VAD Wind Profile Performance Study

From June 1994 to May 1995, the OSF Applications Branch collected and compared WSR-88D wind estimates with rawinsonde-based wind measurements at 12 locations. The goal of this project was to discover the magnitude, extent, and cause of vertical wind profile disagreements between rawinsonde and radar-derived wind estimates.

The sites selected for the study were Oklahoma City, Oklahoma; Denver, Colorado; Dodge City, Kansas; Topeka, Kansas; Pittsburgh, Pennsylvania; Little Rock, Arkansas; Fort Worth, Texas; Amarillo, Texas; Jackson, Mississippi; Sterling, Virginia; Houston, Texas; and Miami, Florida. The radar and rawinsonde sites were within 16 km of each other (with the exceptions of: Houston's sounding came from Lake Charles, Louisiana--175 km away; Miami's sounding came from Palm Beach--96 km away; and the June Fort Worth data came from Stephenville--80 km away). The results from the noncollocated stations and the collocated sites were comparable and the distance factor was determined to be negligible.

A Root Mean Square Vector Difference (RMSVD) was used to compare the radar-derived winds and the balloon-borne soundings. The mean RMSVD for all comparisons was 10.2 kts with a standard deviation of 7.0 kts. A seasonal trend was evident with summer being far the period of best agreement. Poorest agreement between radar and rawinsonde winds occurred during the winter. Fall and spring were transition periods.

To detect the possible causes of poor agreement, the data were stratified according to the weather observed at the time of the wind profile. The mean RMSVD was calculated for the cases when precipitation (including convective storms) was observed at the station or within range of the VAD algorithm distance limits. The mean RMSVD for precipitation cases (8.5 kts) and standard deviation (5.8 kts) were lower than that for all cases (10.2 and 7.0 kts respectively). This suggests precipitation improved the radar-derived winds, possibly due to the fact that under these conditions numerous scatterers and minimal AP occurred.

Based on this knowledge, all cases which contained inversions, fog, and haze, were removed. Forty-four percent of the total winter observations included fog, haze, or the presence of inversions compared to 16% for summer and 18% for fall. There was little change in the summer and fall RMSVD values when the inversions, fog, and haze cases were removed; however, the winter RMSVD values improved from a mean RMSVD of 12.7 to 9.4 kts. The frequency of anomalous winter wind cases (i.e., RMSVDs greater than 20 kts) decreased from 18% to 6%. This suggests that winter inversions (beam ducting and lack of scatterers) have a significant effect on radar-derived winds.

Little change was observed in the fall RMSVD values when the inversions, fog, and haze cases were removed. Hence, something other than inversions are causing the disagreement. Fall RMSVD values were larger than summer values but less than winter values. The effect of the fall bird migration should not be discounted as a cause. Further analysis of the data is needed to determine the causes of the high RMSVD's in the fall.

Additional radar, sounding, and wind profiler data were collected from Melbourne, Florida and the nearby Kennedy Space Center from June 1995 through November 1995. This dataset was combined with radar information from Miami and soundings from Palm Beach, Florida collected between June 1994 and May 1995. The goal of this project was to discover the magnitude, extent, and cause of vertical wind profile disagreements between rawinsonde, profiler, and radar-derived wind estimates in the Florida environment.

The VWP algorithm may fail to generate meaningful wind data when few scatterers are present, when statistical and symmetry errors are exceeded in the VAD processing stage, when anomalous propagation (AP) causes the radar beam to bend upwards or downwards, when migrating birds cause a bias in the wind direction and speed, or when a combination of these problems occur.

Overall, wind vector differences between radar and rawinsonde measurements in Florida were somewhat smaller than at the other 11 sites. The mean RMSVD for the total Florida sample was 10.1 kts and the standard deviation of the RMSVD values was 5.3 kts. Recall that the mean RMSVD for comparisons at all 12 sites combined was 10.2 kts and a standard deviation of 7.0 kts. Florida data ranked 5th in overall performance (i.e., mean RMSVD).

Data collection problems limited the number of comparisons made between radar and wind profilers. Six of the 8 comparisons resulted in RMSVD values that were less than 10 kts and the worst comparison had an RMSVD value of 12.5 kts. These values suggest that the radar and wind profiler measurements are in good agreement.

Once the statistical studies identified the frequency and potential causes of the disagreement, a VWP adaptable parameter optimization study was performed by NSSL with cases identified by the OSF. The study was performed on 30 cases with data from several different sites. NSSL acquired archive Level II radar data for each case and the supporting "ground truth" information to perform the study.

The adaptable parameter optimization study was conducted by replaying Level II data. The VAD Range algorithm adaptable parameter (the range at which the wind profile is computed) was varied from 5 to 50 km for each case, and the algorithm performance was determined by calculating RMSVD values.

The 30 cases were categorized as (1) anomalous VWP's thought to be caused by migrating birds, (2) anomalous "zero" velocities caused by ground target contamination, and (3) "control" cases where there was good agreement between the radar-derived winds and the balloon-derived winds. Fourteen cases were accepted as good matches, 10 cases were designated as lacking scatterers and/or having a significant amount of zero velocity values, one case was contaminated by local convection, one case suggests biological contamination, and three cases were categorized as indeterminant could due to a lack of data.

At times a small value for the VAD Range adaptable parameter (10 km) worked best, while at other times a larger value (50 km) worked best. There seemed to be no correlation between algorithm performance and the cause of the discrepancies (e.g., inversions, biological, and lack of scatters). When velocity data were not available at far ranges, setting the VAD Range adaptable parameter to a smaller value reduced comparison errors.

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5. Radar/Raingage Comparisons

The performance of the WSR-88D Storm Total Precipitation (STP) algorithm is being analyzed by comparing high-resolution, radar-estimated accumulation values with raingage measurements. Comparisons performed are similar to the methods of the WSR-88D bias adjustment algorithm which will adjust the STP amounts in real time. The gage data are compared with the radar estimates from nine surrounding bins. The radar bins had a spatial resolution of 2 km x 1° and accumulation resolution of .01 inch. The best matched radar bin is used for comparison. So far, the process has been tested for 44 rain events at eleven WSR-88D sites. The rain events were stratified into 22 convection cases, 17 stratiform cases, and 5 tropical maritime cases. The analysis results indicate that the WSR-88D:

(1) systematically and significantly underestimates rainfall amounts in stratiform and tropical-maritime precipitation,

(2) slightly underestimates amounts at close ranges and slightly overestimates amounts at far ranges for convective precipitation, and

(3) matches most closely with gages located 50 to 150 km from radar site.

Some of the cases were rerun through the WSR-88D Precipitation Accumulation algorithm using base (Level II) data, and using different coefficients for the reflectivity-rainrate (Z-R) relationship. The coefficients were found to have a significant impact on the radar precipitation estimates.

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6. Precipitation Accumulation Algorithm Enhancements

Steps are underway to improve the utility of terrain-based hybrid scans. Currently, the Precipitation Processing System (PPS) builds the hybrid scan at some optimum altitude above the radar (1000 meters). Studies will be conducted to investigate the effects of eliminating the height constraint and using the lowest tilt which isn't blocked. This only requires an adaptable parameter change when running the Hybrid Scan-Occultation file generator program. Using the terrain as a base for the hybrid scan data will force the PPS to use lower tilt angles close to the radar; and because terrain is basically fractal, it should eliminate the sharp "rings" at ranges where the tilt changes. Studies will be performed using data from Monterey, California; Reno, Nevada; and Oklahoma City, Oklahoma. Terrain-based hybrid scan files have been built for Reno and Monterey and soon will be built for Oklahoma City. The next step will be to obtain Level II data from these sites.

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7. Algorithm Performance Survey

In April 1995 the OSF Algorithms Section sent a survey form to all WSR-88D field sites. This included National Weather Service (NWS) Forecast Offices, Center Weather Service Units (CWSU's), River Forecast Centers (RFC's), and Department Of Defense (DOD) weather stations. The goal of this project was to ask WSR-88D operators to subjectively evaluate the performance of 19 WSR-88D meteorological algorithms and products. This survey is a follow up to the one conducted in April 1994 (Lee 1994).

Surveys were mailed to 246 different field sites. A total of 289 responses were received. The breakdown in responses was:

108	DOD
19	CWSU
159	NWS
3	RFC.

In general, algorithm performance was rated slightly higher than in last year's survey, due to experience and confidence gained over the last year. There is less scatter in performance ratings in 1995 as compared to 1994. More responses were received in 1995, and there was more agreement among agencies concerning algorithm performance.

The Echo Tops Algorithm is being used substantially more than a year ago. Forecasters are probably learning to live with the perceived problems attributed to this algorithm. The Layer Composite Reflectivity product jumped ahead of several products in terms of Forecaster Performance Rating. Its frequency of use also increased. The TVS algorithm showed a relatively low score and low usage. This reflects the fact that many sites have not seen a TVS and therefore don't use the product. This is misleading as the OSF recommends that the TVS be used on alert products. Field personnel do not have much of a chance to evaluate an algorithm that doesn't trigger very often.

A significant number of operating locations do not update the WSR-88D environmental wind table as often as recommended. The best wind data possible will be provided to all of the algorithms if the environmental wind table is updated twice a day with an estimated wind profile.

The precipitation products seem to work the best in the central areas of the country and less well in the Northeast and in the West. DOD and CWSU's tend to not use the precipitation products nearly as often as the NWS.

Good performance is reported for the Hail Algorithm in Virginia and the Carolinas, while poor performance is reported in most other areas. Survey results have helped the Algorithm Section of the OSF Applications Branch prioritized current and future algorithm-related work. The comments are especially helpful to the Human Factors Group to understand user concerns about the product displays. The Hail Algorithm is scheduled to be replaced in Build 9.

Reference

1. Steadman, R., and R.E. Lee, 1995: Perceptions of the WSR-88D performance. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 173-175.

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8. WSR-88D Algorithm Testing and Display System

The WSR-88D Operational Support Facility (OSF) on behalf of the NEXRAD agencies tasked the National Severe Storms Laboratory to enhance and make user friendly a software package that NSSL had developed for internal use and for testing algorithms. The result of this work is the WSR-88D Algorithm Testing And Display System (WATADS) which displays base data and executes and displays algorithm output.

The initial release of the WATADS (designated Version 8.0 to coincide with the WSR-88D software Build cycle), scheduled for early 1996, consists of the following algorithms:

WSR-88D Baseline Algorithms	Enhanced NSSL Algorithms
* Mesocyclone * Tornado Vortex Signature * Storm Series * Velocity Dealiasing * Precipitation Processing * Hail Detection * Velocity Wind Profile * Storm Relative Velocity	* Mesocyclone Detection * Tornado Detection * Storm Cell Identification and Tracking * Hail Detection

The display software is a version of the NSSL-developed Radar Algorithm Display System (RADS). The WATADS has some of the functionality of the WSR-88D Principal User Processor (PUP) (e.g., map backgrounds, zoom, and looping). More functionality may be added in future WATADS releases.

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9. NSSL Database Enhancement

NSSL is in the process of collecting information about severe weather and correlating its occurrence with WSR-88D radar data. The goal is to allow users to access a database of weather events and find archive Level II tape information which is associated with the event. A user could also specify a radar and a weather event type and the program would show what Level II data, if any, had been collected. A search can also be made using a Level II tape number to 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 this database and search capability will make it easier to determine what, if any, radar data exists for a given event. A plan exists for placing this database and search procedure on the World Wide Web.

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10. System Enhancements

a. ANOMALOUS PROPAGATION MITIGATION

The NEXRAD OSF has entered into a collaborative effort with the NOAA Forecast Systems Laboratory and the Atmospheric Technology Division within the National Center for Atmospheric Research for testing anomalous propagation mitigation schemes on the WSR-88D System. Using OSF-provided archive Level II data sets, FSL and NCAR are developing and testing AP ground clutter recognition schemes which identify AP and provide clutter filter parameter recommendations. Performance (false alarm rate) and reliability of detection are being determined. FSL and NCAR will also devise and test a method to determine when AP has dissipated and/or weather has formed. Developed techniques will be adaptable to the existing WSR-88D hardware and architecture. [Additional information regarding this effort appears in Section III.K.2.a.]

b. LEVEL I RECORDER AND DISPLAY

In a second task, FSL and NCAR are replicating the Level I diagnostic recorder with enhancements to create a data acquisition, display, and analysis system which allows for collection of continuous Level I data within specified sectors and elevations. [For further information see Section III.K.2.b.]

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D. NOAA Forecast Systems Laboratory

1. WPMM Utility in WSR-88D Precipitation Processing

a. INTRODUCTION

During fiscal year 1995 FSL evaluated the Window Probability Matching Method (WPMM) for potential incorporation into the WSR-88D Precipitation Processing System (PPS). The WPMM has been tested in Australia and Israel for its ability to identify precipitation regimes based on radar echo characteristics and matching those characteristics with surface precipitation measurements from high-resolution raingage reports. The information is used to select Z-R equations that are related to the precipitation regime classifications for windows of data. The procedure provides more accurate radar-derived rainfall rates than obtainable with a fixed Z-R relationship. Initial studies are described in detail by Rosenfeld et al., 1995a, Rosenfeld et al., 1995b, Rosenfeld et al., 1994.

The focus of the FSL evaluation was to reach one of three possible recommendations:

1) that WPMM methods cannot be used with the WSR-88D PPS,
2) that WPMM methods be used in part, perhaps externally, for gaining better understanding of the PPS limitations and performing adaptation parameter studies, or
3) that WPMM methods should be used operationally in place of the PPS functions.

The second recommendation was made and described in a November 1995 report. The study concluded that the WPMM can be used externally to understand and enhance the performance of the PPS. Experience has shown that values for numerous adaptation parameters in the PPS are highly variable and dependent on local climatology. Limited understanding of the potential range of parameter values exists that could help to make parameter selection more flexible and interactive. Therefore, the classification of precipitation regimes in WPMM can offer some important insight for the settings of some of these adaptation parameters. In particular, the maximum reflectivity threshold for hail contamination, the Z-R coefficients, range degradation coefficients, and bias reset values may benefit from knowledge about precipitation regime classifications.

WPMM storm-type classifications may also provide information about precipitation climatology. This is important for effective use as well as future enhancements of the PPS.

b. ADAPTATION PARAMETER INFORMATION

If the adaptation parameters are going to be used effectively, their variability must be understood. The WPMM classification parameters include items such as horizontal reflectivity gradient, height of the freezing level, depth of the warm cloud (above freezing) layer, maximum reflectivity, echo tops, bright-band fraction, and distance from the radar. These parameters, extracted from relatively small windows within the radar field, can be used to classify echoes as convective or stratiform precipitation, continental or maritime storms, hail or non-hail storms, and as precipitation or clutter.

The WPMM methodology may be useful when implemented externally to identify the best value and numeric range of certain adaptation parameters. Because meteorological information is incorporated into the WPMM processing, the tendency to use the adaptation parameters as "fudge factors" can be minimized. WPMM could, in theory, provide real-time adaptation parameters based on current atmospheric conditions and radar echo characteristics. However, in addition to its limited testing in complex precipitation regimes, many WSR-88D sites lack the appropriate raingage data. Thus, identifying a number of key locations with the appropriate data to represent the range of WSR-88D precipitation regimes is a more effective approach. Three adaptation parameters are likely to benefit most from WPMM application:

> *Z-R coefficients*: The WPMM method is designed to handle variations in Z-R relationships. WSR-88D enhancements may be most effective if Z-R coefficient changes are used for precipitation regime classifications associated with average drop size distribution knowledge (such as tropical versus continental precipitation).
>
> *Range degradation coefficients*: Little is known about the optimal settings for mitigating range bias errors, but classifying events by precipitation regimes and radar distance may provide a better understanding of the magnitude of range degradation in different events, and whether it can be reliably corrected.
>
> *Hail reflectivity threshold*: The maximum reflectivity threshold (and thus the maximum rainfall rate) varies with location and season. Determination of classification regimes may provide a meteorologically-based method of setting that threshold.

c. RADAR-RAINFALL CLIMATOLOGY

Classification of precipitation systems may provide more than just feedback on adaptation parameter settings. The WPMM categorizations also give feedback about the frequency of specific types of precipitation. This information will promote understanding of precipitation climatology for the WSR-88D network as well as for specific sites. One particular benefit may be the ability to develop quantitative guidance regarding range degradation. The loss of low-level precipitation information with increasing distance may be difficult to correct with adaptation parameters. Categorizing distance range effects by precipitation regimes may provide useful guidance for interpreting the radar-derived accumulations. For example, a distance at which more than 50% of the precipitating echoes are not being sampled may be 70 km for continental stratiform, 100 km for deep maritime stratiform, 150 km for tropical maritime convection, and 200 km for strong continental convection. In this way there can be a confidence level associated with the precipitation products.

There are other areas where precipitation climatology may assist. An understanding of the PPS performance relative to precipitation regime may be useful operationally. There is indication that the reliability for continental stratiform events may be lower than that of continental convective events. The classification methodology may provide a more thorough understanding of PPS performance, as well as level of confidence in the output, for various sites, seasons, and individual events.

d. SUMMARY

FSL reviewed the literature for WPMM and thoroughly examined three different precipitation events (Kelsch and McGinley, 1995). These were: (1) intense continental convection at Front Range, Colorado, (2) continental stratiform with some convective elements and bright band from Twin Lakes, Oklahoma, and (3) tropical rainfall associated with Tropical Storm Gordon from Melbourne, Florida. FSL recommends that the WPMM methodologies may be useful in part for adaptation parameter studies and perhaps for precipitation climatology studies, particularly as it relates to range degradation and reliability of PPS for various events.

The WPMM relies on using changes to Z-R coefficients for making appropriate adjustments to derived rainfall rates. The complex nature of precipitating systems within the WSR-88D domain will make it difficult to use the adaptation parameters related to drop size distributions only. It is believed that the most effective use of WPMM methodologies will be the categorization of precipitation regimes as a function of atmospheric conditions and radar signatures. Thus, we can learn about several of the key adaptation parameters and develop an understanding of PPS performance as a whole for various types of events.

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E. NOAA Hydrologic Research Laboratory

1. Introduction

The Hydrometeorological Analysis Group (HAG) in the Hydrologic Research Laboratory (HRL) is the group within the National Weather Service which designed and developed the initial WSR-88D Precipitation Processing System (PPS). They are primarily responsible for the on-going evaluation, applied research and development, algorithmic enhancement, and implementation of improved versions of the PPS algorithms and software. The latter activity includes the definition of the operational requirements for improved rainfall estimates to the coding, integration, and testing of upgraded software on the Radar Product Generator (RPG) computer system. The HRL is also responsible for follow-on processing algorithms (called Stages II and III) which further refine, perform quality control, and mosaic rainfall estimates from individual radar sites. This activity also includes the incorporation of real-time raingage and satellite data to produce optimal rainfall estimates that are used operationally in the hydrologic forecast models (the NWS River Forecast System) at the River Forecast Centers and Weather Forecast Offices.

The areas of activity related to WSR-88D algorithm research, development, and evaluation at the Office of Hydrology fall into four major categories:

1) PPS adaptable parameter optimization studies,
2) PPS algorithm enhancement,
3) development and implementation of the Gage Data Support System (GDSS), and
4) Flash Flood Projection (FFP) algorithm evaluation.

2. Adaptable Parameter Optimization Studies

There are about 50 adaptable parameters in the PPS suite of software programs. These parameters control how the algorithms perform and can be refined in time as we gain more experience and as more radar data are collected. This flexibility has been designed into the algorithms to permit relatively quick and easy adaptation of the algorithms at each radar site to the local climatology and conditions.

HRL has been performing optimization studies through case analyses to determine parameter settings which optimize the performance of the PPS. Site-specific studies have not yet been widely pursued as the default parameters used nationwide are not yet fully optimized. The resulting NWS-approved parameter recommendations are then forwarded to the OSF for implementation at field sites. To date, about a dozen of the more critical parameters have been examined and will continue to be refined as needed.

3. *Algorithm Enhancement*

In addition to improving the existing PPS algorithms through parameter optimization, HRL is also active in advanced algorithm development to extend the current functionality and capability of the PPS. This involves making scientific design enhancements to existing algorithms as well as the development of new techniques to improve the radar rainfall estimates. There were four primary areas of concentration in 1995.

a. IMPROVED HYBRID SCAN

In the PPS, the hybrid scan is a two-dimensional mapping of rainfall rates for a given volume scan (similar to a CAPPI) constructed from reflectivity measurements at the four lowest elevation angles of the WSR-88D (0.5 to 3.5°). In the current version of the PPS, there is no attempt in constructing the hybrid scan to smooth across the boundaries of the adjacent elevation angles. An enhanced CAPPI-like construction procedure has been designed, coded, and tested which interpolates data to a constant altitude from two adjacent tilts using an assumed vertical reflectivity profile. This procedure is described in Breidenbach et al. (1995) and has been shown to eliminate the concentric discontinuities of rainfall near the radar which often occurred with the old technique. We are still examining the impact of partial beam blockage on the results.

b. IMPROVED GAGE/RADAR BIAS ADJUSTMENT ALGORITHM

In HRL's 1994 final MOU report to the OSF (Seo et al., 1995), the Kalman filter procedure to compute gage-radar biases was rederived and reformulated. Since then, we have coded the improved algorithm and tested it using several heavy rainfall events. The new formulation is an improvement over the existing procedure to optimally combine the gage and radar rainfall data in the computation of the mean field bias. We plan to implement the new code operationally in the next software release. Preliminary results were presented at the III International Symposium on Hydrologic Applications of Weather Radar (Fulton et al., 1995).

c. ENHANCED RANGE CORRECTION TECHNIQUE

The analysis and correction of degraded rainfall estimates at far ranges, caused by beam filling and beam overshooting, particularly evident in the cool seasons, is an important effort at HRL. Findings thus far indicate that the existing range bias technique, currently not being executed because of a need for long-term rainfall statistics, can be improved upon. Analyses are continuing at HRL to evaluate the severity of range degradation for various types of precipitation and to assess the potential for real-time range correction.

d. BRIGHT-BAND CONTAMINATION REMOVAL

We have begun to investigate existing operational techniques in the international literature for detection and removal of radar rainfall contamination by the bright band. We have developed software to begin proof-of-concept testing, and have tested it on a few rainfall events with bright-band contamination (Seo et al., 1995). This effort is expected to continue toward implementation on the RPG within the next several years.

4. Development and Implementation of the Gage Data Support System

Over the past few years, the Hydrologic Systems Group in the Office of Hydrology has developed a communication software and hardware computer system, called the Gage Data Support System (GDSS), which will supply real-time raingage data from a variety of NWS and other agency's gage networks to WSR-88D's for operational use in correcting rainfall estimates generated by the PPS. This automated system is a Hewlett-Packard, Unix-based computer workstation which assembles a real-time local database of gage data and then passes that information on to several WSR-88D RPG's in the surrounding area via telephone modem transmission. The GDSS will graphically display the location of and information about all available gages in the area and permit hydrologic forecasters to selectively choose, using a graphical user interface, which particular gages will be accessed.

The first prototype system has been installed at the NWS's Mid-Atlantic River Forecast Center in State College, Pennsylvania for operational testing. Other systems will be installed across the U.S. in 1996.

5. Flash Flood Projection Algorithm Evaluation

The Flash Flood Projection (FFP) algorithm, developed at HRL in the 1980s, makes a projection of WSR-88D rainfall fields up to an hour into the future using input from past rainfall accumulations from the PPS. The information is combined with Flash Flood Guidance to assess the likelihood of short-term flash flooding.

Work has begun on the porting of the FFP algorithm to a Unix-based workstation. The algorithm has previously been run on a Prime mainframe computer at the Office of Hydrology. Ultimately the goal is to implement the algorithm on the NWS's Automated Weather Interactive Processing System (AWIPS) workstations at each forecast office. Once the algorithm is running on our workstations, we will perform additional studies to evaluate its performance for a number of past flash flooding events.

6. *Other Collaborative Work*

In addition to the work being done by the HAG at HRL, we are also closely working, through cooperative agreements, with Prof. James A. Smith and colleagues in the Department of Civil Engineering and Operations Research at Princeton University and Prof. Witold F. Krajewski, Department of Civil and Environmental
Engineering at the University of Iowa, on other radar rainfall- related research topics having direct application to the WSR-88D. Basic and applied research activities are being conducted to improve techniques for removing radar returns from anomalous propagation, to optimize Z-R coefficients and other PPS parameters, and to perform statistical analyses of PPS rainfall products for various geographical and climatological regimes across the U.S. (Smith and Krajewski, 1994; Seo and Johnson, 1995; Smith et al., 1995).

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F. 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.

2. Algorithm Development and Enhancement

a. STORM CELL IDENTIFICATION AND TRACKING ALGORITHM

NSSL continues to evaluate the Storm Cell Identification and Tracking Algorithm (SCIT) and has made several upgrades. For example, an enhancement enables the algorithm to identify shallow storms (storms with bases not "seen" by the radar). Specifically, when this option is chosen, two-dimensional cells, in addition to the three-dimensional cells routinely identified, are detected beyond a user-specified radar range. An enhancement to the time-association technique utilizes improved discriminating-distance criteria between first-guess and new cell positions.

Recently, NSSL has also begun evaluating the usefulness of cell-based trends for forecasting storm cell growth and decay. Parameters such as cell volume, Vertically Integrated Liquid (VIL) water, maximum radar reflectivity, height of center of mass, and time rates of change of these parameters are being examined. The usefulness of these additional parameters for a storm growth and decay product will also be studied.

b. MESOCYCLONE DETECTION ALGORITHM

During 1995, NSSL made minor refinements to the Mesocyclone Detection Algorithm (MDA) that included (1) a vertically-integrated density-weighted rotational strength index or Mesocyclone Strength Index (MSI), (2) an ability to monitor low and mid-altitude convergence information, (3) storm depth calculations for classification of low-topped mesocyclones, and (4) neural network empirical functions (e.g., Probability of Tornado and Probability of Severe Weather) and an adaptable weight matrix for allowing future re-training of the network on greater and site-specific databases.

The MDA is currently undergoing rigorous off-line performance analysis and comparison with the baseline WSR-88D Mesocyclone Algorithm. Planned improvements for the MDA include (1) the addition of circulation trends, reflectivity information (e.g., BWER), and near-storm environmental information as additional neural network inputs and (2) the re-training of the neural network on an expanded database using additional inputs and the creation of site-specific neural network weight matrices.

c. TORNADO DETECTION ALGORITHM

A number of enhancements have been added to the NSSL Tornado Detection Algorithm (TDA). The TDA now provides preliminary detections at ~2.5 minutes into the volume scan (after processing the 4.3° elevation angle). This information is available in addition to the detections provided by the full volume scan.

The tracking routine in the TDA is now capable of saving up to 10 previous detection locations and computing up to six 5 minute interval forecast locations. This is an improvement for tracking long-lived circulations. Previously, the TDA only maintained up to two previous locations and computed three forecast locations.

In an effort to better distinguish between tornadic and non-tornadic circulations, the maximum velocity differences for each two-dimensional circulation comprising a single three-dimensional volumetric circulation are integrated to obtain an overall system strength. This parameter is being investigated to determine its usefulness for distinguishing between tornadic and non-tornadic circulations.

Although the tornado detection algorithm has been tested only on a limited database, preliminary results show improvements over the current WSR-88D Tornado Vortex Signature (TVS) Algorithm. Finally, over 50 tornadic events are being analyzed using recorded Level II data from various geographical regions. These events supplement those previously analyzed. The analysis is expected to result in future algorithm improvements.

d. HAIL DETECTION ALGORITHM

To further enhance the detection capability of the Hail Detection Algorithm (HDA) a relative humidity component has been incorporated into the algorithm. The HDA already uses information on the vertical thermal profile (the Warning Threshold Selection Model is a function of the melting level). The potential impact that environmental relative humidity might have on an algorithm was the focus a heuristic study. The 700 mb dew point depression (DPD_{700}) was chosen as a parameter since this value is commonly plotted on NWS upper-air charts. Using available upper-air plots, DPD_{700} values were obtained for 35 cases and were compared to the difference between the actual Warning Threshold (WT) and the optimal WT (the threshold producing the highest CSI) for each day. While there is a substantial scattering of points for low dew point depressions ($DPD_{700} < 8\,°C$), there is an indication that adjusting the WT to higher values for those days having low DPD_{700} values should improve the performance of the algorithm. Therefore, the adjustment A_{RH} was incorporated where

$$A_{RH} = 160 - 20\ DPD_{700} \text{ and}$$

$$WT = WT + A_{RH}\ .$$

If $A_{RH} < 0$, then A_{RH} is set to zero. Also, if the melting level was below 3.0 km, A_{RH} was set to zero. The overall effect was to decrease the POD by 2 percentage points, decrease the FAR by 5 percentage points, and increase the CSI by 2 percentage points.

An evaluation of the accuracy of the Maximum Expected Hail Size (MEHS) parameter was conducted using 430 hail reports from 45 storm days and diverse regions of the country. For each report, a 20 minute time window running from T-15 to T+5 minutes (where T is the time of the report) was used to determine the appropriate value of each radar-based predictor. Since each hail report is assumed to be the maximum size observed at that time and location, the maximum value of each radar-based predictor within the 20 minute time window was selected to correlate with the hail report. At present, three radar-based predictors have been evaluated [the Severe Hail Index (SHI), ΔV (storm-top divergence), and cell-based VIL]. For each predictor an individual MEHS model was developed. The performance of each model was determined by calculating an average weighted error for all 430 hail reports. Interestingly, the average error for VIL is much higher than the errors for SHI or ΔV. Also, the best performance can be obtained by combining predictions of maximum size from both the SHI and ΔV models (i.e., using both reflectivity and velocity information).

e. DAMAGING DOWNBURST PREDICTION AND DETECTION ALGORITHM

NSSL has developed an experimental Damaging Downburst Prediction and Detection Algorithm (DDPDA) that identifies precursors to downbursts, allowing predictions of damaging downburst events, and providing time trends of the precursors. The algorithm examines the radial velocity data for areas of mid-altitude convergence, storm-top divergence, and mid-altitude rotation (all of which have been shown to be precursors to downbursts). Another parameter is the rate of change of the height of maximum reflectivity within the storm. All parameters are used as input to an empirically-developed relationship to determine whether a given storm is capable of producing a downburst within the next 15 minutes. A prediction can be made for either a moderate (wind > 30 knots) or severe (wind > 50 knots) event. If moderate or severe near-surface divergence is found to be associated with a storm, a detection is declared.

During the summer of 1994 and 1995, the DDPDA was tested operationally in the Phoenix, Arizona NWS Forecast Office. Even though the algorithm is still in the early development stages, it has relatively good skill, and real-time operational users have provided favorable feedback. Future work on this algorithm will include testing the algorithm on a larger, more diverse data base as well as enhancing the capability to detect individual precursors. Near-storm environmental information may be included in an attempt to increase the lead time of predictions.

f. NEAR-STORM ENVIRONMENT ALGORITHM

A Near-Storm Environment (NSE) algorithm has been created to provide WSR-88D algorithms (e.g., HDA, MDA, and TDA) information of the storm environment. The current version of NSE incorporates output from the Rapid Update Cycle (RUC) model, which produces hourly surface analyses and three hourly upper-air analysis including 3 hour forecasts out to 12 hours on a 60 km resolution grid. Using RUC output, NSE calculates stability parameters [e.g., Convective Available Potential Energy (CAPE), Convective INhibition (CIN), Level of Free Convection (LFC), Equilibrium Level (EL), etc.] for 3 parcels (a surface parcel, the most unstable parcel in the lowest 300 mb, and an average parcel determined for the lowest 100 mb). Each algorithm-detected storm is matched with the stability parameters of the nearest grid point. In addition, algorithm-deduced storm motion information is combined with RUC output to estimate the storm-relative helicity.

g. VELOCITY AZIMUTH DISPLAY AND VAD WIND PROFILE ALGORITHM

There have been several reported instances where the VAD Wind Profile (VWP) has not matched the wind profile observed by a rawinsonde balloon. It has been proposed that a different range be used for the VAD calculations. Suspected cases from five different WSR-88D radars have been selected for analysis. The VAD_RANGE parameter is being systematically varied from 5 to 50 km in increments of 5 km to determine the impact on the VWP.

3. Radar Data Processing Systems

a. WSR-88D RADAR INGEST AND DATA DISTRIBUTION SYSTEM

The NSSL Radar Ingest and Data Distribution System (RIDDS) is a RISC-based workstation that provides users with a means for accessing the WSR-88D Level II data stream in real time. The system currently 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.

b. WARNING DECISION SUPPORT SYSTEM

NSSL has developed the capability to run a full suite of algorithms in real time and to display the output in a novel way for forecaster interpretation. This concept, called a Warning Decision Support System (WDSS), is designed to read the Level II data stream (RIDDS output) and run the algorithms that have been previously discussed. Algorithm outputs and other radar data products are available for display using the Radar Analysis and Display System (Section III.F.3.d). This system also takes advantage of other operational data streams and integrates this information to provide a more complete diagnosis of storms.

Several real-time operations of the WDSS have been conducted during the past year (Phoenix, Fort Worth, Atlanta, and Pittsburgh). These proof-of-concept tests place the new and enhanced algorithms in the NWS Forecast Offices for a qualitative comparison with the current WSR-88D algorithms. These tests have been enthusiastically received. Not only do the tests provide an opportunity to evaluate the regional variability of the radar algorithms, but they also provide a means for the forecasters responsible for issuing warnings to have direct input in the development of the tools they will be using.

c. WSR-88D ALGORITHM TESTING AND DISPLAY SYSTEM

The WSR-88D Algorithm Testing and Display System or WATADS was developed for the Scientific Operations Officers (SOO's) of the NWS. This tool is an off-line version of the WDSS system that can be used to perform adaptable parameter studies (with the added capability of running and displaying both the WSR-88D baseline and NSSL enhanced algorithms) or to perform case study analyses from Level II WSR-88D data tapes. The user has the ability (through a graphical user interface) to change adaptable parameters and input soundings before running the software. The WATADS software also includes a version of Radar Analysis and Display System (RADS, created specifically for this task.

d. RADAR ANALYSIS AND DISPLAY SYSTEM

The Radar Analysis and Display System (RADS) software allows easy viewing of radar data and algorithm products for both real-time testing and as a post-analysis research tool. This past year has seen the addition of storm-relative velocity images and time-height trends of MDA output. The ability to display the VWP and a hodograph has also been added. Another capability permits the display of GOES-8 satellite data and the overlay of radar algorithm outputs (e.g. storm cell ID's, mesocyclone detections, damaging winds, ... etc.) on the satellite images. Continued enhancement is expected to increase functionality and utility for both real-time and post-analysis use.

e. INVENTORY OF WSR-88D LEVEL II DATA

Over 500 Level II data tapes are contained within the NSSL archives. A task was begun for indexing, relabelling, and cataloging all of the tapes. In addition, a number of tapes have been acquired with the cooperation of the National Climatic Data Center. Verification reports for each Level II tape are also being assembled. This has been accomplished by using the SEvere Local Storm (SELS) Smooth Log as the verification source. All severe weather events that occur within 230 km of a WSR-88D are saved and are used to identify candidate Level II datasets for case studies and algorithm testing. So far, approximately 450 tornado events, 2000 hail events, and 1000 severe wind events have been identified for the Level II data that have been assembled at the NSSL and OSF.

4. Radar Data Preprocessing Techniques

a. RADAR POLARIMETRIC TECHNIQUES

NSSL continues to collect polarimetric weather radar data in rain and winter storms. Rain events relating to convection, stratiform precipitation, and stratiform precipitation with imbedded convection have been recorded. Analysis and comparison with rain totals obtained by the Oklahoma mesonetwork is in progress. Initial comparisons with a micronetwork of 42 densely spaced raingages (one per ~25 km^2) indicates that significant improvement in estimates of rain accumulation can be obtained with the use of specific differential attenuation. The percentage error of total accumulations in 15 different events is 15% for the method that uses specific differential phase and it is 100% for the conventional Z-R method.

An investigation of polarimetric radar measurements to discriminate snow type continues. It appears that vertical profiles of reflectivity factor, differential reflectivity, and specific differential phase can be used for that purpose. In the five cases examined the profiles clearly indicated wet aggregates and dry snow crystals. The snow-rain transition zone is delineated with a decrease in the cross-correlation coefficient (ρ_{HV}) between horizontally and vertically polarized echoes.

b. VELOCITY DEALIASING ALGORITHM

A study was conducted in 1994 which sought the optimization of adaptable parameters within the Velocity Dealiasing Algorithm (VDA) using a limited dataset with six different Nyquist velocities. The study evaluated the different adaptable parameter settings applicable to each Nyquist interval. Although the data set was small, significant differences in the statistical optimization occurred with the different Nyquist velocities; thus separate values of optimized parameters were produced for each Nyquist velocity. Additional datasets are being prepared to further test these adaptable parameter changes for the range of Nyquist velocities expected with the WSR-88D system.

A study was also performed which detailed the testing of several different module configurations of the VDA in an attempt to statistically improve the output of the algorithm when compared to manually truthed data sets. Several convective cases and one clear-air data set were examined. It was concluded that the VDA performed best when given a previous radial for comparison which contained data at all radar velocity gates along with a radial-by-radial loading of adaptable parameters dependent on the Nyquist velocity. Providing data at each velocity gate was accomplished by "building" a previous radial from the actual velocity data where present, and using VAD winds where the velocity data were missing. This configuration, while producing the best statistical performance of the cases examined, still showed many areas which needed improvement.

Consequently, a VDA fault analysis study was undertaken. This visual analysis examined all scans of the in-house data sets for problems using the newly released Build 8 version of the VDA. Faults were classified into several categories along with the reason suspected of causing the fault. Since the fault analysis report, emphasis has been placed on tracking down and correcting problem areas in the code which are responsible for the faults. The code has been modified and new adaptable parameters have been added. This analysis, along with the recommended code changes, have shown continued improvement in the statistical and visual output of the VDA.

c. MULTI-PRF DEALIASING ALGORITHM

A unique data set of WSR-88D data was collected to determine if multiple scans of varying PRF (while keeping the elevation constant) could be combined to reduce the amount of range folded velocity data and effectively extend the unambiguous velocity of the data. A process was developed to read the new data and a prototype algorithm was developed to test the procedure. The algorithm was designed to examine all possible outcomes and evaluate them to determine the most realistic output value. The prototype algorithm greatly reduces the amount of range folded velocity data while reducing the amount of aliased velocity data. (It is unclear at this point how well the velocity dealiasing portion of the prototype algorithm compares to the current VDA.) Some velocity dealiasing errors were observed when storm motion significantly changed the velocity value in a range bin between successive scans. More data from different storm situations have been collected and are awaiting study.

G. NOAA National Weather Service (Regional Offices)

1. Eastern Region

a. INTRODUCTION

The NWSFO in Pittsburgh, Pennsylvania is involved with a project to use the WSR-88D precipitation estimates to determine the potential for flash flooding over small stream basins. The NWS Forecast Office at Buffalo, New York has developed software, called BUFRAD, to mosaic WSR-88D reflectivity data from adjacent radars. Personnel at the North East River Forecast Center (RFC) have developed UNIX workstation software to mosaic WSR-88D precipitation estimates over the RFC's entire area of responsibility.

b. BASIN ESTIMATED RAINFALL

The Areal Mean Basin Estimated Rainfall (AMBER) flash flood warning system uses digital WSR-88D rainfall estimates from a high-resolution polar grid. The grid data are created from the hybrid scan reflectivity generated by the Precipitation Processing System (PPS) algorithm running on the Science and Applications Computer (SAC) HP UNIX workstation. These algorithms were programmed on the SAC and are networked with the RADS workstation. The RADS computer accomplishes the data collection from the Radar Product Generator (RPG) via an interface with the RIDDS workstation, and the hybrid scan output is written to the SAC workstation.

The PPS algorithm on the SAC produces a digital 5-6 minute rainfall product with 1° x 1 km resolution for each volume scan. Rainfall accumulations are quantified to the nearest 1 mm. After the digital rainfall map is produced from each volume scan, the AMBER software computes basin average rainfall for

86 principal areas,

35 major streams (areas > 200 square miles),
1155 primary flash flood streams (areas < 200 square miles),
1260 subdivision flash flood streams, and
140 urban areas susceptible to flash flooding.

Basin average rainfall data for each area are archived to the SAC hard disk for each volume scan. Average rainfall estimates are compared to flash flood guidance for each county, and an alarm message is written to the screen of the SAC for any basin that has basin average rainfall in excess of 60 percent of flash flood guidance. Forecasters can request stream information for any basin in the data base and examine rainfall estimates for time periods from 5 minutes to 24 hours.

In order to implement AMBER, a basin analysis for flash flood prone streams must be included in the data base. The analysis matches the 1° x 1 km WSR-88D grid to user-defined stream basins. With the introduction of WSR-88D Software Build 9, a digital rainfall product will be produced each volume scan with a resolution of 1° x 2 km. The use of a 30 minute (or longer) product update interval would result in reduced lead time for flash flood warnings. An AMBER User's Guide is in preparation.

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2. Southern Region

a. COMBINED SHEAR PRODUCT STUDY

The Weather Service Forecast Office in Little Rock has begun to look at the Combined Shear product for the identification of small scale features including frontal vortices (gustnadoes) and small tornadoes that go undetected by the existing algorithms. A tornadic event on November 11, 1995 near Des Arc, Arkansas provided impetus for the study. The Combined Shear product depicted a subtle vortex signature. A mesocyclone was not detected by the radar or identified by the operator before tornado touchdown. Tornado formation was very sudden and may have been connected with a vortex moving northeastward along a line of thunderstorms. Two people were killed by the storm. A severe thunderstorm warning had been issued. TVS signatures in other storms well to the southwest distracted attention away from the Des Arc storm.

The Combined Shear product also has been used with some success in identifying "shear zones" for commercial aircraft in the Little Rock terminal area. The shear observations have been passed to local approach control and to the Center Weather Service Unit at Memphis for their use. At least one pilot report of moderate to extreme turbulence was received after an observation was passed along.

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3. *Western Region*

a. WSR-88D PROOF-OF-CONCEPT PROJECT

The National Weather Service Western Region has begun a project to optimize WSR-88D utilization in mountainous regions. The National Severe Storms Laboratory, the NEXRAD Operational Support Facility, the Salt Lake City Weather Service Forecast Office, and the University of Utah are also participating in the project.

The NSSL's Radar Interface and Data Distribution System (RIDDS) and Radar Analysis and Display System (RADS) have been installed at the Salt Lake City WSFO. The RIDDS system allows the recording of base data at the Forecast Office which will facilitate collection of significant datasets for post analysis. Weather phenomena of interest include microbursts, damaging winds, snow storms (including lake-effect snow events), and flash floods.

Since the Salt Lake radar site is 2000 feet above the valley floor, one of the first goals of the project is to determine how well low-altitude weather phenomena are being detected. A Change Request has been submitted to the OSF lowering the lowest tilt from 0.5 to 0.2 degrees. Once a "test" Volume Coverage Pattern is implemented, the detectability of low-altitude weather will be reevaluated. Work is planned to optimize the WSR-88D PPS algorithm. Currently, radar bright bands and beam blockage result in discrepancies between radar precipitation estimates and raingage measurements.

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H. NOAA Techniques Development Laboratory

1. *Detection of Severe Local Storm Phenomena by Interpretation of Radar and Storm Environment Information*

Many operational features of the WSR-88D were incorporated specifically to aid forecasters in the detection of severe local storms (damaging winds, large hail, and tornadoes). One interpretive product, the Severe Weather Potential (SWP) algorithm, yields an index proportional to the probability that an individual thunderstorm cell will soon produce any type of severe weather phenomena. The SWP is based solely on radar information, namely vertically-integrated liquid and storm horizontal extent.

Forecasters have long known that critical values of many radar indices for severe weather change with the storm environment. In particular, shallow storms with moderately high VIL values are much more likely to produce severe weather in the spring than in the summer. Consequently, an automated solution was sought for the problem of adapting severe/nonsevere VIL thresholds to environmental conditions. In particular, new algorithms have been developed that incorporate radar data and estimates of upper-air temperature and wind vectors. The algorithms yield probabilities of severe weather and large hail occurrence within the vicinity of a thunderstorm and are valid within a square region 44 km on a side and for 30 minutes after the radar observation. Comparative verification tests indicate that the new radar/environmental severe weather algorithms produce 10-15% fewer false alarms than does the operational SWP algorithm.

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1. Kitzmiller, D.H., and J.P. Breidenbach, 1995: Detection of severe local storm phenomena by automated interpretation of radar and storm environment. NOAA Technical Memorandum, NWS TDL-82, 33pp. (Appendix D) (An abridged version of this report is reviewed in the Bibliography Section.)

2. Quantitative High-Resolution Rainfall Forecasts by an Extrapolative-Statistical Method

A common approach to short-range precipitation forecasting involves the extrapolation of gridded radar reflectivity fields. As a refinement of the basic technique, a large number of extrapolative, 0-1 hour rainfall amount forecasts were prepared and then statistically correlated with a 4 x 4 km analysis of the rainfall observed during the valid period. The relationships between the purely extrapolative forecasts and the observed rainfall amounts are then be used in interpreting other extrapolative forecasts prepared in real time. This extrapolative-statistical approach to rainfall forecasting implicitly accounts for echo decay and uncertainty in the extrapolation process and employs statistical techniques often used to produce forecasts of sensible weather from the output of numerical weather prediction models.

The initial phase of this study was based on RAdar DAta Processor II (RADAP II) observations collected at Oklahoma City, Oklahoma. The verifying rainfall analyses were derived by applying the WSR-88D Z-R relationship to radar observations during the validation period. The echo velocity used for extrapolation was estimated by pattern matching within a sequence of images during the 30-minute period prior to the forecast initial time. In practice, the extrapolative-statistical algorithm produces the probabilities that the 1 hour rainfall will exceed 0.1, 0.25, 0.5, and 1 inch in each 4 km grid box. These probabilities are functions of the extrapolative 0-1 hour rainfall forecast, the 0-1 hour vertically-integrated liquid (VIL) forecast, and the 0-30 minute rainfall forecast. A categorical rainfall amount forecast for each grid box is then produced by comparing the probabilities to preset thresholds. The categorical forecasts are for amounts in the five intervals < 0.1, .1-.24, .25-.49, .5-.99, and ≥ 1 inch.

Because it utilizes a variety of statistical predictors of rainfall, the extrapolative-statistical method yields measurable improvement over purely extrapolative techniques. For categorical forecasts made with the dependent data sample, 31% of the forecasts for amounts > 0.1 inch were in the correct category and 82% were within one category of the correct one. For a limited number of independent cases, utilizing WSR-88D Level II data, we found that 32% of the forecasts were correct and 82% were within one category.

I. U.S. Air Force Phillips Laboratory

1. A Short-Term Cloud Forecast Scheme Using Cross Correlations: An Update

A trajectory-based cloud forecast technique based on cross correlations has been used to generate a set of loopable forecast IR images that are nearly indistinguishable from the real images. Importantly, the methodology can be run in a few minutes on current generation work stations. Advective velocities are generated through cross-correlation matching of multiple subsets of the two frames. The technique is an excellent candidate for transition to operational use in base station environments and as a "first-in" tool, when the use and/or availability of many conventional data sources may be restricted. The only data required to produce forecast images several hours into the future are two IR satellite images spaced not more than one hour apart. Recent work focused on improving the scheme by eliminating (or reducing) previously reported problems including spurious advection of terrain, contamination at the edges of the image domain, and lack of procedures to infer cloud development and dissipation.

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2. Mesocyclone Modeling

A long outstanding and important problem is the distinction between tornadic and non-tornadic mesocyclones. Part of the problem is believed to be with the oversimplification inherent in current conceptual single-Doppler mesocyclone models. It is conventional to assume a circular flow pattern in the interpretation of mesocyclone data where vorticity is uniform within the core region and zero elsewhere. However, experience shows that the circular model represents only a first-order approximation to the mesocyclone flow. Moreover, multiple Doppler analyses often show that mesocyclone flow fields can depart significantly from the circular pattern and may have complex vorticity structures. Phillips Laboratory has been working on an improved mesocyclone model (the "elliptical mesocyclone model") to accommodate the observed variations in physical shape and the internal structure of the vorticity and divergence fields.

The elliptical model has been developed and tested on data from the 1977 Del City, Oklahoma mesocyclone. One result of this work is that the distribution of divergence and vorticity within the mesocyclone core is related to the shape of the neutral (zero) Doppler contour that separates the mesocyclone velocity peaks. Multiple-Doppler analysis indicates that the mesocyclone undergoes tremendous evolutionary changes in the structure of vorticity and divergence fields prior to tornadogenesis. It is possible that these changes may be monitored with single-Doppler data.

During fiscal year 1996 the process of fitting the elliptical mesocyclone model to single-Doppler data will be automated. The model will be applied to mesocyclone cases collected with the WSR-88D. Emphasis will be on interpreting evolutionary changes in mesocyclones within tornadic and non-tornadic storms.

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J. MIT Lincoln Laboratory

1. Data Acquisition Rate Needs and Strategies

a. CLUTTER AND DEALIASING PROBLEMS

The Federal Aviation Administration's (FAA's) Integrated Terminal Weather System (ITWS) (under development by Lincoln Laboratory) utilizes NEXRAD data in the generation of a number of graphical and alphanumeric "products" for air traffic control supervisors, traffic planning specialists, and airline operations personnel. These include precipitation reflectivity maps, real-time "dual-Doppler" gridded winds, and information on severe storm features such as hail and mesocyclonic circulations.

One significant issue encountered in the use of NEXRAD data by ITWS has been high levels of ground clutter residue near the radar and broad-area clutter on the low-elevation angle tilts during conditions of anomalous super-refractive propagation conditions. While NWS meteorologists utilizing NEXRAD data can recognize these artifacts and ignore them, the ITWS automated algorithms are not designed to cope with time varying levels of clutter in their input data streams. Similarly, non-meteorologist aviation users of NEXRAD composite products such as Flight Service Station specialists advising general aviation pilots have found clutter contamination (especially that due to AP) to be a significant operational problem. The problem is particularly acute when the AP arises from cold outflows due to thunderstorms near the radars. In such cases, the NEXRAD Information Dissemination Service (NIDS) vendors typically cannot edit AP on the basis of satellite data nor do the users expect to see AP induced false storms in close proximity to actual storms.

Since the current ITWS prototypes utilize wideband communications links to ingest NEXRAD base data, surrogate NEXRAD "products" have been generated that include appropriate clutter prevention. For the ITWS 1994 Demonstration/Validation (DemVal) testing at Memphis, Tennessee and Orlando, Florida one or two low-elevation tilts from "layered" or "composite" reflectivity products were excluded on a range-dependent basis in essence establishing a lower bound of 2 km Above Ground Level (AGL) for reflectivity data used to create the layers. The procedure effectively edits AP out to a range of approximately 130 km from the NEXRAD. This was operationally useful in the ITWS DemVal testing at Memphis and Orlando. However, the technique was not adequate at Dallas/Ft. Worth, Texas where there are major aircraft merging fixes 200 km and 240 km from the airport.

Accordingly, we are actively investigating several other options for editing AP at longer ranges where the bottom tilt may be the only tilt at which an operationally significant storm cell is observed during normal propagation conditions. Possible solutions could involve:

1) Flagging of echoes with low mean-Doppler velocity and spectrum width as likely ground clutter. This technique has proven successful in eliminating AP-induced clutter from reflectivity maps generated by the ASR-9 Weather System Processor (WSP).

2) Storm motion (or lack thereof).

3) Clutter patch optimized texture discriminants where the AP clutter parameters associated with a region are "learned" during times when only AP is present (e.g., with evening or early morning radiative cooling).

An initial editing algorithm for the FAA composite layer product based on a site-adaptable lower limit for the layer (typically 2-3 km) and low velocity/spectrum width was sent to the OSF in November 1995 for inclusion in Build 10. Evaluation of the motion and texture editing editors should be completed by June 1996.

2. Interpretive Techniques

a. GENERATION OF TEXT AND CHARACTER GRAPHICS MESSAGES FOR PILOTS

Pilots in flight currently access Surface Aviation Observations (SAO's) over the Aircraft Communication Addressing and Reporting System (ACARS) data link to get updated information on weather at their destination airport. Algorithms have been developed to provide improved terminal weather information by analysis of TDWR data that could be utilized by NEXRAD to provide information at non-TDWR airports.

Two types of Terminal Weather Information for Pilots (TWIP) messages currently generated are a text-only message and a character graphics map. In order to ensure their operational utility, these products were developed in consultation with a group of experienced pilots. The TWIP Text Message is intended for typical ACARS cockpit displays, which are roughly 20 characters wide by 10 lines high. The TWIP Character Graphics Depiction is intended for the cockpit printers available on some aircraft that are at least 40 characters wide. Both products provide strategic information to pilots about terminal weather conditions to aid flight planning and improve situational awareness of potential hazards.

The TWIP Text Message consists of four sections: header, runway impact, current storms, and expected/previous conditions. The header provides the airport identification and the report time in Greenwich Mean Time, plus a line identifying the message as terminal weather information. The second section indicates whether any active runway is impacted by a microburst, gust front, or moderate or heavy precipitation (VIP level 2 or above).

The third section indicates whether any storms (VIP level 2 or greater) are within 15 nm of the airport. The first line of the text indicates the presence of one or more storms. The next lines list the three closest storms to the airport reference point. If more than one storm exists at a given range, then the most intense is listed first. Each storm is described in terms of distance to the reference point (in nautical miles), azimuthal extent, and intensity (moderate or heavy precipitation). The azimuthal extent is given in terms of starting and stopping compass octant (e.g., NE) in the clockwise sense; if the storm is less than 1 nm from the airport, then the azimuth is given as all quadrants (ALQDS).

The fourth section of the message indicates if there is expected precipitation, previous wind shear or microburst, or no storms within 15 nm of the airport. Expected precipitation times are determined by linear extrapolation of the current precipitation locations using correlation tracker storm motion estimates. If moderate or heavy precipitation is expected at the airport within 20 minutes, then the expected precipitation line is issued, followed by a line showing the time the precipitation impact is expected to start. If more than one type of precipitation impact is expected, then only the most severe expected impact will be shown. Also, the expected precipitation must be more severe than the current runway impact in order to be displayed.

If there was a previous microburst or wind shear runway impact event, the fourth section will note the previous impact (also indicated by a leading period) plus the beginning and ending time of the impact on the following line. When there are no storms within 15 nm of the airport or any runway impacts, the message consists of the single line "NO STORM WITHIN 15 NM".

The TWIP Text Message is generated once per minute whenever weather is near the airport. When there is no weather within 15 nm, the update rate drops to once very 10 minutes.

b. CHARACTER GRAPHICS DEPICTION

The TWIP Character Graphics Depiction has moderate precipitation indicated by "-"; heavy precipitation indicated by a "+"; and microbursts indicated by the letter "M". A gust front impacting the airport is indicated by "G"s. The runway location is indicated by "X"s, except where the gust front impacts them as indicated by an asterisk (*). [A key to the symbols is provided.] Other features are horizontal and vertical distance scales in nautical miles and storm motion information.

A detailed comparison for two significant weather events (one at Orlando and one at Memphis), each lasting approximately two hours, was done between the TWIP messages and the corresponding SAO. It was found in every case that the TWIP messages provided more accurate and timely information than the SAO. In general, it has been found that the surface aviation observation is often late in depicting terminal weather hazards (especially in rapidly evolving situations), provides less information than TWIP (e.g., distance to storm, speed of movement, wind shear hazards), and frequently continues to depict hazardous weather conditions up to an hour after the weather condition has ceased to exist.

Work is in progress on a proposed implementation of the TWIP functionality as a retrofit to the operational TDWRs. Under this approach, the TDWRs would generate TWIP products and provide TWIP and TDWR products to users via the National Airspace Data Interchange Network.

c. NEXRAD REFLECTIVITY DATA COMPRESSION FOR COLOR COCKPIT DISPLAY

Important information needed by pilots of general aviation aircraft is the location and severity of hazardous weather. The Mode Select (Mode S) data link has the capability to provide this weather information directly to the pilot. Low cost Mode S data link avionics and associated data link applications in combination with the Mode S data link offer the potential to improve safety for general aviation.

Reduced costs for full color cockpit displays and data links are making it feasible to display NEXRAD reflectivity products in a cockpit. However, the direct transmission of NEXRAD data would require far more bandwidth than is currently available with any practical data link implementation. A need clearly exists for considerable data compression to permit routine transmission of weather graphics to the cockpit.

Two specialized image compression algorithms have been developed that maintain the overall morphology of weather images while maintaining reasonable image data size. The Polygon-Ellipse algorithm exploits the inherent geometric shape of the weather phenomena by representing them as a series of polygons and ellipses rather than discrete pixels. Instead of transmitting the large amount of data required to describe the individual pixels, the algorithm needs to transmit only the location and shape of the geometric forms that make up the image for reconstruction on the aircraft display. By using the Polygon-Ellipse algorithm, we can take an image that requires 131,000 bits to transmit and reduce it to less than 2400 bits, which is a message size that can be transmitted to an aircraft from the rotating antenna of a Mode S surveillance sensor in two scans (roughly 10 seconds).

The Weather-Huffman algorithm employs a Hilbert transformation of the NEXRAD reflectivity followed by a Huffman coding to achieve data compression. In cases where a large number of weather features necessitate further compression, the Weather-Huffman algorithm reduces the spatial resolution of the NEXRAD image while retaining gradient information prior to the Hilbert transformation and Huffman coding. A typical 131,000-bit NEXRAD image is reduced to approximately 2400 bits with this technique.

Extensive human factors investigations have been carried out to show that the key information required by the pilots for flight route decision making is retained in the image compression process. Additionally, an ongoing, real-time in-flight demonstration using NEXRAD mosaic data began in the Washington, D.C. area during the summer of 1995. In 1996, this program will be expanded to the full northeastern part of the country.

3. Gridded Winds Analysis

Lincoln Laboratory has developed Terminal Winds, a 3-D gridded wind analysis for ITWS (Cole and Wilson, 1995; 1994). This product provides wind estimates on a grid with a horizontal resolution of 10 km and an update rate of 30 minutes, and a grid with a horizontal resolution of 2 km and an update rate of 5 minutes using data from TDWR and NEXRAD Doppler weather radars, surface stations, and aircraft. The key element in supporting the high space-time resolution is the use of Doppler radar data.

The analysis procedure used in Terminal Winds is based upon a least squares technique that directly analyzes Doppler data to extract the maximum amount of information. The technique is closely related to both optimal interpolation and standard multiple Doppler analysis methods. The technique more fully utilizes the information contained in the Doppler data than other multiple-Doppler techniques such as the Local Analysis and Prediction System (LAPS) (Cole et al. 1993). Also, there is potential to produce a quality VAD-like wind estimate from datasets which are too sparse to produce useful estimates from traditional VAD algorithms. Additional upgrades to the wind analysis are being considered to allow the analysis to estimate derivatives of the horizontal wind fields and to enhance its utility for specific applications. Potential applications of the Terminal Winds technique include forecasting the initiation, growth, and decay of convective weather, forecasting damaging winds, and use as input to numerical weather prediction models.

ITWS systems will be located at airports with a combination of frequent convective weather and a large volume of air traffic. The spatial domain of the ITWS Terminal Winds product includes approximately 40 percent of the U.S. population and covers regions likely to experience severe weather.

4. Gust Front Detection and Tracking Using the Machine Intelligent Gust Front Algorithm

Together with the FAA, Lincoln Laboratory has developed a Machine Intelligent Gust Front Algorithm (MIGFA) that provides real-time detection and tracking of thunderstorm gust fronts and other wind shift boundaries (such as sea breeze fronts). Input includes radar reflectivity and radial velocity information provided by radars such as the Terminal Doppler Weather Radar (TDWR), the Airport Surveillance Radar with Weather System Processor (ASR-9 WSP), and the WSR-88D (NEXRAD). MIGFA would be suitable as a primary component of the NEXRAD "damaging winds" product.

Previous generation gust front detection algorithms developed for TDWR (and currently being tested by NSSL for NEXRAD) have relied on one-dimensional (radial) fixed thresholding of Doppler velocity imagery to detect convergent shear boundaries. These techniques have provided modest performance where gust fronts are oriented favorably for Doppler detection and signal-to-noise ratios are high enough to generate reliable clear-air velocity estimates. However, they do not take full advantage of all the information contained in Doppler radar imagery (e.g., reflectivity thin lines and feature motion). By contrast, MIGFA uses multi-dimensional, knowledge-based signal processing techniques developed by Lincoln Laboratory to recognize and track gust fronts with Doppler weather radar data.

Briefly, the algorithm works as follows. Reflectivity and velocity data are passed through a series of feature detectors that look for a variety of gust front signatures in radar data (reflectivity thin lines, velocity convergence, thin-line motion, convergence motion, etc.). The feature detectors employ a special technique called Functional Template Correlation to produce pixel-by-pixel maps of probabilities indicating the degree of match between the matched filter employed by the feature detector and the characteristics of the input data at the pixel location. Individual co-registered probability maps, or "interest images," are combined at the pixel level to produce a combined interest image that represents the assimilation of all sources of evidence (positive or negative) present in the radar imagery. Only after all of the evidence has been accumulated, is a threshold applied to extract the high-interest regions indicating the likely locations of gust fronts. (Delayed thresholding after full data assimilation is a key to robust detection where signatures are weak or not always present.) Tracking is accomplished by establishing point-by-point correspondence with prior detections on the basis of spatial proximity, similar motion, ... etc. A tracking history is maintained to allow construction with 1 min extrapolations of future gust front locations.

MIGFA has been extensively field tested by the FAA and Lincoln Laboratory during real-time demonstrations of the ASR-9 WSP and the Integrated Terminal Weather System. A comparison of MIGFA using TDWR data and the current TDWR gust front detection algorithm (GF88), conducted during 1993 field tests in Orlando, Florida, revealed that MIGFA substantially out performed GF88 both in terms of "hit/miss" probabilities (POD and FAR) as well as the more qualitative length-based scoring metrics: Percent Length Detected (PLD), and Percent False Length Detected (PFD). See (Troxel and Delanoy, 1994) for details. As part of on-going ITWS research, a version of MIGFA has been configured to operate on WSR-88D data that would be suitable as a primary component for a NEXRAD "damaging winds" product as well as being a forecaster aid for convective initiation forecasts.

MIGFA was constructed using SKETCH, a computer environment developed at Lincoln Laboratory for the rapid prototyping of algorithms. SKETCH is based on Austin Kyoto Common Lisp (AKCL version 6.05), which is a public domain implementation of Common Lisp that complies with the ANSI Common Lisp Standard. The algorithm has been run on a SUN SPARC station running SunOS 4.1.3. Efforts are currently underway to increase software portability and maintainability through re-coding of the algorithm in the C++ language.

5. Structure Analysis Detection and Feature Tracking Techniques

a. STORM TRACKING

The current ITWS cell tracking algorithm is based on the TDWR cross-correlation tracking algorithm which uses image pattern matching to determine the most likely spatial shift in an image feature within a bounded area. The technique performs well with splitting and merging cells. The original TDWR tracking algorithm used precipitation data from a single radar (TDWR) and generated a single product (storm motion vectors) for display.

Prior to the ITWS 1993 real-time demonstrations in Orlando and Dallas/Ft. Worth, the tracking algorithm was expanded to take in data from a variety of radars. For the past three summers, the ITWS storm motion algorithm has been running at various ITWS [Orlando, Memphis, Dallas/Fort Worth) and WSP (Albuquerque, New Mexico)] sites generating storm motion vectors from NEXRAD as well as ASR-9 radar data. In 1993, the Storm Extrapolated Position (SEP) display product was added to provide a graphical representation of future storm positions based on current motion estimates using ASR-9 radar data. This year in Albuquerque, the SEP product also was generated from NEXRAD-like radar data. As part of the development of the Growth and Decay product, work continues to determine how to set the available tracking parameters to capture storm envelope motion instead of the storm cell motion currently required by ITWS.

b. THUNDERSTORM EVOLUTION/DAMAGING WINDS PREDICTION

As part of the development of a Microburst Prediction algorithm for the FAA, Lincoln Laboratory has discovered very effective ways of mapping regions of storm growth and decay and of producing accurate 10 to 15 min forecasts of precipitation fields. This algorithm also provides estimates of the damaging surface winds produced by the outflow of these storms. The algorithm has undergone operational testing in Memphis, Dallas/Fort Worth, and Orlando (during the summers of 1994 and 1995). Further improvements in lead time for storm prediction can be gained by coupling this work with MIGFA and by developing additional precipitation and Doppler velocity structure analysis capability. This work is ongoing.

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K. National Center for Atmospheric Research

1. Research Applications Program

a. RADAR ECHO PREDICTION ALGORITHM

The Radar Echo Prediction (REP) algorithm operates on the principle of pattern matching. Although the algorithm can be used on any type of precipitation event, emphasis to date has been on predicting the motion of snow bands. The algorithm ingests two successive radar CAPPI's at 500 m altitude above the terrain. A clutter map is used to remove ground targets and the data are thresholded in both reflectivity and contiguous area to remove low reflectivities and small areas of non-meteorological echo. After this pre-processing, REP divides the latest radar image into a number of overlapping boxes. The reflectivity field within each box is then compared to all the possible locations it could have moved from at the earlier scan time. For each possible location a root mean square difference is calculated over all the grid points contained within the box. The location that contains the minimum RMS is then considered the most likely location of the box at the earlier time. The difference in location of the box at the two times and the difference in time between the two scans is then used to determine a best estimate of the velocity for that portion of the radar image. The average reflectivity within each box is also computed both at the latest time and at the earlier time to determine an intensity trend. The velocity field and trend information is used to extrapolate the radar images into the future.

REP has been used on an experimental basis during Research Applications Program (RAP) field studies over the last several years. Algorithm validation for an entire winter season is nearing completion. The algorithm will be used on an experimental basis for nowcasting winter weather in the Chicago area during the winter of 1995-1996.

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b. THUNDERSTORM AUTO-NOWCASTER ALGORITHM

For the past several years, NCAR has been developing a real-time rule-based system for forecasting the initiation, evolution, dissipation, and movement of convective storms. Radar, earth satellite, surface, and environmental sounding information are utilized. (Only the radar data are essential.) Time and space specific forecasts up to 1 hour are made. Key components of the forecast system are:

1) the detection and extrapolation of existing radar echoes,
2) the detection and extrapolation of boundary-layer convergence lines,
3) retrieval of the three-dimensional boundary-layer wind,
4) numerical model assimilation to predict future locations and characteristics of convergence lines, and
5) GOES-8 visual and IR imagery to identify cloud type.

All components of the algorithm were successfully executed in real time during the summer of 1995.

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c. HAIL DETECTION

During the summers of 1992 and 1993, NCAR conducted field programs in northeastern Colorado with the goal of evaluating hail detection techniques. The acquired dataset includes measurements from NCAR's NEXRAD-like Mile High Radar and CP-2 multiparameter radar. Verification data were provided by hail chase vehicles, a network of volunteer observers, and severe weather reports received by the National Weather Service Forecast Office in Denver, Colorado.

As a beginning, the existing WSR-88D hail algorithm and a two-part algorithm upgrade proposed by NSSL (POH giving the probability of any sized hail and POSH the probability of severe hail > 19 mm in diameter) were evaluated. Investigation showed that the CSI for the NEXRAD "hail" determinations was 0.47. When "probable Hail" and "hail" designations were considered "hail" the CSI was 0.72. For hail of any size, the POH component of the NSSL algorithm had a CSI of 0.82 at the 50% probability level. For severe hail, the POSH component had a CSI of 0.25 (the highest among all parameters tested. For severe hail, the probabilities of detection were high (60 to 98%) but so were the false alarm rates (75 to 80%). Details are described in a technical report (Kessinger and Brandes 1995).

The reflectivity-based algorithm work provides an important benchmark for the evaluation of dual-polarization and dual-wavelength techniques for detecting hail. The first phase of this effort involved the verification of the multiparameter radar signatures of hail with in situ measurements (Brandes et al. 1995).

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d. TURBULENCE DETECTION

Within the aviation community there is considerable interest in the avoidance of turbulence and the possibility of detection with weather radar. Consequently, a small program was begun at NCAR to evaluate the usefulness of the current NEXRAD turbulence algorithm (Cornman et al. 1995). Simulated WSR-88D three-layer turbulence products and a potential high-resolution upgrade are being compared to in situ turbulence measurements made with a research aircraft. Preliminary results, using the high-resolution information as an example, show relatively low correlation between aircraft and radar estimates of eddy dissipation rate (a correlation coefficient of 0.36). The correlation between aircraft measured turbulence and spectrum width was 0.46 suggesting the that current algorithm actually degrades this important information source. Both simple short-term modifications to the existing algorithm and long-term improvements in turbulence detection are being sought.

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2. Atmospheric Technology Division

a. ANOMALOUS PROPAGATION CLUTTER MITIGATION TECHNIQUES

The Atmospheric Technology Division (ATD) within NCAR is developing concepts and strategies for automatic AP clutter mitigation at the RDA level to improve the data quality of the base data stream. Much of this work is being done in collaboration with the NOAA Forecast Systems Laboratory and the NEXRAD OSF. The primary focus is to improve WSR-88D clutter processing to minimize reflectivity losses while maintaining coverage of precipitation and clear-air echoes. During the past two years we have collected and analyzed clutter data statistics from the Mile High Radar (MHR) in Denver and developed an initial AP clutter recognition scheme based on the "texture" of the radar reflectivity, radial velocity, and spectrum width data. We have also developed a reflectivity compensation technique based on a Gaussian spectrum model and its moments. In FY 95 an effort began to test and evaluate this recognition scheme as implemented in an artificial neural network structure. We have collected several cases of known AP clutter, with assistance from the OSF, on which to train and test the network. Our long range goal is to develop an AP clutter recognition algorithm that can be implemented in Build 11 (1997) which will identify areas of AP clutter which the radar operator can suppress with clutter filters, if desired. Initially, the radar operator will be an active element in the processing loop. Eventually, we expect an automatic recognition, suppression, and compensation scheme to be placed in operation. This advanced capability will likely require new processing hardware as well as software.

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b. ARCHIVE 1 DATA ANALYZER RECORDER/BASE DATA DISPLAY

ATD and FSL have designed and built an Archive 1 Data Analyzer (A1DA) which accesses the digital inphase and quadrature (I/Q) data, analyzes its spectral components, and writes data to Exabyte tape for later detailed analysis. The A1DA is a Unix client using X windows server and written in C. It is transparent and totally isolated from the RDA, thereby allowing a non-intrusive real-time digital data access and a RDA data quality monitoring capability. The digital data allows development of new RDA processing techniques and will serve as the basis for a new hardware and/or software signal processor platform.

The Level II base data (reflectivity, velocity, and width) is also accessed and can be displayed in real time on a PPI color display for data monitoring, calibration, and diagnostic work. An antenna angle readout of azimuth and elevation is a part of the interface. The A1DA is being used at the OSF testbed radar KOUN3 for diagnostic tests and data monitoring. A second unit is being constructed in FY 96 for use by ATD and FSL in acquiring AP clutter data.

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c. NETWORK CALIBRATION TECHNIQUES

ATD and FSL have reviewed the technical need for a network level reflectivity calibration procedure and identified an engineering strategy for initiating and performing this calibration. We have determined that a comprehensive calibration project is required to maintain and improve the accuracy of the radar precipitation products. Furthermore, as data from multiple radars become widely used, reflectivity differences due to adjacent mis-calibrated radars will provide limitations in generating mosaics of quantitative reflectivity-based products.

The study concludes that large economic benefits will accrue from small percentage improvements in reflectivity accuracy, that cost-effective methods can be implemented for assessing and regulating calibration variation at the network level, and that an automated calibration procedure is necessary for maintaining an accurate network level calibration. The study recommends that an engineering calibration action team be formed which would define network calibration requirements, devise an effective work plan, perform the necessary calibration effort, and validate the network calibration procedure.

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d. KOUN3 TESTBED RADAR INSTRUMENTATION

ATD and FSL will design, implement, test, and integrate diagnostic and performance monitoring instrumentation on the OSF testbed radar (KOUN3) in Norman, Oklahoma. The first stage of implementation, to be delivered in FY 96, will emphasize power and environmental monitoring variables. The instrumentation will likely use PC LabView software for graphics and statistical analysis of the data. The Archive 1 Data Analyzer will also be an important but independent component of this radar instrumentation.

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e. RDA "SUNCHECK" UPGRADE

ATD and FSL have investigated and recommended a number of changes to the RDA System Operability Test "suncheck" routine to allow for improved system calibration. Solar calibration aids allow network wide as well as site level calibrating of the base data reflectivity. The routine was known to have redundant terms that required manual and inconsistent corrections. Several enhancements to the software and procedures were made to allow calibration consistency improvements and to increase the utilization of the output data from the routine for calibration control. These procedures and software enhancements have been tested at KOUN3 and are being integrated into Build 10 (1996) via the OSF Configuration Change Request channel.

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f. ARCHIVE 2 RECORDING EXTENSIONS AND FORMAT

ATD and FSL have proposed to the OSF to write additional information to the Archive 2 tapes to facilitate more complete base data interpretation in 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. Messages include transmitter, receiver, and suncheck calibration parameters, site adaptation parameters, clutter filter maps and filter parameters, and supplemental scan information.

We have proposed that the OSF remove thresholding from the recorded base data (i.e, to record every range gate of reflectivity, velocity, and width, regardless of the signal to noise ratio and the local threshold value). The individual user of the base data would be able to independently specify a threshold depending on the application. We have initiated a Configuration Change Request in Build 10 (1996) for these items.

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g. RANGE/VELOCITY AMBIGUITY REDUCTION TECHNIQUES

ATD, 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 OSF and approval to begin charging is expected in FY 96. 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. We will explore four selected techniques that we believe have merit in mitigating the present range/velocity ambiguity restrictions:

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

2) Phase coding of the transmitted pulses to allow selective coherence of echoes in different range intervals.

3) Determination of the Nyquist interval of aliased velocities by analyzing and combining independent estimates from all pulses within a beam and from adjacent range and azimuth bins.

4) Use of staggered Pulse Repetition Time (PRT) techniques to extend both the unambiguous velocity and range.

Other techniques will also be explored. We will collect Archive 1 (I/Q) data from either the OSF or the Denver WSR-88D and analyze the spectra to determine whether the radar imposes limitations on any of the techniques. The emphasis will be on defining techniques that are readily adaptable to the WSR-88D for the short and long term.

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h. WET RADOME ATTENUATION CORRECTION

ATD and FSL are developing a simple technique to determine when the WSR-88D calibration (or equivalently the radar reflectivity and precipitation rate) should be compensated for wet radome attenuation. Since this loss affects both the transmitted and received power, relatively large values of 1-2 dB are typical. Additional environmental monitoring for measuring the localized rain rate is necessary.

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i. POINT TARGET CENSORING SCHEME

ATD and FSL have developed a technique for enhanced point target censoring to improve the base data quality. The technique is especially useful in removing point clutter caused by large, isolated objects on the ground, such as radio towers, or aircraft in the air. The processing was implemented as a neural network feature recognizer and suppressor.

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L. Colorado State University

1. Detection of Large Hail

a. EXAMINATION OF DUAL-POLARIZATION SIGNATURES

This work combines surface observations of large (> 2 cm) hail with simultaneous dual-polarization measurements collected by the CSU-CHILL radar. Negative ZDR values were found in the core regions of the three storms investigated. Localized reductions in the correlation between the horizontally and vertically polarized returns adjusted to zero time lag ($\rho_{HV}(0)$) and appreciable differential phase shift due to scattering appeared to result from the precipitation composition (i.e., the hail/rain fraction and the degree of asymmetry in the larger hailstones). The multiparameter hail signatures were susceptible to varying degrees of contamination due to the effects of differential attenuation and three-body scattering.

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b. MULTIPARAMETER RADAR STUDIES OF LIGHTNING IN SEVERE HAILSTORMS

A combined storm electrification and multiparameter radar dataset from a hail-producing severe thunderstorm was collected with the CSU-CHILL radar on 20 June 1994. The multiparameter data were used to remotely sense the time evolution of near-surface rain and hail rates. These precipitation trends were then compared to cloud-to-ground lightning characteristics documented by the National Lightning Detection Network (NLDN). During the time period in which the storm was generating large hail (> 2 cm), the predominant polarity of the cloud-to-ground lightning changed from negative to positive. The prevailing lightning polarity returned to negative shortly after the storm's significant hail production ceased. It should be noted that similar relationships between large diameter hail and positive cloud-to-ground lightning were found in a supercell storm observed by the CSU-CHILL radar on 7 June 1995.

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2. *Refinement of Radar Estimated Rain Rates*

a. STUDIES USING SPECIFIC DIFFERENTIAL PHASE

Raingage measurements from 20 June 1994 have been compared to rainfall estimates made by the specific propagation (K_{DP}) method. The storm generated a swath of heavy rainfall (maximum total precipitation of 3 in) across a raingage network. The K_{DP} method was generally found to give more accurate rainfall estimates than that from conventional Z-R techniques. This result was found to be true even when the radar beam was partially blocked over the gage site.

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b. MULTIPARAMETER RADAR RAINFALL ESTIMATION USING NEURAL NETWORK TECHNIQUES

A neural network has been supplied with full PPI volume scan multiparameter radar data and with rainfall measurements taken by a 20 gage network during the Convection and Precipitation/Electrification Experiment conducted in Florida during the summer of 1991. A subset of the gage observations were used to "train" the neural network in the development of quantitative relationships between the radar measurements and the surface rainfall. The radar rainfall relationships developed during the training phase were then used to develop rainfall estimates at the remaining gage locations. Four storm events were used to test this new methodology. In all cases, the rainfall estimates obtained by the neural network method were more accurate than those obtained from either conventional Z-R or Z-Z_{DR}-R relationships.

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M. Florida State University

1. Introduction

Work at Florida State University relating to NEXRAD algorithms is focused in six areas: (1) tropical algorithm development and validation, (2) precipitation estimation, (3) networking of radars, (4) evaluation of radar performance, (5) improvement of severe storm data bases, and (6) the development of a database of interesting radar events (an event catalog). A brief update on each follows:

2. Tropical Algorithms

We have developed a whole set of algorithms and products that run self-contained with no real-time input, but also allow for independent data to be input (i.e., sea level pressure). Products include storm trends, projection of hazards, and appropriate course of action. Present activity is in the assessment of these algorithms with new data, display enhancements, and flood prediction. Earlier versions of this work have been described in several conference preprints.

3. Precipitation Estimation with Radar

The focus of our work is in Florida, and by extension, the Southeast. We are looking at comparison of raingage data in Florida and comparing this with rainfall estimation by season and rainfall event type.

4. Networking of Radars

As part of the precipitation study and to provide wide-area information on rainfall rates and amounts, we are developing optimum methods of combining data from several radars to provide "seamless" and accurate precipitation estimates over all contiguous space.

5. Evaluation of Radar Performance

We completed a study on how the warning time and probability of a warning being given has varied for a sample of Weather Service Offices before and after the installation of WSR-88D's. After WSR-88D installation there was an approximately 20% improvement in the likelihood of a warning being given before tornado touchdown. There was also an increase in the average lead time. In addition to better hardware, some of the improvement may be related to staff training and changes in personnel and office management. This work has been accepted for publication in *Weather and Forecasting* and will appear in 1996.

6. Improvement of Severe Storm Data Bases

We have reanalyzed the spatial distribution of tornado frequency, removing biases due to population and proximity to Weather Service Offices. Indications are that this results in an approximate 60% increase in probable tornado occurrence. There is a corresponding adjustment in performance indicators. Preliminary results from this study will be described at the *18th Conference on Severe Local Storms,* in 1996.

7. Database of Interesting Radar Events

We are developing an on-line data base of interesting weather events observed by WSR-88D network radars. We are initially doing this for the state of Florida.

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N. Jackson State University

1. A Study of the Intrinsic and Extrinsic Characteristics of the Rain/Snow Line

The determination of the rain/snow line during the cold season is of great significance given the social and economic impacts of snow in the New Jersey-New York metropolitan area. The location and characteristics of the rain/snow line affect airport and marine operations, snow removal, emergency services, schools, and many businesses across a wide area. Unfortunately the forecast of the expected location of a rain/snow line is somewhat elusive and often based on incomplete or inadequate climatological information. Although model output can be helpful in identifying storm structures, their inconsistency in doing so and the non-static nature of the line do not allow for successful predictions in general. It has therefore been more practical to follow the evolution of the rain/snow line in a nowcast mode of operations.

In an effort to improve the forecast of rain/snow lines in the study area, it is proposed that an operationally oriented approach be used to first define their intrinsic characteristics. This may be accomplished through the use of Doppler radar imagery by assessing the temporal and spatial characteristics according to the bright-band phenomenon and velocity data in conjunction with ground truth provided by observing sites and spotter networks. The rain/snow line may be defined according to its width, movement, and orientation; and these may be related in turn to the synoptic setting and the environmental conditions. Rain/snow line structures may also provide insight for forecasts of snowfall accumulation, runoff, wash-away, and surface accumulations of slush and ice.

WSR-88D data from Brookhaven and Mount Holly, archive level II and IV (products recorded on the principal user processor), will be used to identify and monitor bright-band phenomenon for the duration of precipitation events across New Jersey and southeastern New York (including Long Island). The bright band will be examined with regard to its utility to portray the rain/snow line according to surface-based reports of precipitation type. Significant problems in identification of lines with radar imagery, such as the orientation of the line with respect to the radar beam, and microphysical parameters will also be studied. Base velocity information will be used to determine the role of wind shifts, shear zones, and perhaps coastal fronts.

Rain/snow lines will be characterized according to their initial location, orientation, shape, width, and movement. Any significant changes occurring on time scales of less than one hour; a characterization of the intensity of precipitation ahead of, within, and behind the line; and the determination of relationships to the pre-existing synoptic pattern and its temporal evolution will be studied. GOES-8 observations and surface reports will be used to determine the snow/no-snow boundary prior to and following precipitation passage and to relate the behavior of the rain/snow line to preceding and cumulative impacts. The importance of ocean water temperature distribution and mesoscale dynamic effects will also be investigated. The observed characteristics of the rain/snow line will be related to social and economic impacts. This information will then be used to formulate appropriate forecast guidance that could be provided in real-time and for planning purposes.

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O. McGill University

1. Atmospheric Remote Sensing

McGill operates a number of atmospheric remote sensors. The equipment, partly located at the J.S. Marshall Radar Observatory and partly at the downtown campus, includes:

1) an S-band Doppler radar and X-band transmitter/receiver on the same antenna (polarization diversity on the S-band will be available in a year),

2) a vertically pointing high-resolution X-band radar,

3) a UHF (915 Mhz) wind profiler and Radio Acoustic Sounding System (RASS), and

4) a ceilometer.

All remote sensors record data 24 hours a day, 365 days a year. The combination of research and operations is a unique feature of McGill's facilities.

2. Display and Algorithms

Data from the S-band/X-band scanning radar and from the UHF/RASS radar are integrated into a single software package called RAPID (Rapid data Analysis, Processing and Interactive Display), which can be used with either real-time or archived data. RAPID includes a number of display products (e.g., CAPPI and PPI images), algorithm outputs, and animation products. We briefly describe those elements that are not standard. All products in DISPLAY and

ALGORITHMS menus are generated in real time. Other items are produced interactively upon "point and click" action.

Vertical sections (VERT) in DISPLAY refer to RHI and HARPI (Zawadzki and Ballantyne, 1968) sections. These are chosen from the SELECT menu. The ANIM menu allows time animation (with a selectable number of images and time intervals) or scans through a number of heights (for CAPPI), a number of azimuths (for RHI), and ranges (for HARPI). Space resolution on CAPPI and PPI is selectable in SELECT. TIME ANIM can be applied to all ALGORITHMS functions as well. The TIME menu can also be used to select, visualize, and analyze archived data.

The ALGORITHMS menu includes precipitation forecasts (PFORECAST) obtained by using persistence and advection and by filtering out increasingly larger precipitation scales for increasingly longer forecast times (Bellon and Zawadzki, 1994). Accumulations are available at user selectable intervals and resolutions. Storm advection is obtained from vector velocities derived by cross-correlation (nine vectors are computed for the radar area). GUST algorithm, based on the work of Emanuel (1981) and Stewart (1991), is also available.

A three-dimensional wind retrieval algorithm and display for stratiform situations is under development (LINEAR WIND). It makes use of the UHF profiler data in combination with the linear wind assumption.

In addition to those displayed in the ALGORITHMS menu, two additional algorithms (MESOCYCLONE and OVERHANG) are computed as part of a supercell suite of products and displayed (usually on CAPPI's).

The GENERATE menu can be used to create vertical cross-sections along user selectable lines, a precipitation forecast at a user selectable point, and a 3-D wind retrieval obtained by the method described in Laroche and Zawadzki (1994) and Kilambi et al. (1995). Data from the UHF profiler is presently being integrated with the data of the S-band radar for the better interpretation of information. The long-term objective for RAPID is to incorporate a data assimilation cycle (see Laroche and Zawadzki, 1995).

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P. University of Oklahoma/Center for the Analysis and Prediction of Storms

1. Introduction

The Center for the Analysis and Prediction of Storms (CAPS) conducts research designed for eventual use with WSR-88D data in three areas: (1) analysis of winds over broad regions 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, which is termed Single-Doppler Velocity Retrieval (SDVR), and (3) retrieval of thermodynamic variables from a sequence of wind analyses with the Doppler radar data serving as the primary data source.

2. Model Initialization with Radar Data

CAPS adapted the Forecast Systems Laboratory's Local Analysis and Prediction System (LAPS) to work with real-time and archived Level II data streams from the WSR-88D. A Cartesian radar remapper was written to make use of NSSL's WSR-88D data reader, which ingests data from either a real-time feed through the NSSL RIDDS system or from WSR-88D archive tapes. Additionally, we have developed a more general analysis program that is designed to properly account for the varying accuracies and varying data densities encountered when the radar data are combined with other data sources. The output of one of the SDVR techniques could also be incorporated in this scheme. This analysis puts the data directly on the Advanced Regional Prediction System (ARPS). [ARPS is the CAPS non-hydrostatic numerical forecast model.] Separately, we are investigating methods for correcting phase-position errors in model forecasts using the WSR-88D data (Brewster, 1991). The goal of the radar analysis work is to produce initial conditions for ARPS so that real-time forecasts of thunderstorm initiation, movement, and development can be made. This work is currently being extended to cases from the VORTEX field experiment and is comparing forecasts with and without radar data as input. We are using these results to fine-tune the analysis procedures and aim to use radar data in real-time prediction experiments planned for the spring of 1996. We also foresee application of the model to wintertime forecast situations. The work involving LAPS is described in Brewster et al. (1995).

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3. Single-Doppler Velocity Retrieval Techniques

The SDVR research involves three separate techniques developed at CAPS as well as a comparison project that includes two other velocity retrieval techniques developed elsewhere. All five schemes are summarized in Shapiro et al., 1996. Briefly, the CAPS-developed schemes include: 1) simple adjoint applied to radial winds (Xu et al., 1995), 2) conservation of scalar fields (Shapiro et al., 1995), and 3) conservation in a moving reference frame (Gal-Chen and Zhang, 1993). Data from research radars covering several different scenarios are being used in the development and testing. These cases include a microburst, quiescent boundary-layer phenomena, multicell convection, and a severe thunderstorm (Shapiro et al., 1996). To date, the retrieval schemes have not been applied on WSR-88D data. Plans call for the modification of the schemes for acceptance of Level-II WSR-88D data and their incorporation into a package of routines for initializing the ARPS model.

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4. Thermodynamic Data Retrieval from Radar Analyses

Thermodynamic data retrieval involves applying the techniques originally put forward by Gal-Chen (1978) to the ARPS model using input from a time-sequence of SDVR wind analyses. Like the SDVR techniques, the eventual goal is to use these data as part of the ARPS model initialization package. To date, this scheme has been tested using research Doppler radar data and simulated radar data.

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Q. South Dakota School of Mines and Technology

1. Interactive Radar Analysis Software

The Interactive Radar Analysis Software (IRAS) package provides analysis and display capability of Level II data on a UNIX work station. Numerous options are available via menu selection that allow the user simple interaction with the data. A few of these options are PPI, CAPPI, RHI, VIL, vertical cross sections, echo heights, average rain rate, and area-time integrals for precipitation analyses. In addition, selections are provided for customized color graphics, animation loops, and overlay maps.

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2. Area Time-Integrals

The Area-Time Integral (ATI) technique uses the low elevation scans over a storm's lifetime to provide an estimate of total rainfall. The method, which employs a fixed threshold as a discriminator of the raining area, works well when the details of internal storm structure are not required. Very strong correlations (> 0.98) between the ATI and estimated rainfall are not unusual. The method is applicable at the storm scale and for fixed watersheds as small as 75 km^2.

References

1. Johnson, L.R., and P.L. Smith, 1994: The relationship between radar area-time integrals and areal rainfall. *Preprints, 11th Conf. on Biometeor. and Aerobiology,* San Diego, California, Amer. Meteor. Soc., J51-J54.

2. Johnson, L.R., P.L. Smith, T.H. Vonder Haar, D. Reinke, 1994: The relationship between area-time integrals determined from satellite infrared data and by means of a fixed-threshold approach and convective rainfall volumes. *Mon. Wea. Rev.*, **122**, 440-448.

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3. Scan Strategies

Optimization of scan rates and the minimum useful elevation angle for scanning have been investigated. Dwell time for reflectivity measurements is the dominant factor in determining scan cycle times. Times can be reduced by employing some integration in range, with accompanying loss of range resolution, or by easing required precision of the reflectivity data. Most of a potential increase in sensitivity to low-lying echo features could be obtained by lowering the base scan elevation to about 0.3° above the radar horizon; any further reduction would result in a significant enhancement of ground-clutter echoes and cause greater multipath interference in the elevated portion of the beam.

Reference

1. Smith, P.L., 1995: Dwell-time considerations for weather radars. *Preprints, 27th Conf. on Radar Meteor.,* Vail, Colorado, Amer. Meteor. Soc., 760-762

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R. Hughes STX Corporation

1. Evaluation of Doppler Spectrum Width in the Detection and Forecasting of Significant

Weather Events

Hughes STX (HSTX) began a new task to investigate the utility of the WSR-88D Doppler spectrum width as a parameter that may provide additional insight into detection and forecasting of significant weather events associated with storms. The initial focus is to determine those spectrum width features that are reliably identifiable within storm structures and that are significant in themselves or are correlated with other storm structures. Initial analysis has focused on a 6 hr period of heavy thunderstorm development in the vicinity of Melbourne, Florida, during March 25-26, 1992. Data were acquired from the Melbourne WSR-88D Doppler radar. This data segment includes periods of large hail, damaging winds, and heavy rainfall. Bowed radar reflectivity factor echoes, typical of nearby cell merger and/or strong wind influences are evident. Low-level forcing that results in the development of a new convective line is also observed.

Initial analysis of the WSR-88D Doppler spectrum width data shows significant structure associated with most storms. The spatial fields of spectrum width generally show good correlation with expected regions of strong forcing and precipitation growth. High spectrum width values are observed about the periphery of some, but not all, storm cores. This is in agreement with old observations of high turbulence levels associated with portions of updraft cores. On the other hand, there are unexpectedly high three-dimensional spatial correlations between very high reflectivity factor (> 45 dBZ) and spectrum width (> 8 m s^{-1}), with some three-dimensional structures branching throughout the storm volume. While some of the significant spectrum width structures clearly appear to be dominated by phenomenological influences, other regions appear to be dominated by shears in the radial velocity fields.

In storm areas of lower reflectivity factor, the spatial structure of the spectrum width field takes on the characteristics of precipitation fields; isocontours incline downwind and occupy unexpectedly large portions of the storm volumes. These observations prompted a histogram analysis of spectrum width within broad storm environments. A "quick look" at the frequency distribution of spectrum width for all storms reveals a spectral form quite similar to that of a turbulence power spectrum field, with a peak (most frequent value) near 4.5 m s^{-1}. In general, the spectrum width values are routinely spread across a range of 0.5 to 16 m s^{-1}.

To ascertain the degree of correlation between spectrum width and other factors, a series of thresholded 2-parameter histogram analyses were constructed. Initial results were unimpressive, mostly due to a lack of adequate thresholding control of input data products.

While there appears to be much useful information within the WSR-88D spectrum width measurements, the large range of data values and lackluster data quality in unfolded range areas raise some concern regarding data quality and relative importance of contributing sources.

To this aim, software is being developed to automatically estimate the shear in three dimensions, the shear contribution to the spectrum width, and the trends over time as a function of storm type, range, and location with the storm volume. In addition, the correlation between spectrum width and storm structure will be investigated. The platform employed for test and development is an HP 9000/750 running UNIX 9.1 and AVS software.

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2. Storm Structure

HSTX continues to refine and test the storm structure algorithm it has developed for Phillips Laboratory. The algorithm combines information from multiple radar reflectivity images in a B-scan format to yield the border of the Bounded Weak Echo Regions (BWER's) and Weak Echo Regions (WER's). The analyses are examined for regions of high reflectivity within the core region of supercells, for patterns of high-low-high reflectivity factor in the core region, and for gradient direction transition zones in the core region. Other parameters such as gradient magnitude are computed but have been found to be less useful.

Upon identification, areal and volumetric characterizations of the BWER/WER feature are computed. A possible additional parameter is the storm perimeter. The concept of reflectivity deficit within the BWER/WER feature using the maximum and minimum reflectivity in two and three dimensions is also being explored. Other parameters combining reflectivity factor information and areal and volumetric weighing of reflectivity are under consideration.

Testing has switched from model data to Level II data for a small number of storms. A larger database is being developed for further testing. Trends in the two and three-dimensional characterizations of the BWER/WER feature will be followed and related to the reported severe weather events. Initial testing has begun.

Reference

1. Smalley, D.J., R.J. Donaldson Jr., F.I. Harris, S.-L. Tung, and P.R. Desrochers, 1995: Quantification of severe storm structures. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 617-619.

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3. Lightning Prediction in Air Mass Thunderstorms

The goal for this task is to develop parameters that will indicate of the onset of lightning activity. There have been many studies relating the evolution of reflectivity structure to lightning but no one has attempted to adapt these studies to a real-time application. Precipitation distributions within convective storms have been correlated by others with the onset of lightning. Useful parameters, which can be monitored in real time, include the radar echo top, the rate of echo top growth, the maximum reflectivity above -10° C, and the height of maximum reflectivity within the storm. Consequently, software was written to compute areal and volumetric statistics for any three-dimensional scalar field. After applying data thresholds and identifying representative areas and volumes for each storm volume, the above parameters are monitored and assessed as to their potential for lightning prediction.

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4. Frontal Structure

An algorithm has been developed that will extract the three-dimensional structure of atmospheric fronts. The algorithm computes gradient vectors for both reflectivity and radial velocity fields. Pattern recognition techniques extract features and their derivatives from the radar data. The information is then combined into a single three-dimensional representation of the front. One of the principal strengths of this analysis technique is the availability of the gradient vector fields not only for frontal extraction but also for quantitative evaluation. The procedure has been applied to two frontal cases and shows considerable promise for evaluating changes in frontal structure and associated weather. In the coming year, the technique will be automated and tested on a large number of cases.

Reference

1. Tung, S.-L., D.J. Smalley, F.I. Harris, and A.R. Bohne, 1995: Evolution of three-dimensional frontal structure. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 488-490.

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Programmatic Reference

1. Harris, F.I., D.J. Smalley, and S.-L. Tung, 1995: Radar studies of aviation hazards. Hughes STX Corp., Scientific Rpt. No. 2, 23pp. (Appendix D)

S. LORAL Defense Systems, East

1. Three-Body Scatter Spike

LORAL continues to develop and evaluate potential techniques for possible implementation on the WSR-88D. In particular, the Three-Body Scatter Spike (TBSS), a radar artifact caused by non-Rayleigh microwave scattering when large hydrometeors are present (Lemon 1995a, 1995b), is thought to be a viable indicator for very large hail. When observed with the S-band WSR-88D, it is almost certainly caused by large hail having a substantial (10-15%) liquid water content. A sufficient but not necessary condition for large hail, the TBSS often associates with surface hail 6 cm in diameter or larger. Also, storms exhibiting a TBSS are frequently accompanied by violent winds.

2. Deep Convergence Zones

The Deep Convergence Zone (DCZ), described in Lemon and Burgess (1993) and Lemon and Parker (1995), is a vertical extension surface gust fronts in severe thunderstorms which in some storms may extend to 13 km AGL. Because radial gate-to-gate shears are so strong, velocity gates along the DCZ may be removed by the WSR-88D velocity dealiasing algorithm causing "drop-out" gates in the velocity products. Radial shear or convergence values reached 54 m s^{-1} in 250 m at approximately 4 km AGL in one storm. It has been shown that the DCZ in at least two instances was associated with surface winds of 50 m s^{-1}. Mesocyclones, TVS's, and large surface hail may also be associated with the boundary.

3. Donut Echoes

The enhanced sensitivity of the WSR-88D enables the detection of elevated non-precipitating cloud layers and even temperature inversions which appear as donut shaped rings in the radar base products (Lemon and Queotone 1995). Study shows that considerable information can be derived from these observations, i.e., the base, top, slope, and rate of descent of the layers. The lowering of echo layers has proved useful for determining the onset of precipitation--particularly snow. Similarly, the lowering of bright bands can be used to infer the moistening and evaporative cooling of underlying layers and hence to anticipate the transition from rain to snow.

4. Volcanic Ash

The possibilities for using the sensitivity of the WSR-88D radar for monitoring volcanic eruptions were studied by Krohn, et al. (1995). The authors suggest that the radar can provide estimates of the onset, type, and intensity of eruptions. In some instances, surface volcanic ash accumulation might be estimated with a "Z-ash" relationship used much like a Z-R relationship to estimate surface rainfall accumulations.

References

1. Lemon, L.R., 1994: Recognition of the radar "Three-Body Scatter Spike" as a large hail signature. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program office, 373-387.

2. Lemon, L.R., 1995: Recognition of the "Three-Body Scatter Spike" as a large hail signature. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 533-535.

3. Lemon, L.R., and D.W. Burgess, 1993: Supercell associated deep convergence zone revealed by a WSR-88D. *Preprints, 26th Int. Conf. on Radar Meteor.*, Norman, Oklahoma, Amer. Meteor. Soc., 206-208.

4. Lemon, L.R., and S. Parker, 1996: The Lahoma storm deep convergence zone: Its

characteristics and role in storm dynamics and severity. *Preprints, 18th Conference on Severe Local Storms,* San Francisco, California, Amer. Meteor. Soc. (in press).

5. Lemon, L.R., and E.M. Quoetone, 1994: Interpretation of the radar-centered "Donut" signature. *Postprints, 1st WSR-88D User's Conference,* WSR-88D Operational Support Facility, NEXRAD Joint System Program office, 102-111.

6. Krohn, M.D., L.R. Lemon, and J. Perry, 1994: WSR-88D application to volcanic ash detection. *Postprints, 1st WSR-88D User's Conference,* WSR-88D Operational Support Facility, NEXRAD Joint System Program office, 113-124.

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. For example, polarimetric measurements are regarded as being important for future radar upgrades but are considered as having low impact because the WSR-88D does not currently have dual-polarization capability. 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. "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
Bulletin of the American Meteorological Society
Journal of Atmospheric and Oceanic Technology
Journal of Applied Meteorology
Journal of the Atmospheric Sciences
Monthly Weather Review
Natural Hazards
Quarterly Journal of the Royal Meteorological Society
Weather
Weather and Forecasting
III International Symposium on Hydrological Applications of Weather Radars
1st WSR-88D User's Conference
6th Conference on Aviation Weather Systems
14th Conference on Weather Analysis and Forecasting
21st Conference on Hurricanes and Tropical Meteorology

Papers Reviewed

Antonio, M.de A., 1995: Rainfall estimates with radar: Effects of the distance, area and integration time. *Proceedings, III International Symposium on Hydrological Applications of Weather Radars*, São Paulo, Brazil, 291-299.
[Moderate impact. An interesting study in which radar estimates of rainfall were made for select integration times and ranges and then compared to gage measurements. Results show a minimum in G/R ratios at a distance of 50 km and then the usual increase with range (a factor of 2 increase at 150 km). Also, G/R ratios decreased as the area of accumulation increased from 16 to 120 km^2 and for longer averaging times.]

Atlas, D., A. Ryzhkov, and D. Zrnic, 1995: Polarimetrically tuned Z-R relations and comparison of radar rainfall methods. *Proceedings, III International Symposium on Hydrological Applications of Weather Radars*, São Paulo, Brazil, 386-395.
[Low impact. Several methods of estimating rainfall with radar are investigated. These include the Marshall-Palmer relationship, Area-Time Integrals (ATI's) using the Marshall-Palmer relationship, ATI's based upon a Probability Matching Method (PMM), and a polarimetric method using specific differential phase (K_{DP}) in combination with the Marshall-Palmer relation for low rain rates. Best results were obtained using the specific differential phase measurement. Results with the ATI method and the probability matching method were mixed. The latter test was thought inconclusive because of assumptions required to determine probability density functions of R and Z.]

Aubagnac, J.-P., and D.S. Zrnić, 1995: Identification and quantification of hydrometeors in a supercell storm using radar polarimetry. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 105-107.
[Low impact. Measurements of Z_H, Z_{DR}, and K_{DP} are compared with numerical simulations of hydrometeors (rain, solid-ice-hail, spongy hail, and graupel) for consistency. Tests are made for pure rain, pure solid phase precipitation, and for mixed-phase precipitation. The final product delimits rain, mixed phase, solid hail, spongy hail, and graupel regions within thunderstorm.]

Bluestein, H.B., S.D. Hrebenach, C.-F. Chang, and E.A. Brandes, 1994: Synthetic dual-Doppler analysis of mesoscale convective systems. *Mon. Wea. Rev.*, **122**, 2105-2124.
[Moderate impact. If a storm system moves at a near constant velocity and the storm (or a portion thereof) passes through a significant angular displacement in a time interval that is relatively small compared to the total lifetime of its larger-scale features, a dual-Doppler analysis can be performed by treating observations spaced in time as simultaneous measurements from two different radars. The proposed synthetic dual-Doppler method was applied to two mesoscale convective systems. The large-scale cyclonic circulations within the stratiform region and the general convergence within the convective zone were reproduced. Averaged winds agreed favorably with VAD analyses. Significant differences found for small-scale features were attributed to their differential motion and short lifetimes.]

Boccippio, D.J., 1995: A diagnostic analysis of the VVP single-Doppler retrieval technique. *J. Atmos. Oceanic Technol.*, **12**, 230-248.
[Moderate impact. The VVP (volume velocity processing) method for retrieving wind fields is examined. Sensitivity to nonsystematic (random) errors and systematic errors due to scales larger than the analysis domain are discussed. A fundamental limitation with the technique is collinearity, i.e., poorly conditioned matrices of independent variables and cross products. Several tests with the VVP method are conducted in which terms are ignored (e.g., particle fall speed, vertical shear terms, ... etc.) and the size of data gaps is varied. Results show that the method tolerates large sector data gaps. An optimal set of parameters is the basic-state wind field and the horizontal shear terms.]

Borga, M., D. Da Ros, S. Fattorelli, A. Vizzaccaro, 1995: Influence of various weather radar correction procedures on mean areal rainfall estimation and rainfall-runoff simulation. *Proceedings, III International Symposium on Hydrological Applications of Weather Radars*, São Paulo, Brazil, 146-157.
[Low impact because of the small sample. An intercomparison of rainfall estimates made by rain gages, radar, and a combination of radar and raingage information is made for a single event over a small watershed. Ground truth was provided by hourly areal precipitation accumulations computed from 19 rain gages. Correcting the radar data for attenuation, beam blockage, and the vertical profile of reflectivity resulted in significant improvement in the rainfall estimate compared to estimates computed from the raw radar data. The improvement was evident even when gages were used to adjust the raw and corrected radar data.]

Brandes, E.A., J. Vivekanandan, J.D. Tuttle, and C.J. Kessinger, 1995: A study of thunderstorm microphysics with multiparameter radar and aircraft observations. *Mon. Wea. Rev.*, **123**, 3129-3143.
[Low impact. Measurements collected with a multiparameter radar (dual-polarization and dual-wavelength) from a hail storm were compared to particle measurements made by a research aircraft. Radar measurements of Z_H and Z_{DR} agreed well with computations based on observed particle distributions. The Z_{DR} parameter clearly depicted the melting layer and the hail shaft.]

Brown, V.J., A.R Holt, 1995: Rain rate estimation by dual-wavelength radar. *Proceedings, III International Symposium on Hydrological Applications of Weather Radars*, São Paulo, Brazil, 578-586.
[Low impact. Dual-wavelength measurements have been suggested as a means of determining rain fall rates. The advantages with dual-wavelength systems is that rainfall rate is more linearly related to attenuation than to reflectivity and that attenuation is less sensitive to drop size variations. The disadvantages are that rainfall rates must be heavy or path lengths must be long for significant attenuation to occur. Another advantage of dual-wavelength systems is that the measurements can be used to specify hail regions within thunderstorms. The assumption is that attenuation due to hail will be small and large positive dual-wavelength ratios (DWR's) will recover to small values once the radar signals pass through the region of non-Rayleigh scattering. In the study, S-band/X-band and S-band/C-band pairs were used to estimate rain rates from attenuation and from specific differential phase (K_{DP}). Rain rates computed from attenuation for a small sample of thunderstorm observations were found to be consistently greater than those computed from K_{DP}. The difference

is thought to be due to the presence of wet hail. The difficulty or dilemma with the dual-wavelength system is that for the detection of hail (particularly when estimating size) the attenuation due to rain must be accounted for, and for the estimation of rain rate a correction must be applied for the presence of hail.]

Cannon, J.W., 1994: A WSR-88D winter season view of orographical influences in Albany New York and its role in composing short term forecasts. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 147-158.
[Low impact. Several storm cases are used to illustrate the effects of orography, gravity waves, and lake effects on snow storms.]

Carbone, R.E., 1995: Future opportunities and impacts of earth-based remote sensing in operational meteorology. *Preprints, 14th Conf. on Weather Analysis and Forecasting*, Dallas, Texas, Amer. Meteor. Soc., 352-357.
[Low impact. A nice summary of remote sensing fundamentals. Of import are the discussion of rainrate estimation by conventional (Z-R), dual-wavelength, and polarimetric methods.]

Choy, B.K., and S.M. Spratt, 1995: Using the WSR-88D to predict east central Florida waterspouts. *Preprints, 14th Conf. on Weather Analysis and Forecasting*, Dallas, Texas, Amer. Meteor. Soc., 376-381.
[Low impact. An operational procedure in which WSR-88D measurements are used with local climatological and environmental information to predict the occurrence of waterspouts and non-mesocyclone tornadoes. The radar is used to monitor the movement of sea breezes and outflow boundaries and the rapidity of new convective growth in favored areas of waterspout development. This work was also presented at the WSR-88D Users' Conference (Spratt and Choy 1994).]

Chrisman, J.N., D.M. Rinderknecht, and R.S. Hamilton, 1994: WSR-88D clutter suppression and its impact on meteorological data interpretation. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 9-20.
[Low impact. The paper gives a pedagogical description of the three clutter suppression techniques used with the WSR-88D. In particular, the Default Notch Width Map, Bypass Map, and Operator-Defined Clutter Suppression Regions are described. Cautionary remarks and guidance are provided to reduce the impact of the filtering on valid meteorological data.]

Collier, C.G., P.J. Hardaker, C.E. Pierce, J. Rippon, I.D. Cluckie, D. Han, 1995: The use of life cycle models of convective systems in forecasting heavy rainfall. *Proceedings, III International Symposium on Hydrological Applications of Weather Radars*, São Paulo, Brazil, 477-487.
[Moderate impact. An object-oriented approach is used to automatically detect and then to forecast the evolution of precipitating systems. An key component of the scheme is an ability to forecast new growth. High-resolution low antenna elevation data are used. A simple four-step scheme for removing ground clutter is also presented. The process involves removing radar reflectivities that are less than those in a clutter map, reflectivities with low rain rates, echoes with small areal coverage, and low-level echoes which do not have a corresponding echo at the next higher elevation

angle. Vertical profiles of reflectivity are used to determine likely trends in future storm development.]

Collins, W.G., 1995: Pinellas County Florida waterspout case of July 8 1994. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 160-162.
[Low impact. A case study of a waterspout outbreak. The environment was characterized by large CAPE and small low-level SRH. The storms formed along convective lines and exhibited strong increases in maximum VIL just prior to spout formation.]

Conway, J.W., K.D. Hondl, M.J. Moreland, J.M. Cordell, R.J. Harron, 1995: Improvements in the WSR-88D dealiasing algorithm: The pursuit of the final most important gates. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 145-147.
[Moderate impact. The report describes work in progress that is directed toward reducing the number of velocity data gates that are improperly dealiased or removed from the data field with the current WSR-88D dealiasing algorithm. Some success for TVS's was obtained by resetting the adaptable parameter which controls the number of consecutive gates deemed as noise to one. Study of the radial built for comparison with the velocity measurements revealed that it was better to build the radial from observed velocities when available and then to fill gaps with large-scale (rawinsonde) winds. This work is also discussed in Section III.F.4.a.]

Cornman, L.B., E.A. Brandes, B. Clem, and G. Cunning, 1995: Detecting convective turbulence using Doppler radars. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 311-313.
[Moderate impact. The spatial scales causing aircraft sensed turbulence and the impact of the simplifying assumptions generally invoked to estimate turbulence with radar are reviewed. Turbulence estimates, using the methodology of the NEXRAD algorithm (the Layer Composite Turbulence Maximum), were then compared to turbulence (eddy dissipation rates) measured by aircraft. Results showed considerable scatter and a consistent overestimate of the observed turbulence. An example of a potential algorithm that incorporates the spectrum width measurement and the local variance of the radial velocity measurements, as an estimate of the non-stationary component of the wind field, is shown. The authors suggest that other information streams, such as, velocity, shear, radar reflectivity gradients, and signal-to-noise ratio--combined in a fuzzy logic algorithm--should be examined.]

Costa, R., M.L. Bugalho, M. Saramago, M.E. Van Zeller, J. Corte-real, and M.R. Dias, 1995: Objective classification of precipitation types using weather radar. *Proceedings, III International Symposium on Hydrological Applications of Weather Radars*, São Paulo, Brazil, 66-74.
[Moderate impact. Radar estimates of area rainfall and hourly values of relative vorticity are used to derive radar adjustment factors at gage sites. A quadratic surface is then fit to the individual calibration gages to yield a field of adjustment factors. The authors suggest that the regression coefficients can be used to classify precipitation type and hence determine optimum Z-R relationships.]

Crook, A., 1995: Numerical simulations initialized with radar-derived winds. Part I: Simulated data

experiment. *Mon. Wea. Rev.*, **122**, 1189-1203.
[Moderate impact. A boundary-layer numerical model is initialized with simulated radar data. The model is that developed by Clark at NCAR and the thermodynamic retrieval method is that of Gal-Chen (references provided). A series of tests are performed to study the impact of time tendencies, intermittent data, and random errors. In an interesting test in which the velocity tendency terms are ignored, the retrieved buoyancy has the wrong sign.]

Crook, A., and J.D. Tuttle, 1995: Numerical simulations initialized with radar-derived winds. Part II: Forecasts of three gust front cases. *Mon. Wea. Rev.*, **122**, 1204-1217.
[Moderate impact. In this paper the methods tested in Part I (Crook 1995) are applied to horizontal wind fields derived using the TREC method and surface mesonetwork winds. In a case using only TREC winds, a broad baroclinic zone (~20 km across) is found in the retrieved thermodynamic fields as determined from the radar data. The baroclinic zone collapses to a more realistic width of 5 km as the numerical model is integrated in time. In two other cases, data from a mesonetwork were also available for use in the forecast model. In these examples, surface wind and buoyancy measurements were found to improve the final analysis, and forecasts showed marked improvement over persistence. One of the interesting problems with thermodynamic retrievals is the lack of observations to verify the results. Mesonetwork sensors typically do not depict the details of frontal circulations. In the absence of accepted comparative tests, root-mean-square (RMS) errors, computed from differences in forecast and observed values, are used for verification. The numerical model forecasts proved better than both extrapolation and persistence forecasts. Also, forecast errors were reduced when surface data were assimilated into the analysis.]

Dankers, T., 1994: Observing CSI bands using the WSR-88D. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 159-168.
[Low impact. Numerical model data are used to diagnose convective symmetric instability in two snow band cases. The narrow beam and greater sensitivity of the WSR-88D are credited with early band detection.]

Dasey, T,J., A. Denneno, and R. Boldi, 1995: The integrated terminal weather system (ITWS) storm cell information algorithm. *Preprints, 6th Conf. on Aviation Weather Systems*, Amer. Meteor. Soc., 372-377.
[Moderate impact. Storm cell characteristics are displayed in textual format when radar display users point to the reflectivity pattern of individual storms and click with a mouse. Displayed information includes echo top, existence of hail, lightning, and mesocyclones. While the product was designed for the aviation community, the synthesis of convective hazard information has import to many users, particularly if tendencies are also appended.]

Divjak, M., 1995: Ground rainfall estimation from radar measurements aloft. *Proceedings, III International Symposium on Hydrological Applications of Weather Radars*, São Paulo, Brazil, 300-308.
[High impact because of range bias implications. Radar rainfall estimates made from radar reflectivity information were improved through the application of corrections based on mean vertical

gradients of radar reflectivity. The scheme is patterned after that developed in Europe (references provided). Compared to gages, the corrected data show smaller scatter than the uncorrected data. The spread of radar-to-gage ratios decreased from 2.6 to 2.3. The correlation between radar and gage amounts increased from 0.53 to 0.63. There was a significant reduction in the mean overestimates of rainfall at intermediate ranges where bright bands were a problem and a reduction in the underestimates of rainfall at distances greater than 100 km.]

Eyerman-Torgerson, K., and R.A. Brown, 1995: The hail spike signature of the Carson, ND hailstorm of 11-12 July 1989. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 80-82.
[Low impact. C-band radar observations of a hail spike associated with a storm which produced baseball-sized hail are described. The great length of the observed spike (as much as 25 km) and its presence at relatively low reflectivity values (50 to 53 dBZ) is attributed to enhanced non-Rayleigh scattering at C-band.]

Fabry, F., 1995: Vertical profiles of reflectivity and precipitation intensity. *Proceedings, III International Symposium on Hydrological Applications of Weather Radars*, São Paulo, Brazil, 344-350.
[Moderate impact. High-resolution radar reflectivity profiles from a vertically pointing radar are examined. Five vertical profile types are identified: low-level rain, rain with bright band, rain without an apparent bright band, showers, and deep convection. The argument is made that low-level rain events are not important hydrologically. The shape of the of the reflectivity profiles for the last three categories showed little variation below the 0°C level. Examination of rain with bright-band cases shows that the thickness of the bright band increases with precipitation intensity. Interestingly, the shape of the profile, as defined by vertical gradients of reflectivity, shows little change with precipitation intensity. Hence, it may be possible to model the profile by using information from a relatively small number of antenna elevation angles.]

Fattorelli, S., R. Casale, M. Borga, and D. Da Ros, 1995: Integrating radar and remote sensing techniques of rainfall estimation in hydrological applications for flood hazard mitigation, The European Contribution: Perspectives and Prospects. European Commission on Science, Research, and Development, Associazione Italiana di Idronomia, 72pp.
[Moderate impact. The report gives an excellent summary of radar and earth satellite techniques for estimating rainfall. Radar topics include attenuation, AP, variability of reflectivity in the vertical, ground clutter, beam blockage, radar raingage comparison, and adjustment techniques. Other sections describe the integration of radar and satellite rainfall data in hydrological modelling for flash flood forecasting and European research activities concerning hydrological applications of radar and satellite sensors for rainfall estimation.]

French, M.N., H. Andrieu, and W. Krajewski, 1995: Uncertainty in vertically integrated liquid water content due to radar reflectivity observation error. *J. Atmos. Oceanic Technol.*, **12**, 404-409.
[Low impact. Estimates of errors in derived quantities are important for determining confidence in stochastic forecast systems. While errors in individual reflectivity measurements may be low, errors in derived quantities can become large when taking discrete vertical samples. The coefficient

of variation in estimated VIL values is shown to be much larger than that in radar reflectivity.]

Frisch, A.S., D.H. Lenschow, C.W. Fairall, W.H. Schubert, and J.S. Gibson, 1995: Doppler radar measurements of turbulence in marine stratiform cloud during ASTEX. *J. Atmos. Sci.*, **52**, 2800-2808.
[Low impact. A vertically pointing K-band Doppler radar is used to examine turbulent motion in nonprecipitating stratiform clouds. To prevent droplet terminal velocity contamination of the velocity measurement the analyses is restricted to clouds with radar reflectivity < -17 dBZ. Nighttime velocity profiles (obtained at 3 min intervals) are dominated by downdrafts at the top of the cloud layer, while daytime profiles exhibit intense downdrafts in the cloud's lower portions. Variance calculations showed maxima in the upper regions of clouds and near cloud base. The maxima are attributed, respectively, to cloud-top radiational cooling and to buoyancy introduced by condensation near cloud base.]

Fulton, R., D.-J. Seo, J. Breidenbach, and E. Johnson, 1995: Performance testing of the WSR-88D precipitation algorithm. *Proceedings, III International Symposium on Hydrological Applications of Weather Radars*, São Paulo, Brazil, 109-117.
[High impact. The algorithm uses a specified number of hourly precipitation totals (currently 50 possible gages) and a Kalman filter to determine mean bias corrections for radar rainfall estimates. Mean differences were then applied as adjustment factors to raw radar rainfall estimates for the next hour. Mean bias errors and radar estimates at the majority of gage sites were improved.]

Gagnon, R., D. Ferraro, F. Pratte, and A. Zahrai, 1995: WSR-88D Archive I data analyzer. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 148-150.
[High impact. A portable system is being developed for acquiring, recording, displaying, and analyzing real-time inphase and quadrature information obtained with the WSR-88D. Range and azimuth limits can be specified for data collection and several options for storing data are available.]

Garza, A.L., 1994: Flash flood and precipitation data from the Hawaii Molokai WSR-88D. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 230-237.
[Moderate impact. Two heavy rain events in Hawaii are described and the utility of WSR-88D products are evaluated. The precipitation products tended to underestimate the actual rainfalls but maxima matched the regions of heavy rainfall.]

Giuli, D., L. Baldini, and L. Facheris, 1994: Simulation and modeling of rainfall radar measurements for hydrological applications. *Natural Hazards*, **9**, 109-122.
[High impact. A stochastic space-time model for generating ideal rainfall patterns and simulating errors due to spatial changes in drop-size distributions, attenuation, and beam blockage is described. The model allows rapid quantitative evaluation of alternative and integrated processing algorithms as applied to radar data. Because several error sources can be handled simultaneously, the model could be useful for obtaining optimal solutions for complex situations. For example, the added value of dual-polarization measurements or the effect of a bright band in a system plagued with measurement errors can readily be investigated.]

Glass, F.H., and R.W. Przybylinski, 1994: Operational considerations for the detection of mesocyclones at long ranges. *Postprints, 1st WSR-88D User's Conference,* WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 427-438.
[Moderate impact. Potential problems in detecting mesocyclones at distant ranges from the radar are discussed. The authors point out that decreases in mesocyclone intensity, as determined from rotational velocity, can result from the mesocyclone being positioned largely within the radar beam so that outbound and inbound radial velocities tend to cancel.]

Golden, J.H., and C. Goodall-Gosnell, 1995: Tornadic waterspout detection by the WSR-88D. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 7-9.
[Low impact. A case study is presented in which a tornadic waterspout that occurred relatively close to the radar but was undetected is presented. The authors suggest that waterspout formation was tied to boundary-layer convergence zones and that monitoring of these boundaries is requisite for improved warnings. Further, they suggest that detection of waterspouts and the search for precursors would be facilitated by an increased number of scans at lower antenna elevation angles.]

Gorgucci, E., G, Scarchilli, and V. Chandrasekar, 1995: Application of dual polarization radar rainfall technique for operational monitoring over the Arno river basin. *Preprints, 27th Conf. on Radar Meteor.,* Vail, Colorado, Amer. Meteor. Soc., 95-97.
[Low impact. Rainfall estimates are derived from radar reflectivity measurements at horizontal polarization (Z_H) using two Z-R relationships and from a combination of Z_H and Z_{DR} measurements. The smallest errors were found with the dual-polarization relationship. A second test involved the matching of probability densities of the three radar-derived estimates with raingage measurements. Again, the dual-polarization based algorithm fared best.]

Green, G.D., 1994: Arizona severe thunderstorm/flash flood climatology and a qualitative assessment of the WSR-88D and WDSS. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 450-461.
[Moderate impact. Severe weather problems endemic to Arizona include microbursts and flash floods. Recommendations are made for a damaging wind (microburst) and automated flash flood algorithms.]

Grumm, R.H., D. Nicosia, and G. Forbes, 1994: WSR-88D observations of conditional symmetric instability snowbands over central Pennsylvania. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 125-137.
[Low impact. A case study is presented that uses WSR-88D products and numerical model data to examine the orientation of snowbands. The authors conclude that the orientation of the snowbands is consistent with indications of conditional symmetric instability as determined from synoptic data.]

Guoqing, L., G. Wenzhong, Z. Xueru, W. Dinghao, and Z. Ji, 1995: Two-dimensional dealiasing of Doppler velocities. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 154-155.
[Moderate impact. Velocity gates in subregions are dealiased in a least squares sense. Advantages with the scheme would seem to be that errors do not propagate. Computed parameters are the

variance of the observed velocities, the variance of the noise, the ratio between the noise and signal variance, median velocity, and mean velocity. Boundaries of folded velocity regions are then determined and a minimum found in a smoothness function which considers gradients in the velocity field. Analysis details are sketchy. This paper is companion with Shouxiang et al. (1995).]

Hagelberg, C., and J. Helland, 1995: Thin-line detection in meteorological radar images using wavelet transform. *J. Atmos. Oceanic Technol.*, **12**, 633-642.
[Low impact. Wavelet transforms are used to detect radar thin lines. Such lines are associated with boundary-layer convergence and are frequently the loci of new thunderstorm development. A two-dimensional wavelet that is symmetric and directionally selective is used. The wavelet transformation is computed for a discrete set of scales and orientations. Locations where the transform is large indicate high correlation between the wavelet and the reflectivity pattern. To reduce the number of scale images (i.e., the mapped transforms), fuzzy logic is employed to remap the scale images. This procedure is followed by a filtering operation to produce an interest image of multiscale-multidirectional information designed for input into an expert system for feature detection. The multiscale feature of the analysis seems attractive for removing clutter and for detecting thin lines not represented by a particular spatial scale.]

Hanna, E., 1995: How effective are tipping-bucket raingauges? A review. *Weather*, **50**, 336-342.
[Low impact. Measurement problems with tipping-bucket gages are reviewed in the context that there is no accepted standard. Tipping-bucket gages use wedge shaped buckets which when filled tip to trigger an event recorder and to empty the bucket. The achievable quantitative resolution with such a gage is dependent on the bucket size. Small buckets lead to greater resolution due to the greater frequency of tips but have greater measurement bias due to the loss of rainfall during the period in which the bucket tips. Another problem with tipping gages is that time averaged rainfall rates are determined and not the details of the precipitation event. As with all gages, wind turbulence is also a problem. Ground level gages are the most effective but funnel types are nearly as good. Studies suggest that wind turbulence may cause areal mean precipitation to typically be underestimated by ~10%. Under strong wind conditions even larger losses, which would outweigh any instrumentation errors, are to be expected.]

Henry, S.G., 1995: Evaluation of automated, short-term thunderstorm forecast rules. *Preprints, 6th Conf. on Aviation Weather Systems,* Amer. Meteor. Soc., 83-88.
[Low impact. An automated procedure for forecasting the evolution of existing convection and the initiation of new convective activity is described. Radar data are used to identify the location of clouds, thunderstorms, and boundary-layer convergence lines. This information is combined with estimates of environmental stability, as determined from surface and sounding observations, and with storm motion to produce 30 min forecast boxes of convective activity. A list of rules weighing the pre-existence of thunderstorms, clouds, and convergence boundaries and the environmental instability is applied. Several examples are shown. A critical factor for improved forecast accuracy is a capability to detect clouds having radar reflectivities of ~10 dBZ.]

Hipólito, J.R., and A. Rodrigues, 1995: Comparison of two compression algorithms for radar data. *Proceedings, III International Symposium on Hydrological Applications of Weather Radars,* São

Paulo, Brazil, 209-214.
[Moderate impact. The paper compares two methods designed to reduce data storage requirements and to facilitate the transmission of datasets. The Run Length Encoding method in its simplest form replaces strings of bytes with two bytes (one which declares the number of bytes in the run and another which declares their value). The Lempel-Ziv-Welsh algorithm replaces strings of bytes with codes. Every observed string is assigned a code that is stored and used again when the string is repeated. Tests revealed that both methods have large compression ratios (80-85%) but that the Run Length Encoding method is three times faster.]

Huckabee, K.L., 1994: Two limiting cases of the WSR-88D. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 405-411.
[Moderate impact. Two examples of microbursts occurring in close proximity to a WSR-88D and with no apparent identifiable features are described. The author concludes that the small temporal and spatial scales of these events makes the issuance of warnings with lead times very difficult. The suggestion is made that the highest resolution data be examined and that more frequent low-level radar scans are required.]

Illingworth, A.J., and D. Zrnić, 1995: Workshop on weather radar polarimetry for research and operational applications. *Bull. Amer. Meteor. Soc.*, **76**, 555-558.
[Low impact. This workshop brought together members of the research and operational communities to discuss needs for polarimetric radar measurements within the science and operational communities. There was general agreement concerning the need for verification of the polarimetric signatures. In particular, those in operations stressed the need to demonstrate the advantages of polarimetry for precipitation measurement, for improved flash flood forecasts, and for better hail detection and warnings.]

Jackson, M.E., and R.T. Jesuroga, 1995: The ATMS convective area guidance product. *Preprints, 6th Conf. on Aviation Weather Systems,* Amer. Meteor. Soc., 78-82.
[High impact. The cross-correlation tracking method is used to produce short-term forecasts of convective activity. The technique is applied to a time series of vendor-supplied radar mosaics. Motion vectors are filtered in time to ensure consistency. Results for 15 min forecasts of echo $\geq$ 30 dBZ show a POD of 0.63, a CSI of 0.45, and a FAR of 0.38.]

Jarboe, J.M., R.M. Steadham, A. Sellakannu, R.E. Schlegel, S.S. Sanger, 1994: Preliminary results from the human factors evaluation of the radar analysis and display system during the summer 1994 operational test in Phoenix. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 470-475.
[Moderate impact. An experiment to evaluate a radar display product is described. "Guest operators" were trained under a four part program that concluded with a proficiency test at the end of the training session. A key component in the evaluation was the video recording of the operator activities. Preliminary results reveal that the majority of operators were able perform 15 basic tasks at the end the training session.]

Johnson, J., 1995a: Identification of clear air roll turbulence and low level wind shear event by the WSR-88D radar. *Preprints, 6th Conf. on Aviation Weather Systems,* Amer. Meteor. Soc., 491-496.
[Low impact. An interesting case study of aircraft-encountered turbulence at low levels. The turbulence is thought to have been caused by Kelvin-Helmholtz instabilities that developed on the leading edge of outflow from a mesoscale convective system.]

Johnson, J.T., 1995b: Use of enhanced WSR-88D severe weather detection algorithms in the FAA's integrated terminal weather system. *Preprints, 6th Conf. on Aviation Weather Systems*, Amer. Meteor. Soc., 362-365.
[High impact. The paper describes enhanced algorithms for storm identification and tracking, hail detection, mesocyclone detection, and tornado detection. Comparison with the existing WSR-88D algorithms show marked improvement in the detection of individual cells within storm clusters, greater specificity of hail events, greater mesocyclone detectability at far ranges, and improved tornado detection.]

Joss, J., and R. Lee, 1995: The application of radar-guage comparisons to operational precipitation profile corrections. *J. Appl. Meteor.*, **34**, 2612-2630.
[Moderate impact. A summary of the analysis procedure employed by the Swiss to estimate rainfall with radar is described. Emphasis is placed on reducing the effects of ground clutter, occultation, beam broadening with range, and the natural variability of rainfall with height.]

Kelly, D.S., 1994: A comparison of high resolution precipitation accumulation estimates from the WSR-88D precipitation algorithm with rain gage data. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 185-192.
[Moderate impact. The study compares radar rainfall estimates made with the WSR-88D with gage measurements. For three storm situations and 398 gage/radar comparisons it was found that radar estimates significantly exceeded gage amounts in only 4% of the comparisons. Reasonable agreement occurred in 35% of the comparisons. The remaining cases (61%) involved significant underestimates of the precipitation.]

Kelsch, M., and C. Subramaniam, 1995: Radar-derived products for emergency management decision making. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 74-76.
[Low impact. FSL has been developing a multimedia display of weather variables for the use of emergency management users (non-meteorologists). The product, which is designed to retain the details of weather events, allows users to define specific weather needs and to tap NWS-generated data sources (e.g., model output, severe thunderstorm warnings, and special weather messages).]

Kennedy, P.C., and S.A. Rutledge, 1995: Dual-Doppler and multiparameter radar observations of a bow-echo hailstorm. *Mon. Wea. Rev.*, **123**, 921-943.
[Low impact. In the study, a multiparameter hail detection algorithm that incorporates radar reflectivity, differential reflectivity, and the zero-lag cross correlation between reflectivities at horizontal and vertical polarization (ρ_{HV}) is described. The method is thought applicable for large

hail (> 2 cm in diameter) and for temperatures > 0°C. Hail designations were made for individual measurement volumes when reflectivity exceeded 45 dBZ, Z_{DR} < -0.5 dB, and ρ_{HV} < 0.92. The utility of the algorithm was not verified against hail reports.]

Kessler, E., and B. Neas, 1994: On correlation, with applications to the radar and raingage measurement of rainfall. *Atmos. Res.*, **34**, 217-229.
[Low impact. A cautionary note is given when using correlation coefficients for comparing radar and raingage measurements of rainfall. The suggestion is made that correlation coefficients between related variables (e.g., radar and raingage estimates of rainfall) are sensitive to the range and distribution of values and that the correlation should be normalized according to the range in values. For radar estimated and raingage measured rainfalls, it is recommended that logarithms of the variables be used.]

Kitchen, M., R. Brown, and A.G. Davies, 1994: Real-time correction of weather radar data for the effects of bright band, range and orographic growth in widespread precipitation. *Quart. J. Royal Meteor. Soc.*, **120**, 1231-1254.
[High impact. Using a set of RHI scans, radar precipitation estimates are corrected for bright-band effects, range biases, and the orographic growth of stratiform precipitation. RMS errors in the precipitation rate estimates are reduced by 63%.]

Kitzmiller, D.H., and J.P. Breidenbach, 1995: Probabilistic nowcasts of severe local storms based on radar and storm environment data. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 68-70.
[Moderate impact. Attempts to improve the Severe Weather Potential (SWP) algorithm by adding environmental data to the current parameters of storm size and vertically integrated liquid (VIL) are described. The environmental information was taken from analyses and forecasts of the Nested Grid Model (NGM). For the northeastern U.S., where wind damage is prevalent, a combination of maximum VIL, the coverage of VIL > 20 kg m^{-2}, and the wind speed at 700 mb produced the best results. For the plains, where hail events dominate, optimum predictors were VIL, the freezing level height, the u component of the wind at 500 mb, and a stability parameter based on 1000 and 500 mb data. Improvements were 10-15% in terms of FAR's. Tests on an independent dataset generally showed improvement with POD's > 0.7.]

Klazura, G.E., and D.S. Kelly, 1995: A comparison of the high resolution rainfall accumulation estimates from the WSR-88D precipitation algorithm with rain gage data. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 31-34.
[High impact. High-resolution radar-estimated rainfalls obtained with WSR-88D's for 23 events are compared to gage observations. The radar/gage pairs were determined by examining all radar bins in a 3 by 3 matrix that centered on the gage location. If the range of radar bin estimates straddled the gage value, the best match was used. If all radar bin estimates were either higher or lower than the gage value, the radar bin that was closest in value was used. Mean biases were determined for each event by summing all gage values and then dividing by the total of radar rainfall estimates (method 1) and by averaging the ratios of gage and best match radar estimates (method 2). The bias defined by method 2 was generally much higher. For method 1, mean gage to radar ratios for

stratiform events were 1.70 and for convective events they were 0.91. This result would seem to demonstrate the potential value of rainfall product with a variable Z-R relationship that could be selected based on precipitation type. In this study, fair agreement between radar estimates and gage observations was achieved in 63% of the comparisons. Radar estimates were greater than gage amounts 27% of the time and less than gage amounts 10% of the time.]

Kostinski, A. B., 1994: Fluctuations of differential phase and radar measurements of precipitation. *J. Appl. Meteor.*, **33**, 1176-1181.
[Low impact. The Introduction gives a concise explanation for the physical basis for rainfall estimation with the specific differential polarization phase shift (K_{DP}). A Gaussian model is used to study how the pulse to pulse reshuffling of raindrops (Rayleigh fading) and consequent decrease in the cross-correlation between copolar echoes ($|\rho_{HV}|$) influence the magnitude of fluctuations in differential phase ϕ_{DP}. It is found that relatively small changes in $|\rho_{HV}|$ can have a profound influence on ϕ_{DP}. Precipitation estimates in cases with wet snow or hail will require considerably more pulses to achieve accuracy comparable to that in "rain only" situations. If $|\rho_{HV}|$'s are approximately equal at gates used to compute K_{DP}, the ϕ_{DP} standard deviations at the two gates are equal; and errors in K_{DP} are larger than those in ϕ_{DP} by the square root of 2.]

Kuhl, S.C., 1994: A preliminary investigation of the WSR-88D storm relative velocity map product for tornado events within the Eastern Region of the National Weather Service. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 339-350.
[Moderate impact. The study indicates that suggested thresholds for detecting tornadoes based on differential velocity measurements with mesocyclones and TVS's may be too high for tornadoes occurring in the Easter Region. An archive of storms is being assembled for future study.]

LaPlante, R.E., 1994: Evolution of a lake effect snowstorm over northeast Ohio. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 138-146.
[Low impact. The paper presents a case study in which multiple snowbands evolve into a single intense snowband as the wind (determined from the VAD wind profile) became parallel to the elongated axis of Lake Erie.]

Laroche, S., I. Zawadzki, 1995: Retrievals of horizontal winds from single-Doppler radar clear-air data by methods of cross correlation and variational analysis. *J. Atmos. Oceanic Technol.*, **12**, 721-738.
[High impact. Four methods for retrieving horizontal wind fields from single-Doppler radar observations are compared in a case study of a sea breeze front. The methods include (1) TREC (Tracking Radar Echoes by Correlation), (2) a minimization method which combines TREC with constraints for reflectivity conservation and local wind uniformity, (3) a variation of (2) using a conjugate gradient method, and (4) a variational approach that also uses a momentum equation for radial velocity. The authors note that significant short-term changes in the "clear-air" reflectivity patterns occurred even for radar observations spaced only minutes apart. Such changes would represent a severe test for techniques based on the assumption of conservation of reflectivity. A

number of experiments were performed at different spatial resolutions and using 2 and 3 time levels. In general, with methods 1-3 results improve with 3 time levels (despite the assumption of stationarity for longer periods) and for coarser grids. Best results were obtained with the full variational approach with constraints for reflectivity conservation and radial velocity momentum and select weighing of the reflectivity field in a convective cell (implied vertical advection).]

Lee, J., and R. Crane, 1995: Use of Doppler velocity spread in the detection and forecast of regions within storms that may be hazardous to aircraft operations. *Preprints, 6th Conf. on Aviation Weather Systems*, Amer. Meteor. Soc., 497-502.
[Moderate impact. The spectrum width measurement is the primary component of the current turbulence algorithm available on the WSR-88D. A comparison of the spectrum width measurements from the Twin Lakes WSR-88D and NSSL's Cimarron radar revealed that both radars detected the same structural features. However, spectral width estimates from the Twin Lakes radar are found to be about one half that of the Cimarron radar. No explanation for the bias was given.]

Lee, R.R., 1994: Survey results of WSR-88D field sites meteorological algorithm performance. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 1-8.
[High impact. A survey of National Weather Service (NWS) Forecast Offices, Center Weather Service Units (CWSU's), and Department of Defense sites was taken to ascertain the performance of the current WSR-88D meteorological algorithms and products. Highly rated algorithms included Vertically Integrated Liquid, VAD Wind Profile, One Hour Precipitation, Three Hour Precipitation, Velocity Azimuth Display, and Layer Composite Reflectivity. Lowest rated algorithms were Echo Top Contour, Hail, Severe Weather Potential, and Combined Shear. Most used algorithms included VAD Wind Profile, Storm Tracking, Vertically Integrated Liquid, Storm Total Precipitation, Mesocyclone, and One Hour Precipitation. Least used products were Severe Weather Probability, Echo Top Contour, Layer Composite Turbulence, and Combined Shear. Most frequently noted problems were the corruption of precipitation products by AP, bright band, and hail; the need for greater resolution in the lower precipitation amounts; an ability to restart the accumulation of the Storm Total Precipitation; contamination of VAD Wind Profiles due to birds and inversions; difficulties with the Storm Tracking Information in tracking individual cells within larger precipitation areas; and the spurious detection of mesocyclones.]

Lee, R.R., J.L. Ingram, and G.E. Klazura, 1994: A comparison of data from the WSR-88D VAD Wind Profile product and rawinsondes at twelve sites - Preliminary results. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 55-61.
[Low impact. Results show that wind directions agreed within 10° more than 85% of the time and that wind speeds agreed within 5 kt more than 75% of the time. In general, discrepancies could be attributed to beam ducting and the presence of boundary-layer wind shifts or other meteorological phenomena.]

Lemon, L.R., 1994: Recognition of the radar "three-body scatter spike" as a large hail signature. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD

Joint System Program Office, 373-388.
[Moderate impact. A physical explanation and examples of the three-body scatter signature for large hail (usually > 1 inch in diameter) are given. The spike is often seen at a low antenna elevation angle (3-5°) extending radially (10 km or more) behind intense reflectivity cores (usually > 63 dBZ). The three-body scattering signature is usually characterized by weak reflectivity (< 20 dBZ) and zero or weak velocities approaching the radar. The signature is a scattering artifact indicating precipitation where there is none. (The hail falls in the reflectivity core.) The signature is thought to have predictive value but this is not demonstrated.]

Marosi, W.J., and R.H. Grumm, 1994: WSR-88D precipitation verification: Winter 1993-94. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 193-202.
[Moderate impact. Case studies of precipitation events within the Middle Atlantic River Forecast region are presented. Significant underestimates of heavy rainfalls are found in WSR-88D precipitation products when compared to raingage observations and streamflows.]

Mauro, M., 1994: Pictorial chronology of tropical storm Alberto: Part 2. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 214-218.
[Moderate impact. Experiences with a WSR-88D as remnants of tropical storm Alberto passed by are described. The banded radar structure of the storm persisted several days after landfall. The base reflectivity field and time lapse movies were found to be helpful for determining storm motion. Individual cells on occasion became difficult to track in heavy rain areas. The problem was solved by movie looping the VIL product. The precipitation product underestimated the rainfall.]

McAdie, C.J., and A. Sandrik Jr., 1994: Operational use of the WSR-88D during Hurricane Emily, 1 Sept 1993, and Tropical Storm Albert, 3 July, 1994. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 222-229.
[Low impact. The paper describes National Hurricane Center usage of WSR-88D products obtained from tropical cyclones. Of particular interest to the Center are the estimation of maximum wind velocity and the location of the circulation center. Radar-determined wind speeds agreed with aircraft reconnaissance data. The cell tracking algorithm proved useful for finding circulation centers that were not well defined in either the reflectivity or radial velocity fields.]

Melnikov, V.M., 1995: Radar estimation of the turbulent scale in widespread precipitation. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 434-435.
[Moderate impact. A potential method for objectively determining the turbulence outer scale is described. First, the contribution of turbulence to spectrum width (w_t) is determined by removing the effects of radial, azimuthal, and vertical shears. It is then assumed that the term $w_t/r^{1/3}$ (where r is the radar range) depends only on the dissipation rate as long as the maximum size of the radar bin is less than the outer scale. It is also assumed (shown for one example) that the eddy dissipation rate is constant at a given altitude. The width of the radar beam at which eddy dissipation rate or $w_t/r^{1/3}$ begins to decrease defines the outer scale.]

Moller, A.R., C.A. Doswell III, M.P. Foster, and G.R. Woodall, 1994: The operational recognition of supercell thunderstorm environments and storm structures. *Wea. Forecasting*, **9**, 327-347.
[High impact. A number of papers presented at the WSR-88D Users' Conference stressed that the severe weather warning function must involve the integration of information about the storm's environment, algorithm designated storm characteristics, and storm properties recognized as representative of severe thunderstorms but not presently constituting algorithms (e.g., hook echoes). This study seeks to establish a scientific decision making process, linked to conceptual models of supercells, that leads to the forecasting and nowcasting of supercells. The paper reviews the influence of environmental wind shear, wind speed, and instability on thunderstorms. Then the four-dimensional characteristics and environments of supercells are described. The single defining parameter is the updraft mesocyclone. Typical storm environments exhibit large vertical wind shear and, in general, relatively high CAPE. Another severe thunderstorm forecasting tool is the storm relative helicity. On a hodograph, this parameter is graphically equal to the negative of twice the area swept out by the storm relative wind vector in the layer between the earth's surface and the 3 km level. Note that large helicity usually occurs with right turning hodographs but can also occur with straight line hodographs. Changes in SRH, which can occur rapidly in severe storm situations, are readily monitored with VAD wind profiles. Threshold values are still being worked out, but the higher the helicity the greater the likelihood of supercells. The argument is made that supercell detection, particularly at large distances from the radar, will be facilitated by integration of knowledge concerning the storm's environment and the storm's radar characteristics.]

Moriyama, T., and H. Muneo, 1995: Quantitative precipitation forecasting using neural networks. *Proceedings, III International Symposium on Hydrological Applications of Weather Radars*, São Paulo, Brazil, 488-493.
[Moderate impact. An Elman recurrent neural network is used to forecast rainfall rate patterns for periods of 10 to 30 min into the future. The correlation with observed radar-derived patterns is slightly greater than with a multilayer network.]

Morrissey, M.L., 1994: The effect of data resolution on the area threshold method. *J. Appl. Meteor.*, **33**, 1263-1270.
[Low impact. A number of studies have determined a high correlation between mean areal rainfall and the fraction of area covered by radar echoes. This modeling study examines how spatial resolution affects area-time integrals and in particular asks the question as to whether it is appropriate to apply a calibration coefficient found with raingages to radar data. The author determined that significant biases and random error can occur.]

Moszkowicz, S., G.J. Ciach, and W.F. Krajewski, 1994: Statistical detection of anomalous propagation in radar reflectivity patterns. *J. Atmos. Oceanic Technol.*, **11**, 1026-1034.
[Moderate impact. The statistical properties of radar echoes are examined to separate AP and precipitation echoes. Parameters investigated included (1) a term related to the maximum elevation of the echo, (2) the elevation angle of the maximum reflectivity, (3) the maximum reflectivity, (4) a reflectivity gradient term, and (5) the echo height. Tests on an independent data set produced error levels of 0.6 to 5% for meteorological echoes, 12 to 33% for AP, and ~6% for mixed echoes.]

Murphy, R.A., K.J. Pence, J.A. Westland, and R.E. Kilduff, 1994: A comparison study of VIL versus rotational velocity associated with tornadic thunderstorms. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 259-265.
[Low impact. A furthering investigation of a previous suggested connection between decreasing VIL values and increasing rotational velocities at low levels is shown for two additional cases. Although the relationship is thought important, it apparently was not found in two other storms not presented. Hence, the authors conclude that additional investigation is required.]

Neilson, B., and P.L. Stevens, 1995: Indianapolis uses new radar technology to refine hyetographs for CSO model and SSES studies. *Proceedings, III International Symposium on Hydrological Applications of Weather Radars,* São Paulo, Brazil, 191-198.
[Low impact. A network of 25 rain gages and NEXRAD radar images (0.5 and 1.5° tilts) are combined in a system developed by the French (called CALAMAR) to monitor precipitation events in the city of Indianapolis, Indiana. The methodology accounts for the advection of the precipitation pattern between 5 min scans.]

O'Bannon, T., 1994: Anomalous WSR-88D wind profilers - Migrating birds. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 83-87.
[High impact. Large discrepancies between VAD winds derived from WSR-88D's and rawinsonde measurements are found to be consistent with nocturnal migrations of birds. The discrepancies are seasonal, begin after sunset, and usually end by dawn. Because the birds tend have a common alignment, a "butterfly" reflectivity pattern may be present. In normal clear-air situations, migrations create and increase in the areal coverage of echoes.]

Parker, S. and S. Keighton, 1994: Observations of a strong tornado on the northwest flank of a supercell storm in the absence of a strong mesocyclone. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 393-404.
[Moderate impact. The study presents a red flag example that supercells must be monitored carefully. The storm had a strong mesocyclone and well-defined hook echo which diverted attention from a neighboring weak circulation with weak reflectivity which spawned the only tornado produced by the storm.]

Pereira, A.J., and K.C. Crawford, 1995: Integrating WSR-88D estimates and Oklahoma mesonetwork measurements of rainfall accumulations: Hydrologic response. *Proceedings, III International Symposium on Hydrological Applications of Weather Radars*, São Paulo, Brazil, 169-178.
[High impact. A statistical analysis scheme, in which the radar data are used to determine the statistical properties of the rainfall event and gage measured rainfalls are used to "calibrate" the radar, is described. The procedure purportedly maximizes the extraction of signal and reduces the generation of noise by measurement error. Key assumptions are that the background errors are uncorrelated and unbiased. (While radar and gage errors are independent, the argument can be made

that both measurement systems are subject to bias errors.) An implicit but not necessary assumption in the analysis is that the statistical properties of the error field are isotropic. The paper illustrates how the statistical properties of the precipitation pattern define the influence region for determining calibration factors and quantify the sampling error in rainfall estimates as the integration time increases.]

Pratte, F., R.J. Keeler, R. Gagnon, and D. Sirmans, 1995: Clutter processing during anomalous propagation conditions. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 139-141.
[Moderate impact. A three-step process for ground clutter removal, involving clutter identification, separation of clutter and meteorological signals, and compensation for signal power loss is proposed.]

Raghavan, R., and V. Chandrasekar, 1994: Multiparameter radar study of rainfall: Potential application to area-time integral studies. *J. Appl. Meteor.*, **33**, 1636-1645.
[Low impact. The paper describes an application in which rainfall volumes are computed from one-way specific attenuation at X-band (A_X) and compared to area-time integrals (ATI's) computed from radar reflectivity measurements at S-band. Definitive conclusions are not possible because of a small data sample, but there is general agreement in a scatter plot of rain volumes and ATI calculations based on rain volumes generated with the Marshall-Palmer Z-R relationship.]

Ray, C.A., S.E. Koch, and G. Dial, 1995: A study of summertime convergence boundaries in eastern North Carolina using the WSR-88D Doppler radar. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 10-12.
[Low impact. Using the full sensitivity of the WSR-88D in Clear Air Mode, the origins of boundary-layer convergence lines and their role in generating convective storms were determined. Unexpected features included the "Piedmont Trough" which is thought to respond to diurnal heating over contrasting land surfaces. As in previous studies, convective storms generally formed in connection with the observed boundary-layer phenomena and were intensified by their interaction.]

Rosenfeld, D., 1995: Comparison of WPMM vs. regression methods for evaluating Z-R relationships. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 23-25.
[Moderate impact, important for determining climatological Z-R relationships. The paper begins with a review of recent findings using the Probability Matching Method (PMM) to determine Z-R relationships. The technique essentially matches pairs of Z and R that have equal probability. Tests with non-synchronous datasets of Z and R were first used, but subsequent studies revealed that simple regression of Z and R synchronous pairs generally results in better rain estimation accuracy and smaller sample biases. More recent studies have shown that the PMM is as accurate as the regression method provided the Z-R relationship is monotonic. The current study attempts to show that for non-synchronized data the PMM provides more accurate estimates of Z-R relationships. A subsample of disdrometer data were used to determine Z-R relationships by both methods and then applied to the remainder of the dataset. For perfectly synchronous data the two methods gave identical results. But bias and errors increased rapidly with the regression method as time interval between Z and R measurements increased. On the other hand, the WPMM was relatively insensitive

to time difference between measurements.]

Rosenfeld, D., E. Amitai, D.B. Wolff, 1995a: Classification of rain regimes by the three-dimensional properties of reflectivity fields. *J. Appl. Meteor.*, **34**, 198-211.
[Moderate impact. There is considerable evidence that Z-R relationships vary according to precipitation type (i.e, stratiform, convective, and orographic). Because relationships vary in time and space, the use of a single Z-R relationship generally results in significant errors in radar rainfall estimates. Hence, the proper classification of radar echoes is essential for assigning the proper relationships when estimating rainfall. Three characteristics thought important for classifying radar echoes are the horizontal reflectivity gradient $\nabla_r Z$, an effective convection depth, and the fraction of stratiform precipitation as represented by the bright band. Note that the horizontal gradient are computed only in the radial direction "to minimize the effects of smearing the true gradients by the azimuthal beam spreading". The results hold only if the gradients in the radial and azimuthal directions are similar on the average. (This assumption needs to be proved for sub-areas of precipitating systems.) The convective efficiency was defined as the difference in the water vapor mixing ratios at bottom and the top of the radar echo divided by the mixing ratio at the bottom. (The radial gradient of reflectivity and the convective efficiency are both thought to have some value for detecting ground clutter.) The bright-band fraction (BBF) of rainfall was computed as "the fraction of echo area with maximum reflectivities in the vertical within ±1.5 km from the 0°C altitude". A number of potentially valuable relationships for discriminating precipitation type are presented in the paper (e.g, stratiform rain events are largely defined by low $\nabla_r Z$ and high BBF). The convective efficiency was found important for determining the rain intensity distribution. The relationships are somewhat noisy, however, suggesting that some additional refinement is necessary.]

Rosenfeld, D., E. Amitai, D.B. Wolff, 1995b: Improved accuracy of radar WPMM estimated rainfall upon application of objective classification criteria. *J. Appl. Meteor.*, **34**, 212-223.
[Moderate impact. The study proposes to improve rainfall estimates through the selection of Z-R relationships determined from radar-observed parameters. The paper is an extension of the work cited above and previous work by the lead author. The window probability matching method is used to select appropriate relations for small radar sampled areas. The argument is made that precipitation type and consequently drop-size distributions (DSD) are largely defined by horizontal gradients of reflectivity, the vertical gradients of reflectivity, and the character of bright bands. Hence, the parameters of interest are the horizontal gradients of reflectivity, the convective efficiency, the height of the melting level, and the bright-band fraction (BBF). The melting level is used to specify Z-R relationships at far ranges where the radar beam rises above the melting level. Experiments are conducted to study the effect of bright band, the freezing level, reflectivity gradients, cloud depth, and range on Z-R relationships. The effect of sample size to achieve a stable WPMM-based Z-R relationship is then examined. Approximately, 200 mm of total rainfall is needed. The classification method of determining Z-R relationships using radial gradients of reflectivity and range as criteria was then tested by comparison with rain gages and by comparison to mean Z-R relationships determined from the WPMM. The correlation increased from 0.78 to 0.84. The correlation for a power law Z-R relationship was 0.62. The highest correlation (0.86) was found for a classification based on range, reflectivity gradients, and convective efficiency.]

Ruscher, P., K. Gould, J. Korotky, B. Haganmeyer, 1995: Doppler weather radar studies of the Florida sea breeze and associated mesoscale flow systems. *Preprints, 14th Conf. on Weather Analysis and Forecasting*, Dallas, Texas, Amer. Meteor. Soc., 343-346.
[Moderate impact. The high sensitivity of the WSR-88D radar in precipitation mode is used to study sea, bay, and river breeze circulations and their interactions. The implication is that the monitoring of such boundary-layer phenomena will lead to improved nowcasting of convective storms. Also, the progression of a sea breeze front is monitored with the VAD product.]

Sanger, S.S., R.M. Steadham, J.M. Jarboe, R.E. Schlegel, and A. Sellakannu, 1994: Human factors contributions to the evolution of an interactive Doppler radar and weather detection algorithm display system. *Postprints*, *1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 463-469.
[Moderate impact. A team of managers, meteorologists, computer programmers, and human factors specialists was assembled to redesign a radar display system. High priority was given to the design of the user interface (panel control and mouse functions). Features thought important for effective displays are small control panels (relative to information images), the grouping of display functions under single buttons or by color coding, confirmation of changes, and help lines.]

Saramago, M., 1995: Adjustment of the Lisbon weather radar over the Alenquer basin. *Proceedings, III International Symposium on Hydrological Applications of Weather Radars*, São Paulo, Brazil, 92-99.
[High impact. Twenty rainfall events in a 225 km^2 basin equipped with five rain gages were studied. Radar measurements at 5 min intervals were used to make precipitation estimates on grids of 2 and 5 km. Radar data and raingage information were combined in real time by application of a Kalman filter. A quadratic surface was then fit to the calibration factors determined at the gage sites. The method was compared to rainfall estimates made with Theissen polygons using the 5 gages. Significant reductions in root mean square error (from 1.41 to 0.52 mm) and relative error (from 168.6 to 69.3%) were found.]

Sauvageot, H., 1994: Rainfall measurement by radar: A review. *Atmospheric Research*, **35**, 27-54.
[Low impact. The review begins with a description of radar rainfall measurement principals. Described precipitation measurement techniques include the use of single parameter (Z-R) relationships, methods for combining radar and raingage observations, and ATI's. The paper also discusses dual-wavelength and differential reflectivity techniques for estimating rainfall, suggesting that these techniques have not been fully demonstrated.]

Scialom, G., and Y. Lemaître, 1994: QVAD: A method to obtain quadratic winds from conical scans by a Doppler Weather radar network. *J. Atmos. Oceanic Technol.*, **11**, 909-926.
[Moderate impact. An extension of the VAD analysis is described which allows the determination of three-dimensional wind fields for situations in which the horizontal wind components vary quadratically, i.e., the first-order derivatives are linear and the second-order derivatives are constant. The method, a generalization of the VAD technique for two radars, should yield improved wind estimates when the horizontal wind field is nonlinear, e.g., when fronts are present, and the vertical wind varies linearly. The analysis can be performed in the overlap region of network radars or at

single-radar sites under the assumption of wind field stationarity.]

Seed, A.W., J. Nicol, G.L. Austin, C.D. Stow, and S.G. Bradley, 1995: A physical basis for parameter selection for Z-R relationships. *Proceedings, III International Symposium on Hydrological Applications of Weather Radars*, São Paulo, Brazil, 100-108.
[Moderate impact. The study has import for real-time determination of Z-R relationships. Simulated rainfall intensities are used to estimate the coefficient "a" and exponent "b" of Z-R relationships via regression techniques. The uncertainty in a and b is found to be linearly related to system noise. For 100 comparisons with a 3 dB noise level (felt to be representative of radar reflectivity-raingage comparisons) the uncertainty in a and b were ± 50 and ± 0.1 respectively. This uncertainty causes large errors in estimates of intense rainfalls. A comparison between the least squares regression and the probability matching method (PMM) revealed that the PMM underestimates the high rain rates because their probability of occurrence is low (based on 500 radar/gage values).]

Seo, D.-J., and E.R. Johnson, 1995: The WSR-88D precipitation processing subsystem - An overview and performance evaluation. *Proceedings, III International Symposium on Hydrological Applications of Weather Radars*, São Paulo, Brazil, 222-231.
[High impact, because it describes current methodology used by the WSR-88D PPS. The precipitation algorithm uses ground clutter suppressed base radar reflectivity from a hybrid composition of the lowest 4 antenna elevations. The breakdown of range-elevation angle usage is: 0-20 km, 3.35°; 20-35 km, 2.45°; and 35-50 km, 1.45°. For ranges greater than 50 km, the highest reflectivity at either 0.5 or 1.45° is used. Provisions for mean bias correction based on raingage information are built into the system but are not currently activated. Statistics presented in the paper show a variety of range problems with implied underestimates of rainfall at short and far ranges and a relative peak in performance at intermediate ranges that may stem from bright-band effects. Short-range problems are attributed to the clutter suppression algorithm and to the hybrid scan used to generate the precipitation maps.]

Shapiro, A., T. Gal-Chen, J. Zhang, L. Zhao, Q. Xu, H. Gu, C.-J. Qiu, I. Zawadzki, S. Laroche, and J. Tuttle, 1995: Highlights from a single-Doppler velocity retrieval intercomparison project ("bake off"). *Preprints, 6th Conf. on Aviation Weather Systems*, Amer. Meteor. Soc., 541-546.
[High impact. This multi-authored paper presents preliminary results from a comparison of techniques for computing two and three-dimensional wind fields from observations of a single-Doppler radar. TREC, adjoint, conservation methods are examined. For a single case study of a microburst, a simple adjoint using least squares fits to conservation equations for radar reflectivity and radial velocity worked best.]

Shouxiang, S., L. Guoqing, G. Wenzhong, 1995: Ground clutter removal in radar meteorological maps. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 151-153.
[Moderate impact. Local median value and variance are computed for radar observed variables and for noise (mean subtracted). The defining parameters are the difference (r) between the signal and noise variances and the mean of the signal variance (T). The central value in a 5 x 5 matrix is assumed to be meteorological signal when r ≤ T. If r > T, the point is either clutter or a boundary

point. The measurement is then designated as signal or clutter by computing the ratio (R) of the total number of points in the feature divided by the difference between the boundary points and the number of circle points in the feature. For clutter R ≈ 1 and for meteorological echoes R ≈ 1.3.]

Smith, P.L. 1995: On the minimum useful elevation angle for weather surveillance radar scans. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc.,, 669-671.
[Moderate impact. The impact of reducing the current VCP minimum elevation angle of 0.5° to improve the detection of low-level storm phenomena is investigated. The paper concludes that maximum sensitivity to low-level echo features occurs at an elevation angle of 0°; however, the increase in ground clutter contamination at that angle will more than offset the benefits gained. While some adjustment of the minimum elevation angle could be made, e.g., a lowering to 0.25°, the potential improvements in algorithm performance would seem to be small.]

Sohl, C.J., 1994: The use of the WSR-88D in small basin flash flood events: Case examples. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 177-184.
[Moderate impact. Two flash flood situations which were largely overlooked in real time due to even heavier rainfalls in nearby regions are described. The study stresses the need for high-resolution radar data in space and intensity and the need for high- resolution maps of small watersheds.]

Spratt, S.M., and B.K. Choy, 1994: Employing the WSR-88D for waterspout forecasting. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 248-258.
[Low impact. WSR-88D products are incorporated into a system for forecasting waterspouts where previously warnings were largely reactionary. Atmospheric and geographical conditions conducive to waterspout formation are described.]

Steiner, M., R.A. Houze Jr., and S. Yuter, 1995: Climatological characterization of three-dimensional storm structure from operational radar and rain gauge data. *J. Appl. Meteor.*, **34**, 1978-2007.
[Low impact. Algorithms operating on radar volume scans are used to separate convective and stratiform precipitation regions and to estimate precipitation amounts. The argument is made that stratiform precipitation is characterized by absolute vertical velocities being very much smaller than particle terminal velocities; but because the vertical velocity is not known generally, we look to proxies. The use of bright band to define stratiform precipitation is thought limited by beam broadening and poor vertical sampling intervals. Also, the bright band is well defined only when the precipitation is well developed. The authors assert that bright bands are a sufficient but not a necessary condition for a precipitation region to be stratiform. Further, designating only bright-band regions as stratiform will underestimate the stratiform part and overestimate the convective part of the rainfall. Instead, the authors propose an identification system based on reflectivity intensity and the horizontal structure of the precipitation field. Reflectivity > 40 dBZ is considered convective. Any data point whose reflectivity exceeds background values by some threshold is also designated convective. A specified buffer is then also considered convective. Another parameter studied is the

frequency distribution of reflectivity at various altitudes. A method to relate radar reflectivity to rain intensity is then described. The authors note that the way in which the Z-R relationships is formulated is not critical as long as "some form of rain gauge adjustment is performed". The radar estimates at each gage site are determined by using a specified Z-R relationship to estimate the radar rainfall and then by averaging radar bins over an area with 3.5 km radius. In a final step, the radar estimates are then made to conform with gage-based area-averaged amounts by applying a multiplicative constant. This procedure can be adapted for use in the stratiform and convective regions by beginning with appropriate Z-R relationships.]

Stewart, M.R., and J.R. Hedges, 1994: Tornado warnings with the WSR-88D: A review of the 1993 season at Wichita, Kansas. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 269-275.
[Low impact. First experiences with WSR-88D products in a severe weather situation resulted in the issue of several non-verifying tornado warnings. This result was attributed to a lack of familiarity with the products and suggested guidelines for issuing warnings.]

Strager, C.S., and J.W. Kowaleski, 1994: The use of products at a Center Weather Service Unit. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 37-45.
[Moderate impact, because of suggested changes to existing products. WSR-88D products are having considerable impact on the aviation community. The Storm Track Overlay has proven useful for estimating when or if air terminals will be effected by thunderstorms. The VAD Wind Profile is used to designate turbulence layers. Bright-band determinations of the 0°C level (from base reflectivity products), ET product, and the VWP roughly define the vertical limits of icing hazards. Suggested improvements are to lower the 18 dBZ threshold for the ET product, so that the echoes more closely correspond with cloud tops, and to increase the vertical resolution of the product. Because most commercial aircraft fly at altitudes of 30,000 to 40,000 feet, the utility of the product would be improved by increasing the vertical resolution at these heights.]

Sun, J., and A. Crook, 1994: Wind and thermodynamic retrieval from single-Doppler measurements of a gust front observed during Phoenix II. *Mon. Wea. Rev.*, **122**, 1075-1091.
[Moderate impact. A series of experiments in which the three-dimensional wind and thermodynamic fields from a gust front case are retrieved is described. The methodology minimizes the differences between a dynamic numerical model, consisting of the Boussinesq equations and a three-dimensional Poisson equation for pressure, and assimilated observations. Wind fields are verified against dual-Doppler analyses. The thermodynamic fields are checked for consistency by comparing results determined from two independent radar systems. Experiments were conducted to evaluate viewing geometry, the combined use of radial velocity and reflectivity information, temporal sampling, sensitivity to weighing functions, lateral boundary conditions, the effect of penalty functions, and the influence of parameterized diffusion.]

Takemura, K., T. Nishihara, and T. Yoshimoto, 1995: Operational calibration of raingauge radar by 10-minute telemeter rainfall. *Proceedings, III International Symposium on Hydrological Applications of Weather Radars*, São Paulo, Brazil, 75-81.

[Low impact. An operational calibration method for adjusting radar rainfall measurements with telemetered 10 min rainfall data is developed. The hypothesis is that differences in radar and raingage estimates are due largely to short-term changes in the exponent and coefficient parameters of the Z-R relationship. Hence, adjustment factors must be calculated for similarly short intervals. The adjustment procedure accounts for raindrop fall times which can be a significant fraction of the 10 min sampling interval for elevated radar beams. Statistics suggest that calibration factors can be applied to ranges of 20 km from a gage site. At radar locations with more than one gage within 20 km, an inverse distance weighing scheme is used. When applied to a limited sample of independent gage sites, the method reduced the mean bias in the radar estimates but did not appear to improve the spatial distribution of the radar estimate.]

Troxel, S.W., and R.L. Delanoy, 1995: Machine intelligent gust front detection for the Integrated Terminal Weather System (ITWS). *Preprints, 6th Conf. on Aviation Weather Systems*, Amer. Meteor. Soc., 378-383.
[Moderate impact. A system for detecting and forecasting the movement of gust fronts and wind shift lines that has been developed for the Federal Aviation Administration is described. While the primary purpose of the algorithm is to anticipate runway changes at airports, the detection of boundary-layer convergence phenomena has been found important for issuing nowcasts for convective storms. Gust front features exploited by the algorithm include the thin line structure in the radar reflectivity field, the convergence in the radial velocity fields that marks the leading edge of outflows, and the fact that gust fronts tend to move in a direction perpendicular to the convergence zone. A series of feature tests are applied and the reliability of the signatures is determined. For example, one test searches for coincident thin lines and convergence boundaries. Individual tests are combined to produce a chain of points that represent the gust front and to make predictions of future locations. For weak gust fronts (radial velocity differences ≥ 5 and < 10 m s^{-1}) the POD was 0.70.]

Tsintikidis, D., G.J. Ciach, W.F. Krajewski, and E.N. Anagostou, 1995: Radar anomalous echo detection using neural networks. *Proceedings, III International Symposium on Hydrological Applications of Weather Radars*, São Paulo, Brazil, 199-208.
[Moderate impact. A neural network consisting of subjectively and objectively determined radar image descriptors was applied to a set of precipitation echoes, AP images, and mixtures of precipitation and AP echoes. Results with an independent dataset, manually verified, showed that 95% of the precipitation images and 72% of the AP images were correctly identified.]

Turner, R.J., 1995: The operational use of the WSR-88D mid- and high-level layer composite reflectivity products to assess the severe weather potential of thunderstorms. *Preprints, 14th Conf. on Weather Analysis and Forecasting*, Dallas, Texas, Amer. Meteor. Soc., 459-464.
[Low impact. The middle and upper-layer composite reflectivity products are used for "quick look" assessments of severe thunderstorm potential. The products support the use of severe storm detection rules developed by Lemon (i.e., VIP5 echo must extend to at least 27,000-30,000 ft and middle-level echo must be increasing in area and intensity). The author posits that the layer composites are more sensitive to early development aloft than other products, e.g., the VIL product (computed for the entire depth of the atmosphere), and hence provide greater lead time for

determining storm trends.]

Tuttle, J.D., and R. Gall, 1995: Radar analysis of hurricanes Andrew and Hugo. *Preprints, 21st Conf. on Hurricanes and Tropical Meteorology*, Miami, Florida, Amer. Meteor. Soc., 608-610.
[High impact. The Tracking Radar Echoes by Correlation (TREC) method is used to infer the wind field in two storms from the movement of radar reflectivity echoes. The method yields both the circulation center and wind speeds (c.f. Wood 1994, 1994 report). Good agreement is found with aircraft measurements. Additionally, a wavelet analysis is used to portray the small-scale band structure within one of the storms.]

Valeria, D., and M. Paolo, 1995: Measurement accuracy in rainguage-radar adjustment techniques. *Proceedings, III International Symposium on Hydrological Applications of Weather Radars,* São Paulo, Brazil, 52-61.
[High impact. Attempts to improve rainfall estimation with C-band radar and rain gages in Italy are described. Significant time variations in hourly radar (R) and gage (G) rainfalls are found. A plot of log(G/R) versus distance shows considerable scatter about a linear least squares fit, suggesting that mean bias corrections as a function of range alone will be subject to large errors. Autocorrelation functions were then computed for G, R, and G/R using 1 hour accumulations. All correlation functions fall off very rapidly in time. The radar field seems most correlated and the G/R parameter the least correlated in time. Cross-correlation functions behave similarly. The authors suggest that this result is due to the difference in sampling volumes. They conclude that a more accurate adjustment scheme is to use G/R and consider its spatial distribution, weighing each gage observation according to its autocorrelation function.]

Waldvogel, A., W. Henrich, and W. Schmid, 1995: Raindrop size distributions and radar reflectivity profiles. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 26-28.
[Low impact. The paper uses particle observations and vertically pointing radar data in an attempt to establish relationships among bright-band observations and drop spectra and to determine ultimately their influence on the Z-R relationship. A weak relationship was found between the degree of snow crystal rimming and the intensity of the bright band (correlation 0.42).]

Wood, V.T., R.A. Brown, and D.W. Burgess, 1996: Duration and movement of mesocyclones associated with southern Great Plains thunderstorms. *Mon. Wea. Rev.*, **124**, 97-101.
[Low impact. Tornadic mesocyclones endure about 40 min (62%) longer and travel 30 km (63%) farther than their nontornadic counterparts. Mesocyclones producing the most intense tornadoes, as measured by the F-scale, were the most persistent and the most traveled.]

Xiao, R., and V. Chandrasekar, 1995: Multiparameter radar rainfall estimation using neural network techniques. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 199-201.
[Moderate impact. The study combines radar observations (Z_H and Z_{DR}) and a fast learning neural network algorithm to improve rainfall estimates over that produced either with conventional Z-R relationships or with the combination Z-Z_{DR}-R. The advantage with the method is that no assumptions concerning the drop-size distribution or Z-R relationship are made.]

Xingwu, C., and X. Sheng, 1995: Quantitative measurements of precipitation by use of weather radar in the Huaihe River basin. *Proceedings, III International Symposium on Hydrological Applications of Weather Radars*, São Paulo, Brazil, 62-65.
[Low impact. Radar and raingage observations are combined through the use of variational analysis and Kalman filtering to produce improved estimates of rainfall in the Peoples Republic of China. Details of the analysis are provided in a referenced paper. Results for a small number of cases show a significant reduction in radar bias.]

Xu, Q., C,-J. Qiu, H.-D. Gu, and J.-X. Yu, 1995: Simple adjoint retrievals of microburst winds from single-Doppler radar data. *Mon. Wea. Rev.*, **123**, 1822-1833.
[High impact. Experiments using a simple adjoint technique to retrieve the wind field in a microburst case are detailed. The analysis combines a weak vorticity constraint, a first guess field based on previous analyses, and surface wind measurements to improve the retrieval of relatively uniform wind fields. Excellent agreement is found with dual-Doppler analyses when the mean wind advection is strong and relatively steady.]

Zittel, W.D., 1994: Comparison of the performance of the WSR-88D velocity dealiasing algorithm with two other techniques. *Postprints, 1st WSR-88D User's Conference*, WSR-88D Operational Support Facility, NEXRAD Joint System Program Office, 479-487.
[Moderate impact. The paper gives a brief description of velocity dealiasing algorithms developed by NSSL and FSL and then compares their performance to the existing WSR-88D algorithm. Differences prove to be slight, prompting the decision to retain the present algorithm but to make modifications to reduce the number of deleted (unresolvable) data bins and by patterning the algorithm after the NSSL system.]

Zrnić, D.S., and A. Ryzhkov, 1995: Advantages of rain measurements using specific differential phase. *Preprints, 27th Conf. on Radar Meteor.*, Vail, Colorado, Amer. Meteor. Soc., 35-37.
[Low impact. The advantages of using specific differential phase for precipitation measurement are reviewed. These include (1) a relative insensitivity to radar receiver and transmitter calibrations, (2) insensitivity to attenuation, (3) relative immunity to beam blockage, (4) unbiased by ground clutter cancelers, (5) relatively insensitive to drop-size variations, (6) little affected by the presence of hail, and (7) K_{DP} can be used to detect AP. In the paper, the effects of beam blockage, ground clutter canceling, and AP are discussed. Beam blockage corrections to recover reflectivity measurements normally require precise knowledge of the radar horizon and the azimuthal location of intervening ground targets. The specific differential phase shift is not effected by partial beam blockage and should allow measurements to be made at relatively low elevation angles. Results for a single rain event show that RMS differences for K_{DP} are much lower than for Z at 0° antenna elevation. The benefit of K_{DP} in conjunction with ground clutter cancelers comes from the fact that spectral components not filtered by the clutter canceler carry the information necessary to estimate the differential phase. The differential phase signal from AP is characterized by high spatial variation as opposed to small variations in precipitation. Hence, this measurement may be useful for delineating AP when AP and precipitation echoes are mixed.]

APPENDIX A: LIST OF ACRONYMS AND SYMBOLS

AGL	above ground level
AP	anomalous propagation
ARPS	advanced regional prediction system
ATI	area-time integral
AWIPS	Automated Weather Interactive Processing System
BBF	bright-band fraction
CAPE	convective available potential energy
CAPPI	constant altitude plan-position indicator
CAPS	Center for the Analysis and Prediction of Storms
CSI	critical success index
DSD	drop size distribution
ET	echo tops
FSL	Forecast Systems Laboratory
K_{DP}	specific differential phase
LAPS	local analysis and prediction system
MCS	mesoscale convective system
MSL	mean sea level
NWS	National Weather Service
NCAR	National Center for Atmospheric Research
NSSL	National Severe Storms Laboratory
PMM	probability matching method
POD	probability of detection
PPS	precipitation processing subsystem
PRF	pulse repetition frequency
R	rainfall rate
RASS	radar acoustic sounding system
RIDDS	radar ingest and data distribution system
SDVR	single Doppler velocity retrieval
TREC	tracking radar echoes by correlation
TVS	tornado vortex signature
UTC	universal time constant
VAD	velocity azimuth display
VVP	velocity volume processing
VWP	VAD wind product
WPMM	window probability matching method
VCP	volume coverage pattern
UHF	ultra high frequency
Z	radar reflectivity
Z_{DR}	differential reflectivity
Z_H	radar reflectivity at horizontal polarization

APPENDIX B: SURVEY LETTER

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

Request for Information

Now that the installation of the national Weather Surveillance Radar-1988 Doppler (WSR-88D) network is nearing completion, 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. Consequently, 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) Base data or Level II (see Crum et al. 1993) archive of storm phenomena
2) Velocity dealiasing/range unfolding improvements
3) Data quality assessment
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 each organization 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, and either references to or reprints of relevant publications, conference papers, and other reports. The information will be compiled in a summary report and will be distributed to all respondents. The deadline for submissions is December 1, 1995. For further information contact:

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

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

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

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

APPENDIX C: LIST OF ORGANIZATIONS AND INDIVIDUALS CONTACTED

The following table list all organizations and individuals who were contacted concerning the survey. Those who submitted material as individuals or on behalf of organizations are listed below.

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APPENDIX D: SUPPLEMENTAL REPORTS

MIT Lincoln Laboratory:

Chornoboy, E.S., and A. Matlin, 1994: Extrapolating storm location using the Integrated Terminal Weather System (ITWS) storm motion algorithm. MIT Lincoln Laboratory, DOT/FAA/RD-94/2, ATC-208, 71pp.

NOAA Techniques Development Laboratory:

Kitzmiller, D.H., and J.P. Breidenbach, 1995: Detection of severe local storm phenomena by automated interpretation of radar and storm environment. NOAA Technical Memorandum, NWS TDL-82, 33pp.

Hughes STX Corporation:

Harris, F.I., D.J. Smalley, and S.-L. Tung, 1995: Radar studies of aviation hazards. Hughes STX Corp., Scientific Rpt. No. 2, 23pp.