COOPERATIVE INSTITUTE FOR MESOSCALE METEOROLOGICAL STUDIES
THE UNIVERSITY OF OKLAHOMA

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I. Introduction

The University of Oklahoma (OU) and NOAA established the Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) in 1978. Through 1995, CIMMS promoted cooperation and collaboration on problems of mutual interest among research scientists in the NOAA Environmental Research Laboratories (ERL) National Severe Storms Laboratory (NSSL), and faculty, postdoctoral scientists, and students in the School of Meteorology and other academic departments at OU.

The Memorandum of Agreement (MOA) between OU and NOAA that established CIMMS was updated in 1995 to include the National Weather Service (NWS). This expanded the formal OU/NOAA collaboration to the Radar Operations Center (ROC) for the WSR-88D (NEXRAD) Program, the NCEP (National Centers for Environmental Prediction) Storm Prediction Center (SPC), and our local NWS Forecast Office, all located in Norman, Oklahoma.

Management of the NSSL came under the auspices of the NOAA Office of Oceanic and Atmospheric Research (OAR) in 1999. The Norman NOAA groups at that time became known as the NOAA Weather Partners.

Through CIMMS, university scientists collaborate with NOAA scientists on research supported by NOAA programs and laboratories as well as by other agencies such as the National Science Foundation (NSF), the U.S. Department of Energy (DOE), the Federal Aviation Administration (FAA), and the National Aeronautics and Space Administration (NASA).

This document describes the significant research progress made by CIMMS scientists at OU and at our NOAA collaborating institutions during the five-year period July 1, 1996-June 30, 2001. During this period, CIMMS concentrated its efforts and resources on the following five principal research themes: (1) basic convective and mesoscale research, (2) forecast improvements, (3) climate effects of/controls on mesoscale processes, (4) socioeconomic impacts of mesoscale weather systems and regional-scale climate variations, and (5) Doppler weather radar research and development.

II. Research Progress

1. Basic Convective and Mesoscale Research

Dynamic Meteorology

Balanced and Unbalanced Dynamics

Balanced and unbalanced dynamics were studied for three-dimensional substructures embedded in balanced nonlinear symmetric circulations. Four types of unstable modes were identified. The Type I mode was characterized by horizontally tilted bands, similar to the tilted primary mode obtained previously by other investigators. The remaining three modes were highly three-dimensional and emerged consecutively as the base-state Richardson number decreased significantly below the critical value. These modes resembled many observed three-dimensional substructures embedded in frontal rainbands.

Balanced dynamics were also studied relating to cold fronts passing over a three-dimensional mesoscale mountain ridge. A hyperbolic differential equation was derived for the movement of the surface cold front. This equation was shown to be useful for understanding the topographic effects on the evolution of fronts.

Unbalanced dynamics were studied in terms of departures from viscous semigeostrophy (SG) in baroclinic Eady wave and fronts. The unbalanced perturbation was found to be generated mainly by a vector forcing defined by the SG Lagrangian time derivatives of two ageostrophic wind components in the cross-frontal and along-frontal directions. In the case of free-slip boundary condition, the along-frontal wind forcing is weaker than the cross-frontal one and the unbalanced perturbations are generated largely as a linear response in the form of inertial gravity waves to the forcing. In the case of nonslip boundary condition, the along-frontal wind-forcing component is slightly stronger than the cross-frontal forcing, but the unbalanced perturbations are generated in the form of enhanced planetary-boundary-layer pumping immediately ahead of the front and in the form of inertial gravity waves in the warm sector further away from the front.

An idealized two-fluid model of density current in constant shear previously used was extended and tested with ARPS (Advanced Regional Prediction System) model simulations. The numerical results agreed closely with the theoretical analyses. The simulated flow features could be described in terms of locally (small-scale) balanced and unbalanced dynamics.

Semigeostrophic Eady Waves

The geostrophic coordinate transformation was applied to the viscous semigeostrophic (SG) Eady wave solution. In the transformed SG space, the inversion of the geostrophic potential vorticity (GPV) becomes a linear problem, so the development of the Eady wave can be clearly interpreted by the interaction between the upper and lower GPV anomalies. The generation of interior GPV anomaly plumes along the upper and lower fronts in the viscous SG solution can be easily interpreted through its analogy to the intrusion of frontal discontinuities into the interior fluid of the inviscid solution after the surface front collapses.

The SG solutions obtained for the baroclinic Eady wave fronts with two types (free-slip and non-slip) of boundary conditions were analyzed in terms of generation of cross-frontal temperature gradient in the boundary layer. The non-slip semigeostrophic solution was compared with the Ekman-layer model solution to quantify errors in the vertical motion estimated by the Ekman-pumping in the frontal boundary layer during the mature stage of the frontogenesis (near and after the time of inviscid frontal collapse).

Adjoint Theory and Methods

The classic adjoint theory derived for differentiable systems of equations has been found not to be applicable to systems with parameterized discontinuities. To overcome this, the classic theory was generalized, and the generalized adjoint formulations were further developed to deal with various complex situations in numerical models. Problems can be avoided by introducing coarse-grain tangent linearization and adjoint theory without modifying the traditional discretization, although the coarse-grain gradient check can be performed only for finite perturbations. Generalized adjoint formulations with modified discretization and generalized coarse-grain adjoint theory were derived for a vector system of equations that contains parameterized on/off switches. With vector examples, it was shown that the conventional adjoint minimization may have a convergence problem in multi-dimensional space. The problem can be solved by the generalized adjoint with modified discretization or by the generalized coarse-grain adjoint without modifying the traditional discretization in the forward model.

The ability to retrieve two-dimensional horizontal wind fields from WSR-88D radars has been studied. An adjoint-method wind retrieval technique containing predictive equations for reflectivity and radial wind was used. In particular, the potential to retrieve horizontal winds at 500 m from a case involving a non-precipitating outflow boundary was investigated. This research is unique to past single-Doppler radar retrieval studies in that WSR-88D data were used as input to the retrieval technique. Research radars used during field projects, which typically observe the atmosphere at higher resolutions both spatially and temporally than do operational WSR-88D radars, were primarily used here to validate single-Doppler retrieval techniques. In addition, the adjoint-method technique is unique in that a first guess to the retrieval solution is provided through the Velocity-Azimuth Display (VAD) technique. Through the application of the first guess, the adjoint-method retrieval technique has proven to retrieve wind flow with accuracy.

Data Assimilation

A new variational method was developed for Doppler radar data assimilation in combination with other observations. The method uses a set of mesoscale model equations as weak constraints. The equations are discretized in time using an implicit scheme to synchronize the model's time steps with the radar volume scans. The assimilation is cycled every model time step in association with each new volume scan. The method was tested with simulated radar data. It was found that the adjusted fields can reach high accuracy if the observations, model constraints and initial fields are sufficiently accurate.

Because the NEXRAD radar network provides only single-Doppler scanning over most areas in the U. S., research efforts have been undertaken to develop various methods for meteorological parameter retrievals from single-Doppler observations. These previous efforts, however, were focused mainly on retrievals with no background information. To optimally use the background field provided by high-resolution model forecasts, basic research was conducted to examine (i) how the previous retrieval methods should be upgraded in consistency with the general formulation derived for the conditional maximum likelihood estimate based on theoretical considerations, and (ii) how the theoretical formulations should be simplified under certain assumptions to make the analyses and related computations feasible. Along with these studies, prototype 3.5dVAR and simple-adjoint 4dVAR (S4dVAR) packages were developed for Doppler radar data assimilation in combination with other observations. The packages were tested with NEXRAD and SPY1 radar data for several cases. The results were very encouraging and were reported at AMS conferences.

The statistical analysis of the innovation (observations minus forecasts) vector is the most common, and currently the most accurate, technique for estimating observation and forecast error covariances in large-scale data assimilation. Following the work of Hollingsworth and Lonnberg (1986), the technique was further improved and applied to both height and wind innovation data collected for each season from the Navy Operational Global Atmospheric Prediction System (NOGAPS). The major products of the analysis included (i) observation error variances and vertical correlations, (ii) forecast error variances and correlations in three-dimensional space and their spectra as functions of pressure levels and horizontal wavenumber, and (iii) forecast error geostrophy measured, at each pressure level and horizontal wavenumber, by the ratio between the geopotential-streamfunction cross-covariance spectrum and the streamfunction power spectrum.

Low-altitude radar electromagnetic (EM) propagation can be strongly affected by the presence of surface-based and elevated ducts formed by capping inversions in the atmospheric boundary layer. In the presence of an inversion, the refractivity profile is often characterized as being tri-linear, and is determined by three key variables: the base height, the intensity, and the thickness of the inversion. To estimate these duct variables for inversion layers detected from radiosonde observations and/or model forecasts, a 2dVAR package was developed. The error statistics required by the 2dVAR were estimated from the innovations obtained from the Variability of Coastal Atmospheric Refractivity (VOCAR) field experiment. This 2dVAR may open a new path for boundary layer data assimilation in which vertical phase errors can be corrected based on the analyzed inversion base height field.

Stability of Baroclinically Sheared Flows

A spectral model was developed to study the stability and instability of baroclinically sheared flows in three-dimensional space in the presence of diffusivity. This model was used to search for unstable modes over wide ranges of wavelengths (from mesoscale to synoptic scale) and all possible orientations. It is found that in the presence of moderate diffusivity, the most unstable mode changes gradually from a nearly symmetric-type to nearly baroclinic-type as the basic state Richardson number increases (and thus the basic state became less unstable). This fills the gap between the two classic instabilities: the baroclinic instability and the symmetric instability, ranging from synoptic scale to the mesoscale.

COAMPS

A single-Doppler radar data assimilation package was incorporated into the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS, developed by the Naval Research Laboratory). This package performs three tasks: radar data quality control, three-dimensional wind retrieval, and thermodynamic retrieval. The quality control corrects radial velocity errors caused by range folding and velocity aliases. The wind and thermodynamic retrievals make variational adjustments to model produced background fields that minimize the cost function constrained by radar observations and model equations. The package was successfully tested with real Doppler radar data for the 7 May 1995 Oklahoma squall line case.

Our 3D cloud analysis package was further developed to utilize both radar and GOES satellite observation with background fields generated by COAMPS. The package was delivered to NRL Monterey and tested successfully for operational nowcast applications. The package was also used to initialize the COAMPS cloud and moisture fields for several squall line cases. The forecasts were verified against GOES images, NEXRAD radar images, and the products of the National Precipitation Analysis for squall line cases. The results showed positive impacts on short-term forecasts.

Soil-vegetation physics based on Noilhan was upgraded by introducing a skin layer. The upgraded physics was tested with ARM data for two (wet and dry) periods and showed improvements in soil water content and soil temperature predictions. The upgraded physics was also coded into COAMPS and delivered to NRL Monterey for further tests under operational conditions.

Severe Convective Storms

VORTEX-Related Tornado Research

A comprehensive review of historical observations related to tornadogenesis was completed. This study will allow comparison of new results on tornadogenesis to past ones in terms of their consistency. This work has produced a new conceptual model of tornadogenesis, which it is believed, is consistent with historical observations and some of the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX) data sets.

Analysis work was completed on the Dimmitt, TX, 2 June 1995 VORTEX tornadic storm. A comprehensive multi-platform study was conducted of the tornadogenesis phase and three phases of the tornado: intensifying, transition, and weakening. It has been documented that the tornado formed as a descending cyclonic/anticyclonic vortex pair, straddling the rear-flank downdraft, and interacted with a near-ground vortex along the rear-flank gust front produced through tilting and stretching of extremely helicity-rich air. This established a several-kilometer diameter vortex from the ground through the lower levels of the storm. Convergence and stretching led to tornado formation and intensification. The tornado cyclone gradually became engulfed in downdrafts that transported air downward containing smaller angular momentum. The demise of the tornado was associated with the entire tornado cyclone becoming a downdraft.

Analyses of VORTEX field data included an intensive study of the 8 June 1995, Elmwood, OK, nontornadic supercell storm. The focus was on a complete four-dimensional analysis, including airborne Doppler radar from the NCAR ELDORA, and the Doppler on Wheels (DOW) radar. Additional data analyzed include those from "Mobile Mesonet" vehicles. Analyses were completed on several time periods prior to and after so-called "tornadogenesis failure." Preliminary comparisons and contrasts with the tornadic Dimmitt supercell indicated that the differences between supercells with tornadogenesis success and tornadogenesis failure may be far subtler than is typically assumed.

Analysis of the 29 May 1994, Newcastle, Texas, tornadic storm was completed. This storm was shown to be a rapidly developing supercell similar in many respects to existing conceptual models of supercells, with tornadogenesis occurring in a manner similar to the conceptual model of Rasmussen and Straka.

The SubVORTEX-RFD (Rear Flank Downdraft) field program (May-June 1998) concluded with excellent data collected on eight nontornadic supercells. The primary goal of this field program was to collect data on the RFD and determine the role that it, inflow, and near-ground circulation and divergence play in both tornadogenesis success and failure (tornadic and nontornadic supercells).

A significant observational study was completed on the low-level thermodynamic state of tornado cyclones. These are vortices of 1-3 km scale that are present at the ground in most of the supercells that we have observed with mobile mesonet equipment. In a sample of about 30 tornado cyclones, it was found that tornado formation was more likely and tornado longevity greater if the near-ground air in the tornado cyclone is buoyant and potentially buoyant with respect to the storm inflow. The near-ground air within the tornado cyclone is hypothesized to originate in the RFD. These results and hypotheses were further explored using idealized axisymmetric numerical simulations of tornado cyclones containing peripheral downdrafts. The simulations demonstrated that angular momentum-rich downdraft air penetrated closer to the axis of the vortex, leading to larger tangential velocities, when the downdraft arrived at the ground with buoyancy relative to the inflow base state. Based on these findings, we have developed deployment strategies for obtaining a new generation of near- and in situ tornado observations. These included design of an all-weather unmanned aerospace vehicle (UAV) in collaboration with the Department of Aerospace Engineering at the University of Colorado. This remotely controlled, instrumented aircraft should be capable of making state measurements within tornado cyclones and weak tornadoes. In collaboration with the National Geographic Society, we also evaluated strategies for deployment of in-situ optical and state sensors in tornadoes, including a next-generation ‘turtle’ and a multi-camera digital imaging system. These preliminary investigations were conducted in preparation for the next VORTEX, which may be held in the 2005-2008 timeframe.

We also continued to refine and enhance our observational analysis tool set. Roughly 90 percent of our analysis, visualization, and Doppler processing software were ported to Interactive Data Language (IDL) for greater compatibility across our research group and with other groups. Enhancements included the addition of a high-resolution terrain data set for the entire central U.S., allowing us to perform pressure reduction of mobile mesonet data for any experiment we have conducted.

Use of Unmanned Aerospace Vehicles in Severe Weather Research

The primary purpose of this project was to develop the capability to fly UAVs in formation to gather mesoscale meteorological observations. Working with Wyndemere, Inc. we established the goal of producing a small UAV (~1.5 m wingspan, < 15 lb weight) that is capable of autonomous flight. This requires a state engine that can determine the attitude of the aircraft, as well as a flight computer that can direct the aircraft control surfaces based on the combination of attitude information and requested flight path. We established the goal of producing an aircraft that would cost less than $5,000 in materials so that we could easily replace lost or damaged aircraft. Hence, we have utilized concepts such as a GPS-only state engine that does not require accelerometers, magnetometers, or other expensive equipment. Several off-the-shelf 'almost ready to fly' (ARTF) aircraft were built, and the rudimentary state engine and flight computer were tested.

Supercell Climatology

Climatology of the supercell spectrum was completed. It was found that anvil-level storm relative flow is the largest identifiable environmental influence on supercell type. This work was followed by a numerical modeling study using a next-generation cloud model.

Tornado Vortex Signatures

A COMET-sponsored collaborative study of the utility of tornadic vortex signatures (TVS) in very short-term tornado prediction was completed. The premise of the study was that guidance provided by a TVS should increase the probability of a successful (verifiable and timely) warning of certain modes of tornadogenesis. By looking at a relatively large sample of tornadoes observed by WSR-88Ds across the country, we have confirmed that such utility depends on TVS "behavior" and also the deleterious effects of radar sampling on TVS representativeness. Behavior is linked to the way in which the tornado develops, namely, (i) formation aloft, then gradual descent to the ground, or (ii) rapid formation either uniformly over a several kilometer vertical depth or very near the ground. Results indicated that tornadoes within convective lines tended to be associated with "non-descending" TVSs, identification of which allowed a mean tornado lead-time of five minutes.

Storm-Relative Helicity

Several studies related to storm-relative helicity in the environments of tornadic storms have been completed. It was found that helicity varies greatly on scales that are not sampled with present observing networks. The causes of this variation are yet to be determined, although small (~ 1 ms^{-1}) amplitude hodograph loops and similar variations can lead to large changes in helicity.

CAPE

An examination was conducted of all 1992 soundings that had non-zero convective available potential energy (CAPE). Soundings were classified as supercells producing significant tornadoes, supercells not producing significant tornadoes, or non-supercells. SELS log and lightning strike data were used to identify events.

Comparisons of CAPE with standard stability indices (used for evaluating the convective potential of the atmosphere) revealed only moderate correlations. This is because indices such as the Lifted Index measure single-level buoyancy while CAPE measures both integration depth and buoyancy. Normalizing CAPE values by the depth over which the integration takes place provides an index (NCAPE) that is independent of the depth and represents a convenient measure of mean parcel buoyancy. This normalization effectively distinguishes between environments with similar CAPE but that exhibit different buoyancy and integration depth. Also, because the vertical distribution of CAPE can play an important role in convective updraft strength, it is advantageous to vertically partition CAPE and NCAPE into multiple layers. NCAPE may provide a more useful indicator of buoyancy in environments in which the depth of free convection is shallow and total CAPE is small. It is suggested that NCAPE computations be used in combination with CAPE for the evaluation of convective potential.

Static Stability

Two aspects of low- and mid-level tropospheric static stability over the U.S. were examined – its climatological distribution, and the forcing mechanisms responsible for its evolution prior to and during convective outbreaks. Results suggested that the Rocky Mountains play an important role in the creation of low stability during most of the year. The synoptic-scale flow interacts with and modifies this area of low stability to create an area in the Great Plains where severe convection is possible when combined with other favorable ingredients. To investigate the physical processes responsible for modifying static stability during severe weather outbreaks, a severe event in November 1992 was simulated using a version of the Penn State/UCAR mesoscale model.

Derechos

During the late spring and summer months, a type of widespread convective windstorm (a derecho) is an occasional occurrence east of the Rocky Mountains. Study focused on the progressive derecho, which usually consists of a single, large mesoscale convective system in a relatively benign synoptic-scale environment. Given the current inability of operational numerical models and observing systems to consistently resolve weakly forced convective events and our lack of a dynamical understanding, these occurrences remain a significant forecasting and warning problem.

Sounding data from twelve derechos that occurred in weakly forced large-scale environments were composited and objectively analyzed, using the sum of a low pass and a band pass analysis, in an attempt to include important large-scale features in the pre-convective environment. This analysis, which agreed favorably with prior observational studies of progressive derecho environments, was used to initialize the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model Version V (MM5). Major differences in the initial conditions from past simulations included a horizontally inhomogeneous environment, unidirectional shear in upper-levels with weaker shear in low-levels, and a relatively dry mid-troposphere. The model develops an explicitly resolved, derecho-producing convective system, that resembles observations on many scales. Past numerical simulations suggest that the strength and longevity of squall lines results from a balance between the vorticity associated with the environmental low-level shear and the baroclinic generation of vorticity at the leading edge of the cold pool. In contrast, it was found that the production of a deep cold pool and the maintenance of upper-level shear (and associated critical layer) through convective feedbacks are important to the strength and longevity of this simulated derecho. The cold pool, acting as an effective barrier to the flow, provides deep convergence throughout the lower troposphere and the critical layer maintains the updrafts at a favorable location above the gust front, as long as there is significant CAPE within the inflow layer. A strong and mobile meso-high associated with the deep cold pool is the main mechanism that maintains the strong winds over large distances. These results suggest that internal parameters are more important to the evolution of the simulated convective system than its interaction with the initial low-level wind profile, which may partially explain the difficulty in forecasting derecho events.

Quasi-Linear Convective Systems

Study was done on the formation and climatological distribution of tornadoes within quasi-linear convective systems (QLCSs). The horizontal extent of viable tornado-breeding sites is an order of magnitude larger in QLCSs than in individual supercells. QLCS tornadoes can be strong and produce extensive damage despite "conventional wisdom" that suggests otherwise. Also, QLCS tornadogenesis appears to occur, on average, more rapidly than does supercell tornadogenesis from the perspective of Doppler radar. The geographical, seasonal, and diurnal distributions of QLCS tornadoes are unknown.

Research focused on the formation and implications of low-level, meso-gamma scale vortices within QLCSs such as squall lines and bow echoes. Such QLCS vortices, also referred to as mesovortices, are observed frequently, at times in association with tornadoes. Idealized experiments with a numerical cloud model showed that low-level mesovortices develop in simulated QLCSs only when the environmental vertical wind shear is within a relatively narrow range of values and when the Coriolis forcing is nonzero. As illustrated by a QLCS simulated in an environment of moderate vertical wind shear (20 ms^{-1} over a 2.5-km depth), mesovortexgenesis is initiated at low levels by the upward tilting, in downdrafts, of horizontal baroclinic vorticity. Such relative vertical vorticity is vertically stretched, as is also planetary vorticity. In fact, in terms of circulation tendency, the time-integrated contribution to positive circulation by the flux of planetary vorticity is, over a period of less than an hour, comparable to or larger than that due to fluxes of horizontal and/or vertical vorticity. In moderate-to-strong environmental shear, the simulated QLCS evolves into a bow echo whose strongest low-level winds surprisingly are found about 20 km to the northwest of the bow-echo apex rather than just behind the apex, as is typically conceptualized. In other words, what are regarded as the most damaging 'straight-line' winds are induced by the low-level mesovortices. The swath of these winds expands with time, owing apparently to a mesovortex amalgamation, or 'upscale' vortex growth. As with the mesovortex formation, the system-relative location of the damaging winds is dependent on the system-scale dynamics, which in turn is dependent on characteristics of the larger-scale environment.

Severe Winter Storms

A significant winter-precipitation event occurred on 7-9 March 1994 in Oklahoma. Snow accumulations greater than 30 cm (12 in) were measured within a ~50 km wide corridor in northern Oklahoma. On the synoptic- and meso-scales, a correspondence between large snow accumulations and 600-hPa frontogenesis was revealed; the precipitation was formed above the cold-frontal surface, owing to mid-tropospheric ascent associated with the cross-frontal circulation in a region of elevated conditional instability. The location of such a narrow corridor of large accumulations was not, however, disclosed by any patterns in the radar reflectivity data. Indeed, during this event, a snow-accumulation "band" was not associated with a persistent band of enhanced reflectivity, and vice versa. Dual-polarization and dual-Doppler radar data allowed for a novel analysis of storm-scale winter precipitation features, within the context of the larger-scale diagnosis. It was possible, in order of decreasing poleward distance from the surface cold front, to identify (1) elevated convective elements, which presumably functioned as ice crystal “generator” cells and were embedded within a broad region of generally stratiform precipitation; (2) a reflectivity band and associated rain-snow transition zone, the evolution and structure of which apparently were coupled to the effects of melting precipitation and strong vertical wind shear; and (3) a highly-tilted, prolific lightning-producing, *non*-elevated cell that was sustained in the post-frontal air in part by virtue of its rotational dynamics.

First Successful Tornado Forecast Retrospectives

A study was completed of the synoptic setting that led to two destructive tornadoes at Tinker AFB in 1948, the second of which became known as the first successful forecast of a tornado.

Drylines

Through a case study approach, the motion of a dryline within a synoptically active environment in the Southern Plains, along which severe storms ultimately developed, was examined in detail. Observations from research aircraft, surface mesonetwork stations, mobile ballooning laboratories, radar, wind profilers, satellite, and operational surface and upper air networks were examined and combined. Additionally, output from the operational Eta mesoscale model was examined to compare predictions of dryline motion with observations and to aid in interpretation of observations. The dryline in this case (16 May 1991) not only advanced rapidly eastward, but also exhibited redevelopment (loss of definition at one location and gain at another) in at least two instances. Aircraft observations revealed that an eastward redevelopment occurred in the early afternoon and was characterized by a series of four “steps” along the western edge of the boundary layer moisture. The westernmost and easternmost steps coincided with the locations of the dryline before and after redevelopment, respectively. The Eta model forecast initialized at 1200 UTC produced dryline features that were qualitatively similar to observed fields. The eastward motion of a broad area of enhanced moisture gradient agreed well with observations following an initial spin-up period. A north-south moisture convergence axis preceded the rapid eastward motion of the dryline by several hours. Lack of subsidence in the air behind the modeled dryline led to the conclusion that processes other than downward transfer of horizontal momentum by larger scale motions (that would support eastward advection) produced the rapid dryline motion and observed eastward dryline bulge. Results of diagnosing physical processes affecting model dryline motion point toward boundary layer vertical mixing coupled with advection of dry air aloft as vital components in rapid advance of the dryline eastward in this synoptically active case.

The second part of this research focused on multiple boundaries in the dryline environment, initiation of storms in two areas along the dryline, and late-afternoon retreat of the dryline. Aircraft measurements in the boundary layer revealed that both the east-west extent of moisture gradients and the number of linear regions containing large moisture gradients varied in the along-dryline direction. Aircraft penetrations of “thinlines” observed in clear air return from radar revealed that all thinlines contained cross-line convergent signatures and moisture gradients, and that more distinct thinlines were associated with stronger convergence. Significant moisture gradients in some cases were not associated with either thinlines or convergent signatures, leading to the conclusion that clear air targets consisted of other than moisture gradients. Based upon comparison of satellite and radar fields, convective clouds on this day formed at the dryline rather than significantly east of the dryline. The three thunderstorm cells that developed in east-central Oklahoma developed along a 20-km section of the dryline south of a dryline bulge and within a 30-minute period. The storms appear to have developed in this location owing to enhanced convergence resulting from backed winds in the moist air in response to lowered pressure in the dry air to the northwest. Aircraft measurements in the boundary layer and satellite sensed surface temperature both indicated localized warming in this area to the northwest. Farther north there was a 70-100-km segment along the dryline where few convective clouds formed during the afternoon. This coincided with a swath of cooler boundary layer air that resulted from significant thunderstorm rainfall during the previous night. A severe thunderstorm complex that developed along the Kansas-Oklahoma border was initiated at the intersection of the dryline and a cloud line that extended into the dry air. An aircraft penetration of the cloud line about 12 km from its intersection with the dryline showed convergence and deepened low-level moisture at the cloud line. The cloud field that evolved into the cloud line over a period of several hours developed over the area that had received the heaviest rainfall during the previous night. The retreat of the dryline in the central and southern portion of the analysis domain in the late afternoon and early evening included both continuous motion and redevelopment toward the west-northwest. In addition, within the region over which the “jump” took place there were other thinlines in the radar return that were verified to be convergent in the low levels based upon a vertical cross-section derived from aircraft data through both the dryline and a secondary thinline. This dual-mode retreat of the dryline was accompanied by a gradual backing of the winds and a moistening in low levels, based upon clear air radial velocity measurements and soundings.

Quantitative Precipitation Estimation

Synoptic Patterns Associated with Summer Thunderstorms in Arizona

Study continued of the synoptic patterns that bring severe summer thunderstorms to south and central Arizona. Findings showed that a surprisingly large number of days during the summer "monsoon" at Phoenix are actually quite dry; specifically, of the 70 percent of the summer days that are moist, only about 50 percent have thunderstorms over low desert areas. Also, routine sounding data taken at Tucson do not discriminate between storm and no storm days over the central deserts, but lightning data indicate that storms are much more widespread over the entire state (in spite of the lack of signal in the Tucson data) on low desert storm days.

Microburst Structure

A microburst storm that occurred near Phoenix has been studied in depth and a paper was provided to the ROC for its training website. It discusses the structures and likely microphysics of this event. The case illustrates clearly that the collapse of the elevated reflectivity core (presumed due to small hail) lags substantially behind in time the occurrence of the microburst at the surface. This has important implications for methodologies to warn for these events.

Precipitation Estimation Scheme

Research led to a prototype precipitation estimation scheme incorporating both WSR-88D PPS data and GOES satellite data to improve rain estimations over regions of complex terrain. The technique also has great potential for application over flatlands. This effort demonstrated that the combined data approach can mitigate the bright band contamination that makes the operational precipitation estimates nearly useless during winter storms.

Intermountain Precipitation Experiment (IPEX) Field Program

The Intermountain Precipitation Experiment (IPEX) was a field and research program designed to improve the understanding, analysis, and prediction of precipitation and precipitation processes in complex terrain. The project involves scientists from the NSSL, University of Utah, and Desert Research Institute (DRI). The field phase of this experiment was successfully conducted during 31 January - 25 February 2000. A CIMMS scientist at NSSL is one of the program's scientific leads, as the research portion of this project continues beyond the cooperative agreement period. The major scientific objectives of IPEX are to:

- Advance fundamental knowledge of orographic precipitation, with an emphasis on the narrow, steeply sloped Wasatch Mountains of northern Utah;
- Improve knowledge of lake-effect precipitation of the Great Salt Lake;
- Validate and improve high-resolution data-assimilation systems, mesoscale model performance, and quantitative-precipitation forecasts over complex terrain; and
- Validate and improve quantitative-precipitation estimates produced by WSR-88D radars located at high elevation.

These objectives are directly related to two major foci of the U. S. Weather Research Program (USWRP): quantitative-precipitation forecasting and the optimal mix of observations in numerical weather prediction. Results from IPEX have had positive scientific and socioeconomic benefits for the Intermountain West, including Salt Lake City, host of the 2002 Winter Olympics.

IPEX field observing platforms included the NOAA P-3 research aircraft, two portable Doppler radars on Wheels (DOW), two NOAA/NSSL mobile laboratories with cross-chain LORAN Atmospheric Sounding Systems (CLASS), a surface-based microwave radiometer, a vertically pointing S-band radar, supplemental soundings from regional National Weather Service upper-air observing sites, and the Utah Mesonet. Data collected during the field program have allowed project scientists to examine a number of questions and testable hypotheses concerning the interaction of dynamical and microphysical processes during orographic precipitation events, including factors controlling the distribution and intensity of precipitation across a narrow, steeply sloped mountain range like the Wasatch Mountains. The complex interactions between thermally- and terrain-driven circulations that produce lake-effect snowbands of the Great Salt Lake are also examined. Other project activities included validating and improving mesoscale model quantitative precipitation forecasts and quantitative precipitation estimates using WSR-88D radars.

Educational benefits included the participation of graduate and undergraduate students from the Universities of Utah and Oklahoma. IPEX datasets have been and are being used for classroom and laboratory instruction. Early observational and scientific returns include:

- First intensive observations of winter storms in Teton and Wasatch Mountains
- Detailed observations of the two largest storms in the Wasatch Mountains this winter
- Exceptional radar data collected during Valentine's Day wind storm (caused a fatality in Brigham City; 73 mph wind gust in Cache Valley)
- Unprecedented measurements of electrification and lightning in winter storms
- First dual-Doppler radar analysis of a cold front interacting with the Great Salt Lake and surrounding mountains
- Demonstrated value of the Mesowest Cooperative Networks for detailed analysis and short-range forecasting of winter storms (such as might be employed during the 2002 Olympics)
- Testing of experimental forecast products (that might be employed in the future by the National Weather Service for public dissemination)
- Real-time interaction of IPEX scientists and forecasters and National Weather Service forecasters
- Educational experience for 20 University of Utah undergraduate and graduate students who assisted in collection of data and forecasting
- 120 local junior high school students toured the NOAA WP-3D Orion Hurricane Hunter aircraft
- Multiple local media stories helped explain the project's purpose and educate the public about the complex weather forecasting challenges in the Intermountain West
- The NOAA P-3 flew a total of 41 research hours and logged 10,000 miles; about one gigabyte of data was collected per flight
- First use of two mobile Doppler radars in winter-storm research
    - 70 total hours of operation
    - 7 gigabytes of radar data collected during IPEX
    - Unique observations of complex airflow within Tooele Valley
- NWS released 205 additional balloon launches at Salt Lake City, UT (55); Reno (14), Elko (58), and Desert Rock/Las Vegas, NV (9); Grand Junction, CO (16), and Boise, ID (53)
- 100 research balloon launches from the two NSSL mobile laboratories
- One gigabyte of data was collected
- Observed air motions and reflectivity from clouds producing rain, snow, and graupel at very fine temporal and spatial (60 m) resolutions
- Interactions with Ski Patrol at Snowbasin Ski Resort were invaluable in helping maintain in situ measurements on the mountain

Cloud Physics

Radiative Transfer

In collaboration with scientists from Institute of Atmospheric Optics in Russia, a study of radiative transfer in an inhomogeneous cloud medium was conducted. It combined a 3D Monte Carlo model with the CIMMS 3D Large Eddy Simulation (LES) XMP model. The Monte Carlo approach allows for the most accurate calculation of the 3-D fields of radiative fluxes, and can be applied to any irregular cloud geometry. It also accounts for spatial inhomogeneity of liquid water, water vapor, and atmospheric gases. The model employs a computationally efficient maximal cross-section method that allows efficient simulations of 60-160 million photon scattering and absorption events. The study focused on the role of vertical inhomogeneity in the extinction coefficient, asymmetry parameter, and scattering function. It was found that the area averaged radiation fluxes depended not only on the mean values of optical parameters, but also on their spatial variances. The prediction of the higher statistical moments of optical parameters or the probability distribution functions of cloud microphysical variables may be necessary for more accurate prediction of cloud radiative properties.

Data from the April 1997 Atmospheric Radiation Measurement (ARM) Program intensive observing period (IOP) on cloud-aerosol interactions over the ARM Southern Great Plains site were selected for analysis and preparation for modeling studies. The data include in-situ measurements of cloud microphysical parameters of liquid (2 April) and mixed phase (7 April) stratocumulus clouds, as well as cloud radar reflectivity time series. Analyses were completed and LES simulations of the experimental cases were undertaken.

The spectral dependence of the radiative horizontal transport and its effect on the accuracy of near-infrared absorption retrieval was investigated using an LES cloud model with explicit microphysics and a 3D Monte Carlo radiative transfer model. Using measurements made during the ASTEX observational campaign, a field of highly inhomogeneous broken stratocumulus clouds with approximately 50 percent coverage was simulated. It was found that the small-scale (~100 m) variance of the radiative horizontal transport depends significantly on the wavelength. The cloud droplet absorption at λ=1.65 μ leads to the increase in the variance of horizontal transport, *var (E)*, at some cloud locations by as much as 20 percent. The water vapor absorption at λ=0.94 decreases the *var (E)* by as much as 15 percent. As a result, estimates of spectral absorption in the near-infrared using the values of horizontal transport outside the absorption interval (e.g., in the visible range) may be quite inaccurate with errors at some locations as large as 100 percent. In the studied case of a broken cloud field, a much weaker spectral dependence of horizontal transport and a more accurate absorption estimate can be obtained by averaging cloud radiative parameters on a scale of about 500 m.

A collaborative effort between CIMMS and scientists from Florida State University, Los Alamos National Laboratory, and NASA attempted to link a 3D longwave radiative code developed at FSU with the CIMMS LES model. The objective of the study is to investigate the 3D radiation effects on cloud layer dynamics and boundary layer evolution and to evaluate the potential and limitations of the commonly used two-stream delta approximation for radiative transfer models. A set of timing tests was performed with the FSU 3D longwave radiative code using CIMMS workstations.

Cloud Inhomogeneity

The effect of cloud inhomogeneity on the two commonly used parameterizations of the cloud optical depth were studied by contrasting them with the exact definition of optical depth, through the cloud drop distribution function. The results showed that the parameterization, which takes into account the vertical stratification of liquid water content and cloud drop effective radius, can significantly overestimate the true value of cloud optical depth. Another conclusion from the study was that determination of the value of the cloud drop effective radius averaged in both the horizontal and vertical is much more important than simply accounting for vertical inhomogeneity.

Lack of data on cloud variability is the main reason why most current models consider clouds as plane-parallel, horizontally homogeneous combinations of cloudy and clear portions defined by cloud fraction. Unique information on cloud variability can be obtained using data from profiling observational instruments, in particular using cloud reflectivity data from the ARM Program millimeter cloud radar. The cloud inhomogeneity may be described in terms of probability distribution functions (PDFs) and dominant scales of the wavenumber spectra, as well as employing scale invariance analysis. The latter has been widely used over the last few decades to study turbulent flows, including atmospheric turbulence.

We analyzed the usefulness of various statistical tools in describing cloud inhomogeneity. The PDFs provided the sub-grid information on cloud parameters and are an important part of cloud physics and radiative parameterizations in meso- and large-scale models. Spectral and scale invariance analyses are additional tools to characterize cloud internal structure. The spectral analysis locates the dominant wavenumbers, while the scale invariance analysis determines the upper and lower scales that bound scale-invariant regimes of the flow. By combining spectral and scale invariance analysis we can classify atmospheric datasets within the scale-invariant range scale as stationary or nonstationary. The stationarity is fundamental for obtaining meaningful spatial statistics. It indicates the minimal length and resolution of datasets that is needed to obtain reliable statistics. Many commonly used statistical procedures produce ambiguous or even meaningless results for nonstationary datasets.

We performed a preliminary statistical analysis of two cloud systems, representing a low and a mid-level stratocumulus cloud layer, observed over the ARM SGP site on 2 December 2000 and 16 May 2000, respectively. The low stratus layer was capped by a strong inversion at 1200–1300 m with a temperature jump of 7-13° C. The rather small values of radar reflectivity Z with maximum less than –10 dBZ within the layer indicated the absence of significant drizzle. Therefore, the variability of Z reflected most likely the variability of surface fluxes and inhomogeneity in convective organization, rather than drizzle patchiness. In this case, the PDFs are broader at cloud top and more uniform at cloud base. The 16 May 2000 case represented a powerful alto-stratocumulus cloud system spanning in height from 5.5 to about 11 km. The system developed slightly ahead of a warm front and lasted for one and a half days, producing showers on the second day. The maximum radar reflectivities (about 10 dBZ) were near cloud base, indicating accumulation of drizzle, although the drizzle drops were not large enough to reach the ground. Plots of PDFs showed broader distributions at cloud base compared to cloud top. The width and shape of the distribution have important implications for determining cloud microphysical and radiative properties. For instance, a more homogeneous field of cloud reflectivity near cloud top (represented by a narrow PDF) will result in a more homogeneous cloud reflectance field. In addition to the millimeter cloud radar data, the 1-km resolution AVHRR satellite reflectance field for the low stratocumulus case observed on 2 December 2000 was analyzed to compare the dominant scales of variability for radar reflectivity and satellite reflectance fields. A preliminary Fourier analysis indicated that both fields have major common variability features, demonstrating congruence between surface and satellite observational analyses.

Drizzle Parameterization

A drizzle parameterization applicable for cloud-scale LES models was developed. The cloud parameterization was successfully tested using both field observations and simulations with the

CIMMS LES explicit microphysics model. Another study focused on the aerosol processing by marine boundary layer cloud layers using a model with an aerosol tracking option. Results of this research have contributed to the refinement of drizzle parameterizations used in bulk cloud scale models.

The objective of a U.S. Department of Defense/Office of Naval Research ASSERT grant was to provide an opportunity for U.S. citizens to learn about aerosol-cloud-radiation interactions with an emphasis on cloud microphysics, drizzle formation, boundary layer dynamics, and turbulence. A case study was based on the 16 July 1993 flight during the SOCEX field program. During this case of a well-mixed marine boundary layer with abundant drizzle, two aircraft "stacks" were flown (west of Cape Grim, Tasmania) to make thermodynamic, radiation, wind, microphysical, and aerosol measurements over a two-hour period. The microphysical spectra near the surface, at cloud base, and in-cloud were processed. The aircraft data set was supplemented by estimates of back trajectories and mean subsidence, standard synoptic observations, and AVHRR data.

A new integral moment microphysics parameterization for stratiform clouds was developed at CIMMS for cases of moderate and heavy drizzle. This bulk parameterization has been implemented into the CIMMS LES model and its performance evaluated by comparing it with benchmark explicit microphysical simulations. An important part of the parameterization is the link between the ambient aerosol load and cloud microstructure. It was found that the composition of atmospheric aerosol, its non-sea salt (sulfate) aerosol fraction and the shape of the ambient sulfate aerosol spectrum all have a strong effect on cloud microphysical and radiative parameters. A second thrust of the project was the development of cloud drop effective radius parameterization for drizzling marine stratocumulus. In case of moderate drizzle, a quite accurate two-variable parameterization can be used. For heavy drizzle, however, only a three-variable parameterization proves to be sufficiently accurate. A unified form of the parameterization for all drizzle cases, which can be conveniently used in mesoscale models, was formulated. It was concluded that a three-variable full moment parameterization provides the most accurate representation of effective radius in precipitating stratocumulus clouds.

The prediction of cloud microstructure in numerical weather prediction (NWP) models is of paramount importance to accurate weather and precipitation forecasts. Analysis was continued of the feedbacks between precipitation, boundary layer thermodynamical parameters and surface winds in defining the cloud microstructure. In a series of LES experiments, it was found that surface winds affect the stratocumulus drop concentration in a complex way, involving many feedbacks between the intensity of boundary layer turbulence, drizzle, total concentration and shape of the background CCN sulfate spectra. Model simulations showed that the total background sulfate concentration does not uniquely define the effect of surface winds. An accurate formulation of this effect should account for the shape of the background sulfate spectrum; in particular, it is important to account for the number concentration of Aitken nuclei. The latter are activated at supersaturation in the range 0 – 0.2 percent, which is the prevailing range of occurrence in stratocumulus-topped marine boundary layers characterized by moderate turbulence.

Cloud Drop Parameterization

Cloud microstructure plays a crucial role in the persistence and fractional coverage of boundary layer clouds that significantly affect regional weather. A cloud drop parameterization was developed in terms of the prognostic variables available in mesoscale models. The CCN concentrations, as well as the boundary layer turbulence intensity, define the number of activated cloud drops. The parameterization was derived using 36 LES numerical experiments in environments characterized by 12 different CCN concentrations (from 25 to 1000/cm^3) and three levels of turbulence intensity (characterized by values of in the range from approximately 0.06 to 0.27 m^2/s^2). The developed parameterization allows a physically based prediction of cloud drop concentration and takes into account the ambient aerosol concentration, as well as the level of turbulence intensity characterized by the mean vertical velocity variance. This parameterization has been implemented into the COAMPS.

A mesoscale simulation of the cloud/fog system over the central California coastal region was also performed. Analysis showed that COAMPS with the new drizzle scheme captures many important features visible in fine scale LES simulations. The main goal of the simulation is to improve the cloud/drizzle/fog forecast by investigating the feedbacks between mesoscale conditions and cloud/drizzle parameters.

Retrieval Algorithms

The performance of various liquid water retrieval algorithms for clouds was evaluated based on reflectivity data collected by the ARM Southern Great Plains millimeter cloud radar. The evaluation was carried out using observation system simulations. The microphysical data generated by the CIMMS LES model in experiments based on ASTEX and ARM Southern Great Plains IOP observations were used to calculate cloud properties and radar characteristics to verify the retrieval algorithms. The cloud water profiles retrieved from radar reflectivity were compared to those calculated directly from cloud drop spectra. Both non-precipitating and drizzling stratocumulus cloud layers were considered. The retrievals based solely on radar reflectivity data were evaluated against those using a mix of observations from cloud radar and microwave radiometer. It was shown that a combination of cloud radar and microwave radiometer data could significantly increase the accuracy of the liquid water retrieval.

The performance of a number of cloud liquid water (W) retrieval algorithms based on various Z - W power-law relationships was evaluated. Two case studies were considered: a marine stratocumulus layer observed during the ASTEX program on 12 June 1992 and a continental stratus layer observed during the ARM field experiment on 30 April 1994. It was shown that algorithms based on radar reflectivity alone are not capable of adequately retrieving the horizontally averaged vertical profile of cloud liquid water content. The knowledge of the exact cloud droplet concentration does not necessarily improve the retrieval, either, as the errors in these cases are related mostly to the assumption of a prescribed width of the droplet size distribution. The retrieval algorithms can be refined through introduction of an additional constraint based on the independently measured liquid water path. We were able to find the parameters that provide the most accurate retrieval results. Horizontal averaging of liquid water path over the domain of several kilometers does not affect the accuracy of the retrieval. This justifies the use of the algorithm with a passive microwave radiometer even when it has a wider field of view and uses longer averaging times than millimeter-wavelength cloud radars.

A method was developed for retrieval of cloud optical depth and effective radius for stratiform clouds using the data from the ARM millimeter cloud radar and ground observations of CCN number concentrations. The method was tested using the data from the CIMMS LES model initialized with observations taken during ASTEX and ARM Southern Great Plains intensive experimental periods. In addition, the effect of cloud inhomogeneity and variations in cloud base and top were evaluated relative to the performance of various parameterizations of cloud optical depth.

Cloud Analysis

A 3D cloud analysis package was developed by CIMMS, NSSL, and Naval Research Laboratory scientists to utilize GOES satellite imagery data with a model background field generated by the Navy's COAMPS. The analyzed field was used to initialize the cloud and moisture fields for the squall line case over the U.S. east coast on 9-11 September 1999. The model's predictions were verified against the GOES images, NEXRAD radar images, and products from the National Precipitation Analysis. Comparisons were made between forecasts with and without using the 3D cloud analysis. A positive impact of the cloud analysis was seen in the very short term forecast (1-3 h).

Air Quality Modeling

In recent years, considerable progress has been made in adapting numerical meteorological models to the input requirements of air-quality models. Despite this progress, however, serious limitations remain. One of the most significant sources of error affecting air-quality studies using meteorological models is the absence of an adequate representation of shallow convective clouds. These clouds are usually of secondary importance meteorologically, but they can be dominant in terms of air chemistry, providing a vehicle for the vertical transport of pollutants and creating an aqueous reaction chamber in an otherwise dry environment. Our research was directed toward the development and evaluation of a shallow convection parameterization for mesoscale meteorological models, which will greatly enhance the capability of these models to provide a realistic representation of the processes that are important components of atmospheric chemistry, namely turbulence, vertical mixing, and cloud. This included testing, refinement, and evaluation in 1D and 3D model frameworks. Performance evaluation and parameter estimation were based on comparisons with numerous data sources, including several field programs. To allow the broadest possible application, we also maintained modularity, portability and computational efficiency. By meeting these goals, we provided air-quality models with explicit and self-consistent mesoscale meteorological information representing the critical physical processes associated with shallow convection. Thus, we provide the means to enable these models to more realistically simulate the evolution and transport of ozone, particulates, and other pollutants than is currently possible. We anticipate that this development will considerably enhance the overall skill of the air-quality models.

Work focused on providing a mechanism for well-resolved scales in a numerical model to allow for the accumulation and fractional coverage of *inactive* (i.e., decaying) subgrid-scale clouds. In particular, working with a 1D (vertical column) version of the MM5 model, we formulated equations to allow cloudy air mass from (parameterized) active, buoyancy-driven cumulus clouds to accumulate and undergo realistic decay processes within individual model grid elements. This parameterization of the passive phase of shallow clouds included formation and regeneration as a product of active updrafts, as well as dissipation of both liquid water content and fractional area as a function of lateral mixing, cloud-top-entrainment instability, and microphysical effects. This aspect of the shallow convection process is absent in most existing parameterizations, but decaying clouds can have a significant impact on numerical weather prediction because they often cover a fraction of the sky that is an order of magnitude or so larger than the fractional area occupied by *active* updrafts. Moreover, they are critically important for atmospheric chemistry processes.

Boundary Layer Meteorology and Turbulence

Surface Fluxes

To overcome the drawbacks of the conventional Bowen ratio energy balance technique and the profile method, a variational method was developed to compute surface fluxes of sensible and latent heat, using data from the Surface Energy and Radiation Balance Systems (SERBS). This method makes better and more complete use of the data and constraints provided by the surface energy balance equation and the similarity profile equations.

Atmospheric Electricity

Textbook

In February 1998, Oxford University Press published the graduate textbook, *The Electrical Nature of Storms*, written by Don MacGorman (CIMMS Research Fellow) and Dave Rust (NSSL Research Scientist). It has been well received by the scientific community.

Parameterizations

Electrification parameterizations developed have been studied in two models: the ARPS model provided by the CAPS and a model by Straka. We developed additional parameterizations of electrification mechanisms and lightning. Both models give similar results for electrification in small thunderstorms and through the first few flashes of supercell storms. However, they differ substantially at later times in the simulations of supercell storms and other large thunderstorms, because the more sophisticated ice microphysics of the Straka model produces longer-lasting electrification and more realistic maturing and dissipation of large storms. We have shown that the latter model can produce supercell structure and electrification similar to that produced by a kinematic model of the Binger, OK supercell storm. Furthermore, tests of the lightning parameterization developed by MacGorman et al. (1999), with a few added features, have shown that it can produce both cloud and cloud-to-ground flashes that appear similar in many respects to actual mapped flashes.

A new lightning parameterization was developed that simulates the three-dimensional branched structure of lightning channels. Model results indicate that positive cloud-to-ground (CG) lightning flashes can initiate only when a region of negative charge exists below the positive charge region tapped by the flash. This requirement is analogous to the necessity of a lower positive charge region to initiate negative CG lightning from the negative region above. Charge conservation in the thunderstorm model has been dramatically improved, allowing us to investigate ties between cloud-to-ground lightning polarity with the overall thunderstorm charge polarity. We also investigated correlations between lightning and thunderstorm quantities such as updraft mass flux and precipitation ice mass. The growth and decay of the graupel volume appears to correlate well with lightning activity, but this result needs to be tested for full life cycles of a wider variety of storm types.

MCS Electrification and Polarimetric Radar Study (MEaPRS)

The MCS Electrification and Polarimetric Radar Study (MEaPRS) was conducted in central Oklahoma from 15 May-15 June 1998. A small adjunct field program associated with MEaPRS was also performed. The two primary objectives of MEaPRS were to 1) investigate mesoscale convective system (MCS) electrification processes, and 2) improve understanding of polarimetric radar measurements.

In the MCS electrification component, investigators participated in the mobile ballooning of instruments to record lightning field changes, particle charge, and X-rays. Electric field profiles and airborne radar data were obtained in two mesoscale convective systems. Electric field profiles and multiparameter radar data were also obtained in several isolated severe thunderstorms. These storms and storm systems included several in which the majority of ground flashes lowered positive charge, instead of the more usual negative charge. In some of the storms, the three dimensional location of cloud flashes and ground flashes were mapped by a system developed by New Mexico Institute of Mining and Technology and operated by them in cooperation with NSSL during the field program. These data from these storms have been and will be the subject of considerable research by scientists and graduate students during the next several years.

In the polarization radar component of MEaPRS, emphasis was placed on collecting high quality microphysical data with which to compare polarimetric measurements made by the NSSL Cimarron radar. NOAA P-3 flights were conducted in seven mesoscale precipitation systems to document the microphysical structure of several MCS stratiform clouds. Complementary data sets consisting of airborne Doppler radar and ground-based polarimetric radar were also collected. Over a three-month period that encompassed MEaPRS, a 2D-video-disdrometer (leased from Joanneum Research of Graz, Austria) collected data that documented drop size distributions. Disdrometer data were collected for ten distinct precipitation events. These included both convective and stratiform precipitation and at least one event that contained large hail. These data were collected approximately 41 km from the Cimarron radar. Analyses of these data indicated that polarimetric radar derived rainfall is likely more dependent on drop size distribution than drop shape. Researchers also documented the performance of the NCEP Eta model during the experiment.

Some examples of MEaPRS research results to date include the following. A mesoscale convective system on 25 May 1998 produced a series of eight bow-shaped radar echoes that moved rapidly during the night from 0000 UTC to 1200 UTC. Two electric field profiles were obtained in the convective regions of two successive convective bow echoes. The magnitude of the maximum measured electric field, E, was approximately 100 kV per meter. The majority of the ground flashes in the convective region were positive. A third sounding was made in the transition zone about 100-km north-northeast of the soundings in the convective region. There have been very few such transition-zone soundings reported in the literature. This one showed a peak electric field of about 100 kV per meter and five separate charged regions, inferred from the vertical profile of E. The lowest charged region was positive. Another profile was obtained toward the back of the stratiform precipitation region about 55 km north-northeast and downwind of the transition zone launch site. In that sounding, the peak E magnitude was about

25 kV per meter, and there were three alternating charge regions, with negative charge lowest. The final sounding was at the back edge of the stratiform region. The electric field was less than 5 kV per meter along the flight path. The maximum reflectivity in the stratiform rain region was 35-40 dBZ, about typical for mid-latitude mesoscale convective systems. We are continuing to analyze the electric field and inferred charge regions from the soundings in comparison with horizontal winds and reflectivities derived from Doppler radar data.

Results of the analysis of electric-field changes observed at altitudes of 12 km to 15 km MSL suggest that the observed field changes could be related to ground flashes in at least two cases positive ground flashes, but uncertainties in the timing and time resolution make it difficult to determine unambiguously what discharge process is directly responsible for the observed field changes.

An analysis of variations in cloud-to-ground lightning flash rates versus variations in radar-derived storm parameters was completed for three days during which storms produced many positive cloud-to-ground flashes. The goal was to try to quantify the association between positive ground flash occurrence and large hail that had been reported previously. In isolated storms during MEaPRS, trends in large hail production inferred from radar appeared similar to trends in positive ground flash rates, but this was not true of mesoscale convective systems that also produced many positive ground flashes. However, too few storms have been analyzed to determine whether this dependence on storm type is generally valid.

Initial analysis of the soundings and lightning data acquired from some severe storms that produced frequent positive ground flashes suggests that they had a different vertical sequence of polarity in the charge distribution than has been observed previously in severe storms that have no positive ground flashes. However, data from some severe storms that produced positive ground flashes could be interpreted to support a completely different hypothesis: that upper positive charge extends horizontally beyond lower negative charge. It may be that positive ground flashes can be produced by multiple, fundamentally different charge distributions. These inferences will be tested by further data analysis and modeling.

During the summer and continuing into early fall 1998, additional storm intercept operations in conjunction with the MEaPRS field program were conducted. On seven days, 12 balloon-borne electric-field meters, three balloon-borne particle charge detectors, five electric-field-change antennas, and one x-ray detector were launched. The principal tasks involved the electric-field meters and particle charge devices, though sometimes these were launched with a field-change antenna on the same balloon train. Data reduction and analysis, as well as modeling, and comparisons with National Lightning Detection Network (NLDN) data and Lightning Mapping Array (LMA) data (New Mexico Tech), were performed.

Severe Thunderstorm Electrification and Precipitation Study (STEPS)

The field phase of STEPS (Severe Thunderstorm Electrification and Precipitation Study) was based and conducted from Goodland, KS, during May-July 2000. Several undergraduates were hired and participated in mobile ballooning. Volunteers also included minority students and staff from the Goodland NWS forecast office, which served as the host and was deeply involved in the program. The NWS participation blended elements of research and operations. A rich database was collected in spite of a substantial drought in the northwest Kansas area where the project was held. Our particular role in this study involved flying balloons instrumented with electric field meters and an NCAR radiosonde. The sonde is a modification of the standard dropsondes, but configured with a full GPS system ‘engine' that allows accurate tracking inside thunderstorms. More than 30 field meters were flown.

Our objective in STEPS was to determine the electrical structure of the observed storms, and to improve understanding of electrification and of unusual lightning, such as cloud-to-ground flashes that lower positive charge to ground. Soundings were obtained of one tornadic supercell storm, a non-tornadic strong supercell storm, a marginal supercell storm, a mesoscale convective system, and smaller, less severe storms on roughly ten days. A total of approximately 20 useful soundings were obtained.

Two results of our analyses should have a significant impact on our understanding of storm electrification. The first involves the effect of mesocyclones on a storm's charge distribution. We obtained a few soundings in mesocyclones to supplement the one sounding we had obtained previously in 1998. In all cases in which the balloon was in strong updrafts in a mesocyclone, significant charge density was absent below a height of approximately 8 km mean sea level, though outside of the mesocyclone, charge was present at the lower altitudes where it is usually observed. Our initial hypothesis, needing verification by model studies and by additional data, is that the strong updraft shifts graupel formation to higher altitudes and the vorticity and strong updraft combine to interfere with recirculation of graupel into the updraft. Together these two effects prevent charge from occurring at lower altitudes in mesocyclone updrafts. A second involves inverted-polarity storms. By 'inverted-polarity storms' we mean that the normal polarities of charge in two or more vertically separated regions of a storm are reversed. One previously suggested hypothesis as to why storms produce positive, instead of the usual negative, cloud-to-ground lightning is that the charge structure of the storm is inverted. Preliminary analyses both of our soundings and of the lightning mapping data suggest that this occurs in some storms. However, it does not appear to be true of all storms that produce many positive cloud-to-ground lightning flashes. Additional data analysis is needed to verify that the storms have inverted charge structure and to try to understand why.

Other Electric Field Observations

A balloon sounding of the electric field in the trailing stratiform cloud of a bow echo mesoscale convective system revealed only two substantial in-cloud positive charge regions. They were located at 5.1-5.6 km and 6.4-6.8 km altitude, respectively. They were well above the 0° C level of 4.2 km. The two positive charge regions were the likely sources of six positive ground flashes with large peak current (> 32 kA) that occurred within 60 km of the balloon's flight path. The amount of charge transferred by three of these positive ground flashes that made Q bursts is calculated to be in the range of 97-196° C. Flashes of this sort are known to produce sprites and elves in the mesosphere.

Observations of electric-field changes at altitudes of thunderstorms indicated that the changes are lightning. Deploying several balloon-borne electric-field-change antennae in storms during 1998, it was concluded that the observed field changes resulted from charge motion relatively near the balloon and are possibly associated with distant ground flashes.

Mesoscale Modeling

Mesoscale Models as Research Tools

CIMMS scientists, in collaboration with other scientists from NSSL and EMC, have facilitated procedures for the utilization of mesoscale models as research tools. A primary motivation for this effort was a desire to use these models for collaborative research projects with forecasters from the SPC. Both the Penn State/NCAR mesoscale model (MM5) and EMC's MesoEta model were utilized for this purpose. For example, MM5 was used to isolate and understand the important physical processes that led to an unexpected (i.e., unforecasted) changeover from rain to heavy snow during an intense winter storm in February 1998. These models were also utilized for diagnostic analyses of the 21 January 1999 tornado outbreak in Arkansas. In this case, supercell storms were anticipated, but they formed several hours earlier than expected. Diagnostic analysis of model output was used to identify the physical mechanisms responsible for early convective initiation. In addition, both the MM5 and the MesoEta models were evaluated for their predictive capability in severe weather outbreaks, with a focus on the tornado "super outbreak" of 3-4 April 1974.

Ensemble Approach to Forecasting Convective Characteristics

The basic premise used was that convection on the storm scale is a non-deterministic process, making a probabilistic (ensemble) approach to forecasting convective characteristics more effective than deterministic forecasts (convection usually encompasses a spectrum of characteristics). This approach addressed the conditional probability of storm longevity and type (supercell/non-supercell) given that convection occurs. The COMMAS cloud model was acquired from Texas A&M University for this investigation. Verification data sets were obtained and processed for 1995 and 1996 using data from the Dallas-Ft. Worth and Memphis WSR-88Ds. A principal component analysis method was developed for characterizing gross storm characteristics based on modeled vertical velocity and modeled reflectivity. This method constitutes a kind of cluster analysis that can result in complete recovery of the original data set from the derived clusters.

Interpolation of Radar Data to Cartesian Coordinates

Properties of several techniques used for the interpolation of weather radar data to Cartesian grids were evaluated. This was done partly through some theoretical consideration of the properties of the schemes, but was done mostly by empirical testing. In terms of preservation of the phase and amplitude of the input data, predictability of the resultant smoothing and filtering, and relative insensitivity to input data unsteadiness or spatial characteristic, the isotropic Barnes weight function with a constant smoothing parameter appears to be the most desirable of the schemes considered. Modification of the Barnes scheme so that the weight function varies with the data point spacing results in an improved analysis, according to some commonly-used measures of error. Analyses of unsteady input fields, however, suffer from a convolution of data evolution with spatial variations of the weight function. As a consequence, unambiguous assessment of physical evolution is precluded and diagnoses and prognoses based on the analyses become questionable. Collaboration with NCAR scientists ensued to install the

Cartesian Integrated Data Display (CIDD) at NSSL. The system was installed and has allowed access to national scale data (e.g., radar mosaics, satellite images, and lightning information) and products. To tackle the RUC-II aspect of this study, code was developed code to read RUC-II grids, output the environmental parameters of interest for specific forecast times, and calculate the mean mesoscale environment for a specified geographical area ahead of a given linear system.

Instrumentation Studies

Radiosondes

The radiative impact of the relative humidity dry bias in radiosondes launched from the ARM Southern Great Plains Central Facility in 1998 was analyzed with the Community Climate Model (CCM3) stand-alone radiation scheme. More than 800 soundings, uncorrected and corrected for the moisture bias, were used, covering the entire year of 1998. For these preliminary calculations, the cloud cover was not taken into account. Thus, the radiative impact that was obtained can be interpreted as an upper limit. Radiative fluxes were calculated for each sounding with both the uncorrected and the corrected moisture profile. By nature, the moisture bias showed a pronounced seasonal cycle: it was weaker during the fall and winter, and increased dramatically in spring and summer. The modification of the radiative fluxes follows a similar seasonal cycle, which is strongly related to the precipitable water increase induced by the correction. Although radiative fluxes are relatively more sensitive to moisture changes in winter, the larger radiative impact was found during summer/spring. The longwave radiative flux at the surface was found to be particularly sensitive to this correction. For the yearly average, the impact was larger than 2 W/m^2, and frequently reached more than 5 W/m^2 during the moister months.

Vaisala radiosondes (RS-80 and RS-90 versions) were tested in a Thunder Scientific temperature and relative humidity chamber at the ARM SGP Central Facility to examine if a more accurate calibration could be developed than that which accompanies the radiosondes on a paper tape. Three "old" RS-80 sondes (2-3 years old), two "new" RS-80 sondes (less than one year old), and two RS-90 sondes were tested simultaneously in the chamber over the temperature range –15° C to + 25° C and relative humidity from 10-95%. The mixture of old and new RS-80 sondes was included to examine the extent of the sonde dry bias that has been documented by scientists at NCAR and in the ARM Program. The RS-90 sondes were tested because ARM will eventually switch to the new version. After the sondes were calibrated at multiple temperature and relative humidity points, they were launched in pairs.

One hundred sixty dual-radiosonde soundings (i.e., two sonde packages attached to the same balloon) were conducted during the fall 2000 ARM Program Water Vapor Intensive Operations Period (WVIOP). The soundings were made every three hours at the SGP central facility from 1430 on 18 September 2000 through 1130 on 8 October 2000. The dual soundings included Vaisala RH-80H radiosondes from four different calibration lots as well as Vaisala RS-90 radiosondes, the newest sondes produced by Vaisala. The radiosondes were distributed during the experiment so as to conduct pair-wise comparisons between RS-80s, RS-90s, and RS-80s/RS-90s. Some of the radiosondes that were chamber-tested were also flown in dual-soundings made during July 2000. The results of these intercomparisons were used to evaluate both the proposed RS-80H dry-bias correction algorithm and the advantages of the RS-90 radiosonde humidity sensor. This issue is ongoing.

Pyrgeometers

To obtain accurate measurements from the Eppley Precision Infrared Pyrgeometer (PIR), it is necessary to account for a number of factors due to the sensitivity of the PIR to thermal effects. Ideally, three different temperatures should be measured in the PIR system: the temperature of the top of the thermopile, and the temperatures of the PIR dome and case. The standard instrument does not measure the temperature of the thermopile but does measure the dome and case temperatures. The PIR instrument case has a large thermal mass, so the case temperature can be used as a surrogate for the thermopile temperature. However, the thermal conductivity of the glass dome is much lower, indicating that a single dome temperature measurement may not be sufficient. Our study was concerned with the effect of the dome temperature on the calculated longwave radiation. Typically, a single thermistor mounted on the inside edge of the glass dome is used to estimate the dome temperature. Delany and Semmer had three dome thermistors installed by the manufacturer to measure the dome temperature but used circuitry to average the three temperatures and did not have access to the individual temperature measurements. In this study, the manufacturer installed three thermistors on the base of the PIR dome and wired them so that each dome temperature could be measured separately. The three dome thermistors were mounted at 120° increments around the base of the dome.

This sensor was deployed in the field and collected data from 1 January to 31 December 2000. Each day was subjectively categorized as cloudy or clear; for the year there were 66 clear and 66 cloudy days. Results from the cloudy days should resemble the effects of dome heating when the sensor is shaded, as is routinely done in the ARM Program. Therefore, the effects of dome temperature inhomogeneities on calculated long wave radiation should be less than about 2 Wm^{-2}. When the PIR sensor was not shaded (e.g., results from the clear days) but was ventilated, the effects of dome temperature inhomogeneities were as large as 8 Wm^{-2}. When the PIR sensor was not shaded or ventilated, the effects of dome temperature inhomogeneities sometimes exceeded 11 Wm^{-2}.

2. Forecast Improvements

<u>Numerical Prediction</u>

Quantitative Precipitation Forecasting

Improving quantitative precipitation forecasting (QPF) for the 1-2 day forecast period is listed as one of the top priorities of the United States Weather Research Program (USWRP). Achieving this goal depends heavily on providing operational forecasters with better numerical guidance than is currently available. Thus, a considerable amount of effort was applied toward improving operational NWP models, with an emphasis on precipitation parameterizations. To this end, the U.S. Environmental Modeling Center's (EMC's) operational MesoEta forecast model was ported to NSSL. An experimental configuration of the model was run in forecast mode at NSSL in parallel with the operational model at EMC, and in collaboration with EMC scientists. It was configured with the Kain-Fritsch convective parameterization and higher-order numerical diffusion than the operational model contains, both of which are designed to allow the model to produce and retain mesoscale structures. After a series of refinements, the experimental configuration of the model achieved comparable scores on traditional measures of skill for QPF, while providing higher resolution mesoscale guidance than the operational model. New verification techniques were developed so that the accuracy of the model in producing finer-scale features could be better evaluated. Further model refinements are likely to be concentrated in the parameterizations of turbulent mixing, microphysics, and moist convection, all of which have been shown to have a significant impact on QPF. Forecasters from the SPC were in the identification of relevant model output fields as well as the development and implementation of new verification techniques. Daily numerical predictions, comparisons with operational EMC models, and verification statistics were available on the World Wide Web.

Experimental testing of the model was then expanded. NSSL's model configuration differs from the operational version in that it uses the Kain-Fritsch convective parameterization and higher-order, reduced-magnitude horizontal diffusion. A "frozen" version of this experimental configuration was run continuously at NSSL over a year, providing a valuable database for comparison with the operational product. This testing was done in close collaboration with scientists at EMC, the Hydrometeorological Prediction Center (HMC), and the SPC. In addition, in collaboration with scientists from the COMET program, this configuration was made available in a workstation version of the Eta model designed for use by local NWS forecast offices. Automated data collection procedures were put in place for quantitative precipitation forecasts from NCEP's operational models and the experimental version of the model running twice daily at NSSL, and an experimental version of the Weather Research and Forecast (WRF) model running twice daily at NCAR. These data were verified against analyses of both raingage observations and the so-called 'Stage IV' high-resolution multi-sensor precipitation fields from NCEP using equitable threat (ET) and bias scores. These scores were compiled on a monthly basis and updated daily on the web. In addition, a long-term archive of forecasts and analyses from both the operational and NSSL's experimental version of the Eta model was established. This archive contains parameters besides precipitation that are important factors in the prediction of convective initiation and intensity, and will be used for future verification research. Additionally, other measures of ground truth for convective activity, including hourly gridded fields for lightning frequency and various fields derived from radar, were collected and archived during a NSSL-SPC spring research program and will be used for additional verification studies.

QPE SUMS

The QPE SUMS precipitation algorithm was run operationally in four NWS offices as well as the Salt River Project in Phoenix, Arizona. Several improvements were made to the QPE SUMS rainfall algorithm. The algorithm is now capable of ingesting real-time sounding data, surface observations, and rain gauge data. These additional data sources were integrated in the rainfall estimation scheme. Secondly, a verification package was added to the algorithm suite. This package posts statistical comparisons between QPE SUMS gridded rainfall fields and co-located gauges on the Internet daily.

Ensemble Forecasting

Ensemble forecasting of convective weather events using a mesoscale model was conducted. Numerical simulations of the various ensemble members for two events were created using the NCAR/PSU MM5 (Version 2) model. In preparing for this, significant development work and testing was put into coding the adjoint formulation within the Mesoscale Adjoint Modeling System (MAMS) for various parameters that are used to create the ensemble member initial conditions. The two cases chosen for study were the 10-11 June 1985 PRE-STORM squall line that has been well documented in the literature, and the 27-28 May 27-28 1985, PRE-STORM MCS that was the longest-lived MCS during PRE-STORM. Results from the May MCS case illustrated the very different outcomes one can realize by changing the model physical parameterization schemes. During this event, MCSs initiated in the High Plains from South Dakota to Colorado and propagated into Iowa, Missouri, Kansas, Nebraska, or Arkansas over the next 36 hours. The various model runs produced three main tracks, and the longevity of the MCSs varied from 12 to 30 hours. The simulation that best approximated the observed track and lifetime of the MCS was from the Grell convective scheme using the Blackadar planetary boundary layer (PBL) scheme. However, when the Grell scheme was used with the Burk-Thompson PBL scheme, the simulation was substantially different, with the MCS propagating more slowly and dissipating earlier. Thus, changes in just one model physical parameterization scheme can lead to large differences in the numerical prediction. Similar differences were seen in the June MCS case, even though the large-scale forcing for this event was much stronger than for the May case. Several dominant tracks again were found, with some MCSs moving southeastward across Oklahoma into northeast Texas, while others propagated southward across western Oklahoma into western Texas during the same time period.

Ensemble Cloud Model Applications

A three-year effort in developing a way to forecast thunderstorm lifetime using a cloud model ensemble forecasting approach was completed. The forecasts describe the range and distribution of thunderstorm lifetimes that may be expected to occur on a particular day. Such forecasts are crucial for both anticipating severe weather and ensuring the smooth flow of air traffic at busy, hub airports. By extension, any storm characteristic can be probabilistically forecast using this method.

The work was done on eighteen days distributed over two warm seasons. Soundings valid at 1800 UTC, 2100 UTC and 0000 UTC, provided by the 0300 UTC run of the operational Meso-Eta model from the NCEP, were used to provide initial conditions for the cloud model ensemble. These soundings were from a 160 x 160 km square centered over the location of interest and represent a likely range of atmospheric states. A minimum threshold value for maximum vertical velocity within the cloud model domain was used to estimate storm lifetime. Forecast storm lifetimes were verified against observed storm lifetimes, as derived from the Storm Cell Identification and Tracking (SCIT) algorithm applied to WSR-88D radar data from the NWS. When kernel density estimates were applied to the pooled data set consisting of all 18 days, a vertical velocity threshold of 8 m/s resulted in a forecast probability density function (pdf) of storm lifetime that was closest to the observed pdf. One of the most interesting results was that the storm lifetime resulting from a given input sounding could not be determined by analyzing the bulk sounding parameters, such as convective available potential energy, bulk Richardson number (BRN), BRN shear, or storm relative helicity. Standard 2 x 2 contingency statistics revealed that, under certain conditions, the ensemble model displayed some skill in locating where convection was most likely to occur. Contingency statistics also showed that when storm lifetimes of at least 60 minutes were used as a proxy for severe weather, the ensemble showed considerable skill at identifying days that were likely to produce severe weather. Because the ensemble model appeared to have skill in predicting the range and distribution of storm lifetimes on a daily basis, the forecast probability density function of storm lifetime was used directly to create probabilistic forecasts of storm lifetime, given the current age of a storm. Such a function can furnish useful information to air traffic controllers by providing guidance about how soon a storm is likely to affect (or cease to affect) air traffic at a specific location. Similarly, it can provide NWS forecasters with guidance about how likely it is that a particular cell will affect a given community.

Implementation of CIMMS Stratiform Cloud Parameterization into COAMPS

The CIMMS cloud physics parameterization that was implemented into the COAMPS model underwent extensive testing. A mesoscale simulation of the summer cloud/fog system in a clean marine air environment over the central California coastal region produced a broad region of drizzling stratocumulus whose areal coverage was in reasonable agreement with satellite data. The effects of drizzle tended to be more pronounced at the 2 km resolution mesh, where an average drizzle rate became as large as 0.74 mm/day just before sunrise. On this mesh, temperature and total water profiles showed a tendency to become more stable with time, a result of the falling drizzle evaporating, cooling and moistening the sub cloud layer, and suppression of total kinetic energy production. A spatial transition from unbroken stratocumulus to boundary layer cumulus was present across the domain. The effect of drizzle on the cloud microstructure was only readily apparent on the high-resolution mesh, and little fine scale cloud structure was seen in the coarser grids. Results of the study indicate that the physically realistic formulation of cloud/drizzle processes in operational forecast models using an 18 km coarse mesh is still a challenging and unresolved task.

COAMPS, run with the CIMMS bulk drizzle scheme, has been shown to be able to produce the breakup of marine stratocumulus for short timescales at a horizontal grid spacing of 2 km. The presence of drizzle accelerates the breakup compared to that seen when stratocumulus clouds are advected over water with progressively warmer sea surface temperatures. Cloud breakup is manifested as a transition from unbroken stratocumulus to a broken, boundary layer cumulus regime. Modifications to the model's turbulence parameterization produce a more physically plausible boundary layer structure that results in a more realistic treatment of the cumulus regime, specifically more reasonable values of liquid water path, surface drizzle rate, cloud base height, and convective element intensity. COAMPS shows a sensitivity to the depletion of CCN by the drizzle processes, though the lack of an in-situ boundary layer CCN source is somewhat offset by entrainment of CCN as the boundary layer grows with time. Patches of moistened and cooled surface air arising from evaporating drizzle produce a complex structure in the surface flux fields, though COAMPS appears to exhibit only a weak sensitivity to these transient features. Results have been convincing enough that much of the CIMMS drizzle parameterization has been included as part of an effort by the Naval Research Laboratory to systematically improve the treatment of microphysical processes in COAMPS. This work should ultimately lead to improved short-term forecasts (3-24 hours) of marine boundary layer cloud behavior.

A simple treatment of sub-grid variability for the autoconversion process has been derived and implemented into COAMPS. The autoconversion inside a grid is obtained by integrating the process rate over the probability distribution function (PDF) of the cloud variables, and is equivalent to spatial integration of local process rates inside the grid. Sub-grid PDFs are unknown and are represented by gamma distributions. The distribution means are taken to be the grid point values, and the shape parameters are constrained by PDFs of broken and solid stratocumulus cloud fields taken from the CIMMS LES. On the 2 km mesh, including information about sub-grid variability resulted in increased autoconversion rates that lead to enhanced drizzle production and a reduction in liquid water path. The enhanced breakup was particularly obvious in values of cloud fraction, 0.93 for the control run and 0.78 for the sub-grid PDF treatment. Stronger drizzle ultimately led to a more robust convective mode that acts in the model as a positive feedback on cloud breakup, with increased subsidence outside the resolved convective elements resulting in increased dissipation of the stratocumulus deck. This demonstration study showed that accounting for sub-grid heterogeneity can ultimately have a significant impact on the mesoscale characteristics of a stratocumulus cloud system.

Evaluation of ARPS and GDST 1-6 Hour Forecasts

Six-hour forecasts of position, coverage, and strength for five strongly-forced convective events from the ARPS and MIT/Lincoln Lab's Growth and Decay Tracker (GDST) were compared using statistical indices such as Probability of Detection (POD), False Alarm Rate (FAR), and Critical Success Index (CSI). Subjective parameters were also used to evaluate forecasts (e.g., storm intensity, initiation location, movement, growth and decay) including a synopsis of the storm-scale/mesoscale environment. Test cases were selected from the Spring Operations Period 1999 (SOP99) - a real-time forecast testing period that demonstrated the value of initializing the model with Level-III (NIDS) WSR-88D radar data. ARPS forecasts always contained the proper mode and orientation of convective systems providing potential for accurate forecasts. However, ARPS did suffer from some consistent forecast problems associated primarily with spurious convection, areal coverage of higher reflectivities, and intensity of convection. In general, the GDST was able to discern the magnitude of propagation for convective systems as a whole, although it failed to simulate the initiation of new convection. It was able to produce a more accurate forecast over the initial 2-hour forecast period while ARPS forecasts produced more skillful forecasts in the 2-6 hour forecast period. POD and CSI values for the GDST were very near zero by the second hour of the forecast, but higher than the averaged ARPS values through the first forecast hour. Beyond the second hour, the ARPS POD and CSI values rose with POD averaged values near 0.35 and CSI averaged values near 0.13.

Determining the Accuracy of a Fine-Scale Numerical Model

The purpose of this project was to demonstrate the potential level of accuracy of a fine-scale numerical weather forecast system (ARPS) for providing terminal forecast guidance. CAPS conducted a series of real-time operational tests by which 3-km forecasts were generated over select domains. In a subjective sense, the forecasts did well in predicting strongly forced convective events, such as squall lines and large thunderstorm complexes. For verification purposes, however, a more objective method of evaluating forecast accuracy is desired. On scales of 10 km or finer, the traditional method of verification, as used for synoptic forecasts, is not entirely appropriate. This is due primarily to the phase-error. Although a forecast that correctly handles storm initiation, duration, intensity, and general movement can be valuable to pilots and air traffic controllers, errors in the position of a storm at a given time can lead to low probability of detection scores (POD) and high false alarm ratios (FAR). It is essential, therefore, to use techniques that allow for some error tolerance. A "fuzzy logic" approach was used by which a forecast scores high if a storm (identified by reflectivity greater than 41 dBZ) develops within an arbitrary threshold distance of where it was predicted to occur. A case that occurred near Wichita, KS on 21 May 1999 was thoroughly evaluated. A 3-km forecast of this squall line event had been generated in real-time as part of a CAPS spring operational test. The results showed a POD of 0.684 and FAR of 0.784 for the 6-hour forecast. To demonstrate the extent to which phase-error contributed to overall forecast error, the forecasted squall line was shifted spatially to correspond optimally with the radar observations. The verification statistics improved significantly giving a POD of 0.8883 and reducing FAR to 0.587, which indicated that the primary cause of error was due to a phase-lag and showed further that the forecast performed well in predicting the orientation, coverage area, and intensity above a given threshold.

Using a Soil Hydrology Model to Initialize Soil Moisture Profiles for Numerical Weather Prediction Models

A Soil Hydrology Model (SHM) was modified and daily predictions of soil volumetric water content were made at 38 Oklahoma Mesonet sites during July 1997. These predictions were then compared to soil moisture observations made at the Mesonet sites at 5, 25, 60, and 75 cm. Comparisons of time series between the observed and model-predicted volumetric water content at 5 cm revealed similar phase and amplitude changes, a coefficient of determination (R^2) of 0.64, and small mean bias and root-mean-square errors (MBEs and RMSEs) of 0.03 and 0.09, respectively. At 25, 60, and 75 cm, the model performance was slightly worse, with R^2 values between 0.27-0.40, MBEs between –0.01-0.02, and RMSEs between 0.11-0.13. The model response to changes in soil water at these levels was sluggish, possibly due to a lack of ability to model preferential downward water flow through cracks in the soil. Sensitivity tests revealed the importance of specifying the proper infiltration depth, while modifying a previous assertion that the model output is independent of initial soil water content. Tests also showed that the modeling of the conductive processes was relatively insensitive to the specification of the soil hydraulic parameters; and that the processes of precipitation infiltration and evapotranspiration overpower the changes in soil water content associated with vertical water transfer. Finally, the viability of using a much simpler model to initialize soil moisture in the topsoil was demonstrated. However, since much of the water that is extracted from the ground comes from beneath the topsoil, the use of SHM is recommended to resolve the complete vertical profile of soil water. The ability to model the phase and amplitude changes of soil moisture is unique and provides an opportunity to initialize both weather and storm-runoff models with realistic soil moisture values based upon currently available observations.

GCIP Hydrologic Models

The validation of hydrologic models that will be developed for GCIP (GEWEX Continental International Project; GEWEX = Global Energy and Water Cycle Experiment of the World Climate Research Programme) will depend, to a significant degree, on the accuracy of precipitation data, since precipitation is the largest component of the water cycle. Two means of measuring precipitation are rain gauges and radar, and both are susceptible to errors in observation. A three-year study was undertaken to assess the accuracy (bias and error variance) of hourly rainfall as estimated by WSR-88D radars. The reference data sets for determining this accuracy were from a network of rain gauges in Oklahoma. An important goal of the research was to determine the effect of wind on undercatch for rain gauges used in building the reference data set and the effect of sampling error on the validation process. A raingauge testbed was constructed to investigate the undercatch problem. Part of the effort to facilitate this research included establishment of the Environmental Verification and Analysis Center (EVAC) at OU, which collaborates closely with GCIP in developing and applying statistical averaging techniques designed to minimize the error arising from incomplete spatial sampling and field inhomogeneities. EVAC has allowed scientists the opportunity to obtain assessments of quality concerning the accuracy of remotely sensed variables and model output. It has also allowed for two-way data exchange to enhance the quality of the GCIP database and access to data by research scientists.

Improvements in Land Use Specification in MM5-PLACE

In a collaborative project between CIMMS, NSSL, CAPS, the University of Nebraska-Lincoln, and the University of Kansas, the Parameterization for Land-Atmosphere-Cloud Exchange (PLACE) module was used within the MM5 model to determine the importance of individual land surface parameters in predicting surface temperatures. Sensitivity tests indicated that soil moisture and the coverage and thickness of green vegetation (as manifested by the values of fractional green vegetation coverage – fVEG - and leaf area index - LAI) have the greatest effect on the magnitudes of the surface sensible heat fluxes. The combined influence of LAI and fVEG is larger than the influence of soil moisture on the partitioning of the surface energy budget. Real-time, biweekly maximum values for fVEG, albedo, and LAI, derived from the Advanced Very High Resolution Radiometer (AVHRR) sensor, were inserted into PLACE and the changes in model-predicted 1.5 m air temperatures in Oklahoma during July 1997 were documented. Use of this 1-km resolution land cover data provided a clear improvement in afternoon temperature simulations when compared to model runs with monthly climatological values for each land cover type or with constant values across the entire domain. However, temperature simulations from MM5 without PLACE were significantly more accurate than those with PLACE, even when the high-resolution land cover data were incorporated into the model. This is attributed to a warm bias in the PLACE runs that likely is produced by the climatological soil moisture values used for initialization. However, when only the warmest 30 percent of the observations were analyzed, the simulations from the high-resolution land cover data set with PLACE significantly outperformed MM5 without PLACE. The ability to improve model predictions of surface energy fluxes and the resultant temperatures in a diagnostic sense provide promise for future attempts at ingesting real-time land cover data into numerical models. These model improvements would likely be most helpful in predictions of extreme temperature events (during drought or extremely wet conditions), where current numerical weather prediction models often perform poorly. The potential value of real-time land surface information for model initialization is difficult to overstate.

Comparing Two Methods for Wind Analysis: Numerical Simulations of a Severe Convective Event

Previous research has suggested that the traditional method for evaluating spatial derivatives of the wind field (i.e., mapping the individual wind components onto a regular grid and then performing finite differencing) is inferior to a line integral approach, whereby spatial derivatives are calculated directly from the observations. Results from empirical testing suggested that the magnitude of the improvement depends on the degree of irregularity of the data distribution, an expected result. An unexpected result was that the improvement by the line integral method over the traditional approach does not diminish as the wavelength of the input field increases. Overall, the test results make it abundantly clear that the traditional method is generally inferior to derivative estimates via the line integral methodology.

The Weather Research and Forecast (WRF) Model

CAPS, along with NCEP, NCAR, and NOAA/FSL, were involved in developing the NOAA/NCEP next generation forecast system known as WRF (Weather Research and Forecast). This system, designed as a dual research and operational model with emphasis on grid resolutions of 1-10 km, is expected to become operational around 2004 and is anticipated to eventually replace the RUC and Eta models. The primary role of CAPS in the WRF effort is to develop techniques for the assimilation of radar data; particularly those based upon 3D and 4D variational approaches. CAPS has fine-tuned and refined its phase-correction data assimilation schemes. NIDS0-based forecast experiments of the April 2000 Fort-Worth tornadic storms were conducted, with emphasis given to the initialization of microphysical and thermodynamic variables as well as reductions in model spin up. The results obtained thus far are rather spectacular, and initial retrieval experiments using simulated data in the 3DVAR system are encouraging. Efforts are now underway to generalize the Doppler radar data-oriented 3DVAR system and to conduct comparisons against non-variational techniques.

The Advanced Weather Prediction Prototype – AWPP

The first portion of this project was aimed at developing more appropriate verification strategies and methods for meso- and finer- scale NWP models. The second part focused on improving convective parameterizations for operational forecast models utilizing new verification tools and other diagnostic techniques to guide the development of improved formulations. Semi-operational, experimental runs of the Eta model continued in parallel with operational runs at EMC. The experimental version of the Eta model utilized the Kain-Fritsch parameterized convection and 4^{th}-order horizontal diffusion (compared to BMJ convection and 2^{nd}-order diffusion in the operational configuration), and was run four times per day. These four numerical predictions were comprised of two runs using a 0000 UTC initialization time and two runs at 1200 UTC. For each initialization time, the model was first run over a limited domain with 22 km grid spacing, and then it was run over a larger domain with 32 km grid spacing.

Output from all of these runs was made available to the general public via anonymous ftp, supplied to the SPC for viewing on their workstations, and selected fields are posted on the web. Using output from these runs, verification techniques designed to measure the value gained by using higher resolution in the Eta model were developed. Work continued to investigate and diagnose the role played by parameterized convection in the Eta model. In collaboration with SPC forecasters and research scientists, parameterized convective effects were examined and compared in the operational Eta and RUC models, as well as in our experimental version of the Eta model, during a six-week April/May intensive study period. This study concentrated on model forecasts of grid-point soundings, convective initiation and convective evolution. The results of this study were used to guide efforts to improve methods for parameterizing convection in operational forecast models.

Transfer of Knowledge from Research to Operations

Support of SPC Forecasters

CIMMS scientists at NSSL spent time working with forecasters at the SPC in an effort to promote mutually beneficial organized interactions and collaborations on scientific problems.

From January through March 1997, CIMMS scientists worked with the SPC to develop, refine, and test a new winter weather forecast product. CIMMS scientists also worked side-by-side with SPC forecasters during daily simulated operational forecast shifts and issued experimental forecasts for the occurrence of hazardous winter weather within the 48 contiguous states.

From 17 April to 8 June 2001, a real-time forecast and research experiment called the Spring Forecast and Research Program was conducted in the Science Support Area of the NSSL/SPC facility. This program was a collaborative effort, organized by CIMMS and SPC. A diverse group of forecasters and scientists participated, including individuals from CIMMS, NSSL and SPC as well as the Norman NWS Forecast Office, NCEP's EMC, NOAA's FSL, and Iowa State University. The primary goal of the program was to investigate whether operational and experimental numerical weather prediction (NWP) models could be utilized more effectively to predict the initiation and development of severe convection. This overriding objective was mutually beneficial to CIMMS/NSSL and SPC because it incorporated important mission priorities from both sides. Specifically, it promoted NSSL's efforts to evaluate and improve NWP models while it supported the SPC's exploration of ways to reliably increase the projection time for severe thunderstorm and tornado watches. External participants provided very positive feedback from their experiences in this program, inspiring those involved to believe that collaborations between research and operational groups such as these could emerge as a model for the rest of the NWS.

SPC Forecast Verification Program

Work was done to redevelop the SPC's forecast verification program. When the SPC moved from Kansas City to Norman in the mid-1990s, SPC's verification program was discontinued and was in need of replacement. Old methods of verification were applied to SPC products for the years 1970 through 1997 so that a climatological record of forecast verification was available through which to judge forecaster performance. Most of the verification work to date was focused on Convective Watches (severe thunderstorms and tornadoes), which is one of the primary public services that the SPC offers. Software was developed to allow for verification of both Day 1 and Day 2 Convective Outlooks in addition to severe weather watches. With these capabilities, all SPC forecasters now receive feedback on their forecasts. Work continued on methods to verify the new set of experimental probabilistic convective outlooks issued by the SPC. The primary focus was on the Day 1 forecasts of the individual severe weather hazards: hail, wind, and tornadoes. Other work was done to modify software to verify Day 2 and Day 3 probabilistic forecasts.

Support of WSR-88D Operators

The ROC Operations Branch supported WSR-88D field sites in improving the reliability of access to WSR-88D data and assisting operators in interpretation and application of WSR-88D data, products, and algorithm output. These efforts improved the ability of forecasters to accurately apply radar data to their forecast operations and the decision process of issuing severe weather and tornado warnings. The improvements to data quality were even more important with the new weather radar display platforms the NEXRAD agencies are fielding that put more WSR-88D data in front of more users on a continuous basis.

Forecaster Training

Distance Learning

From the inception of the WSR-88D network in 1991 up until 1997, the Operations Training Branch (OTB) of the OSF (now ROC) used traditional instructor-led, classroom based, residential training to transfer research knowledge into skills to achieve documented success in improved weather predictions and warnings. However, because of structural and budgetary changes within the NWS, the OSF moved rapidly to distance-delivery systems employing an array of real-time audio graphics, web-based training, and computer-based training on CD-ROM. As part of standard NWS procedure, collaboration among CIMMS, the OSF/OTB, and the Center for Distance Education (CDE) of the College of Continuing Education (CCE) of the OU was done to evaluate whether the shift to distance-delivery systems adversely impacted overall training results, and especially whether it had degraded forecast and warning skills. The CDE utilized its expertise in the academic field of Instructional System Design to research the effectiveness of the new training delivered to operational field forecasters of the NWS. An initial validation study completed in March 1999 found that although the distance delivery systems had no adverse impact on training effectiveness, weaknesses in some areas of NWS distance delivery systems were noted. Many of these recommendations were addressed in the development of courses that were subsequently delivered beginning in October 1999.

Warning Decision Making Workshop Training

During the latter part of the 5-year period the OTB was transitioned from the ROC to the NWS Training Core, becoming the “Warning Decision Training Branch” (WDTB). With this change in name and management came a more explicit representation of the branch’s purpose: to improve the performance of warning decisions and short-term forecasts for the NWS. Warning

Decision Making (WDM) workshops, held at the COMET facility in Boulder, CO, have been an integral part of delivering warning decision training to NWS personnel. A principle component of these workshops has been the displaced real-time (DRT) scenarios where participants practice warning decision-making techniques in a simulated real-time environment using the Advanced Weather Information Processing System (AWIPS). In the past year CIMMS has supported and made improvements to the DRT software and the data used in the scenarios. One outgrowth of these workshops has been a project for the NWS Southern Region to cost-effectively transfer the DRT workshop software to computers in NWS forecast offices to support local training.

Warning-Related Forecast Improvements

The warning decision making process is multi-faceted, often being improved directly by unique observing systems, analysis tools, data analysis techniques, human factors, or improvements in forecast verification. Progress was made in warning-related forecast improvements with the application of unique radar and satellite sensors and new data analysis techniques. The Terminal Doppler Weather Radar (TDWR) and OU's Doppler On Wheels (DOW) are two radar sensors that have been used to illustrate the sampling limitations of the operational WSR-88D radar and the potential for improvement in warning decision making using these new tools and knowledge gained from analysis of their data. The TDWR data from Salt Lake City, UT were incorporated into an on-line module which featured how TDWR data could have significantly improved the detection and warning of the 11 August 1999 F-2 tornado that struck downtown Salt Lake City. The DOW data for the 3 May 1999 Oklahoma City area tornado were used to illustrate operational radar sampling limitations of tornadoes and the implications for warning decision making. In the 3 May radar analysis, a new technique was developed to infer significant tornado damage using debris signatures in the reflectivity fields. High-resolution satellite data was another unique sensor source used in an analysis of the 3 May tornado outbreak to develop a new technique for detecting tornado tracks remotely that can improve the verification of tornado forecasts. Other warning-related forecast improvements included evaluating satellite-based lightning data during the 3 May tornado outbreak, evaluating how to best use new warning decision analysis tools such as the System for Convection Analysis and Nowcasting (SCAN) and the Flash Flood Monitoring and Prediction System (FFMP), developing a Java-based technique for visualizing boundary relative flow, and developing techniques to ensemble precipitation forecasts.

Warning Simulation

Time is a critical factor in issuing warnings. To effectively research the warning process on many events requires the ability to adequately reproduce as many of the components of the warning decision making process as possible. To this end, CIMMS collaborated with the NWS to develop a research tool called the Warning Event Simulator on a Linux platform to simulate warning events. The simulator has allowed study on the warning decision making process for many recent significant severe weather events across the country, including Birmingham, AL; Columbia, MO; Salt Lake City, UT; Granite Falls, MN; Des Moines, IA; Broome County, NY; and Lancaster County PA. In addition to its use as a research tool, the Warning Event Simulator can be used as an effective training tool for CIMMS scientists and NWS forecasters.

Software Development to Aid Forecasters

SPC Software Development

Software development occurred at SPC that allows the forecaster to interrogate non-synoptic upper air wind data sources. These data sources include VAD wind profiles (VWPs) and wind profiler data, as well as traditional radiosonde data. Owing to the lack of coverage of the twice-per-day radiosonde network in the U.S., the SPC depends heavily on the other asynoptic sources of upper air wind data for the issuance of the Convective Watch and Convective Outlook products that provide national guidance to forecast offices on severe weather potential. A graphical user interface (GUI) was developed that allows forecasters to use data to their fullest extent. Updating and augmenting such information on the SPC web site has improved services to SPC customers.

RIDDS Support, Maintenance, and Installation

In cooperation with the ROC, NWS, and the FAA, NSSL and CIMMS continued to support, maintain and install Radar Ingest and Data Dissemination Systems (RIDDS) during the reporting year. The objective of RIDDS is to support the diverse warning and forecast improvement projects of the cooperating organizations by providing high-resolution WSR-88D and other radar data in real time.

A significant amount of effort was expended to upgrade the RIDDS for Y2K compliance. The RIDDS was retested and certified in accordance with ROC policy in June 1999, and Y2K deployment was completed in December 1999.

Oklahoma Mesonet

Maintenance and operation of the Oklahoma Mesonetwork continued at the Oklahoma Climatological Survey (OCS). Reliable data services included greater than 98 percent real-time data availability and over 99.9 percent availability of research-quality archived data. NWS data users during the 5-year period included NWS forecast offices in Norman, Tulsa, Amarillo, Dodge City, Wichita, and Shreveport, the SPC, and the Arkansas-Red River Basin River Forecast Center in Tulsa. Mesonet data were used frequently in short-term nowcasts as evidenced by numerous references to the Mesonet in various "State Forecast Discussions". In addition, case studies using the data served as important training tools on which to improve NWS operations. The data continued to impact the NWS during its modernization program, especially in the areas of hydrometeorology and radar rainfall calibrations.

Hydrologic modeling activities included providing training sessions to the aforementioned River Forecast Center, setting up hydrologic databases for the Tahlequah basin of the Illinois River in Oklahoma, and developing infiltration parameters for the entire Arkansas-Red River Basin. Activities involving the radar/raingauge calibration included researching the impact of calibrated radar estimates of rainfall on Quantitative Precipitation Forecasts (QPFs), studying the effect those estimates have on the stream-flow hydrograph produced by hydrologic models, writing a tutorial to document the software that supports this hydrometeorological analysis and forecast system, calibrating WSR-88D precipitation data using raingauge observations from the

Oklahoma Mesonet, and working to determine the biases of the WSR-88D radar rainfall estimates.

OK-FIRST

The OK-FIRST (OKlahoma's First-response Information Resource System using Telecommunications) Project has been an initiative by the OCS to improve access to and the use of weather and environmental information by public safety agencies. More environmental information is generated now than ever before, but public safety agencies such as emergency management, fire, and police have had inadequate telecommunication infrastructures to fully access and exploit such information to make informed environmental-based decisions. Sufficient training on how to use such information has also been lacking. OK-FIRST has been supported partially by the U.S. Department of Commerce to provide these services to such agencies, and it has been a collaborative project. A first step in the project included an OCS partnership with Unisys Weather Information Services to allow cost-effective redistribution of WSR-88D data. The State of Oklahoma became involved as an Internet provider through its "OneNet" system. Many training sessions involving over 50 public safety agency participants have been held at OU. The original version of OK-FIRST was based upon NIDS data and thus was limited to the products provided therein. The Level II data provided by the CRAFT Project network afforded an opportunity for the OCS to explore a broader and arguably more effective utilization of radar information for OK-FIRST. The WxScope Plugin software developed at OCS allows for the incorporation of multiple data file formats for the integration of multiple radars, as well as multiple meteorological data formats. This feature results in the capability to integrate surface data (such as NWS ASOS) with the radar data into a single interactive display. OCS also completed a radar-training workshop for 18 additional emergency managers who tested the WxScope v8.0 software.

Climatologies

Onset of Midlatitude Mesoscale Convective Systems

A climatology was developed to aid in forecasting the evolution of MCSs that affect the Southern Great Plains during late morning hours in the summer. Development was a cooperative effort between CIMMS, NSSL, and the NWS forecast offices in Norman, OK, and Dodge City, KS. Work began on the climatology by going through the NCDC hourly mosaic base level reflectivity images from the WSR-88D network. Estimates from this climatology were made of the direction and speed of system motion and the evolutionary tendency of each system. Severe weather events were logged for each system, along with assessment of the initiating mechanism and a description of the synoptic environment in which each event occurred.

Hazardous Winter Weather

Hazardous winter weather is responsible for many fatalities and injuries, and millions of dollars of property damage every year. Few studies have documented the climatology of these events across North America. Research was completed that examined the variability of synoptic and local meteorological conditions associated with freezing rain across the United States.

Results from this study indicated that there are common conditions typically associated with freezing rain at most locations across the U.S.: (1) subfreezing surface layer, (2) nearly-saturated air near the surface, (3) upward motion, and (4) elevated mid-level warm layer. However, the magnitude of these conditions is variable from location to location because of topographical effects. These results are significant to forecasters who may expect a specific combination of meteorological conditions to produce freezing rain for any location.

Additional research associated with this project examined the distribution of freezing rain, freezing drizzle, and ice pellets across North America. These data were analyzed and basic climatological information such as frequency and variability was created.

Forecasting Algorithm Development

Areal Mean Basin Estimated Rainfall (AMBER) Algorithm

The Areal Mean Basin Estimated Rainfall (AMBER) Program has been used in real-time operations for several years at the Pittsburgh, PA, and Honolulu, HA, NWS forecast offices and was implemented as part of NSSL's WDSS at the Tulsa, OK, and Sterling, VA, forecast offices. Work was done to implement an "AMBER-like" functionality in the FFMP Program, which was included in AWIPS Build 5.1.

To obtain quantitative feedback on AMBER's utility as a flash flood forecasting tool prior to its implementation in the FFMP, NSSL was tasked with providing an objective evaluation of AMBER's performance in nine case studies from the Tulsa and Sterling county warning areas. For each case study, archived Level II data from the KINX and KLWX radars, flash flood reports, rain gage data, and flash flood guidance (FFG) values were analyzed to determine the pre-existing hydrologic conditions, the nature of the precipitation event, the accuracy of the radar precipitation estimates, and the extent and severity of the resultant flash flooding. Average basin rainfall rates and accumulations from AMBER were analyzed to determine whether the algorithm would have indicated flash flood potential and, if so, the approximate lead-time.

A formal evaluation of the AMBER flash flood warning decision program was conducted in 2001 as a follow-up to the aforementioned AMBER evaluation. The purpose was to conduct an objective evaluation of the algorithm to obtain quantitative feedback on its performance. The evaluation focused on three flash flood case studies in the Sterling, VA, County warning area. The Digital Hybrid Scan Reflectivity (DHR) product was derived from KLWX Archive Level II data. From this, the 1-km by 1-degree precipitation estimates were derived and used to generate average basin rainfall rates and accumulations in AMBER. The flash flood potential as indicated by the rates and accumulations was analyzed with respect to the occurrence of flash flooding as reported in the publication *Storm Data*. The general conclusions drawn from this evaluation included the following: 1) basins should be delineated with a minimum drainage area threshold less than 10 square miles, 2) flash flooding indicated by AMBER is only as reliable as the precipitation estimate input, 3) average basin rainfall rates are more indicative of flash flood potential in a timely manner than average basin accumulations, and 4) the addition of hydrologic parameters such as basin slope, elevation difference, hydraulic roughness, infiltration characteristics, and antecedent moisture conditions would assist in determining meaningful threshold rates and accumulations as well as improve the detection of flash flood potential.

Satellite-Based Anvil Tracking Algorithm

Development of a satellite-based anvil-tracking algorithm took place. The objective of the algorithm is to detect and track the cold top anvil features that are often associated with severe storms. The algorithm has laid a foundation for further association of other known severe weather signatures (such as the enhanced V-notch and warm wake) with detected storms in satellite data.

System for Convection Analysis and Nowcasting (SCAN) Implementation and Testing

The System for Convection Analysis and Nowcasting (SCAN) underwent several years of testing in a real-time operational setting at the Sterling and Tulsa forecast offices. SCAN was developed and designed as an AWIPS component to provide short-term guidance to forecasters on the probability of severe weather. NSSL, NCAR, and the NWS Techniques Development Laboratory (TDL) developed the system.

Development and testing work was undertaken on algorithms to determine storm severity based on cloud top temperature, height, and/or growth. Analyses of several supercell thunderstorms supported previous research showing correlations between cloud top temperature characteristics and storm severity. Tested and rejected code identified cold cloud aspects in infrared imagery. Computer code for tropical mesoscale convective systems was also developed. An algorithm was ultimately developed that detects and computes trends in temperature and the areal expansion of thunderstorm anvils for the SCAN.

The SCAN/FFMP (Flash Flood Monitoring and Prediction) 1.0 was released to NWS forecast offices and river forecast centers in 2000. Features of FFMP 2.0 have included the AMBER concept to issue the flash flooding warning on small basins that are delineated using River Reach Files Version 3 (RF3) from the U.S. EPA. On the FFMP Image and Table displays, all precipitation and flash flood information is shown for all county warning areas in a basin. NSSL had partnered with the USGS Earth Resources Observation Systems (EROS) Data Center (EDC) to delineate flash flood basins for the conterminous U.S., a necessary component of the FFMP program.

Flash Flood Algorithm Development

Necessary modifications were made to the OU Finite-Element Analysis Hydrologic Runoff Model (OUFEAHRM) to enable its use in real-time forecasting. Data from several case studies were obtained for the Blue River test basin in Oklahoma, including Level II archive radar data, raingage measurements, and streamgage measurements.

Multi-Sensor Estimation of Precipitation

A Neural Network QPE (quantitative precipitation estimation) scheme based on radar, satellite, lightning, and environmental data was proposed to tackle the problem of the multi-sensor estimation of precipitation. Multi-sensor observations for all rainfall events during the STormscale Operational and Research Meteorology-Weather data Assimilation and Verification Experiment (STORM-WAVE) were obtained. The STORM-WAVE project was conducted in a region of 30°N to 45°N and 109°W to 86°W during April-June 1995. Data sources included raingage, radar, satellite, and lightning observations. Numerical model analysis and forecast data were also obtained. Software was written for ingesting raingage, radar, and model data. Some statistical analyses were performed on the raingage data. Software was also developed to stratify radar and model (environmental) data based on raingage observations. Some intercomparisons were performed between raingage, radar and satellite rainfall estimations for the Dallas hailstorm case of 5-6 May 1995 using VisAD software. Software was also developed for remapping WSR-88D radar data onto a three-dimensional regular Cartesian grid.

Precipitation Type Algorithm Testing

The objective of a two-year COMET project was to examine numerical methods of accurately predicting precipitation type using numerical model output. Before COMET funding began, scientists had identified several precipitation-type algorithms and began some preliminary algorithm testing. Resources were devoted to 1) creating a procedure to run experimental precipitation-type algorithms and distribute the numerical output to NOAA/NWS forecasters; 2) develop an evaluation form for forecasters to submit; and 3) creating a website for the project. Several algorithms were run and the output data distributed from a workstation at the Hydrometeorological Prediction Center (HPC). The data were distributed in a format that is easy to view on forecaster workstations and includes numerous plots that show the hourly output from each algorithm as well as ensemble products that show the most likely type of precipitation and a risk assessment (e.g., low, medium, and high) of each precipitation type. Forecaster evaluation forms were created with the assistance of the HPC and SPC to provide forecaster feedback on the usefulness of the algorithm output, the format of the products, and the forecaster's perceived accuracy of the products. Between October 2000 and March 2001, 138 (66 from SPC forecasters and 72 from HPC forecasters) evaluations were submitted, with over 92 percent of those that evaluated the usefulness of the output stating that it had been useful (27 percent), very useful (27 percent), or extremely useful (39 percent) in creating the current NWS product. The evaluations showed that HPC forecasters used the algorithm output most often for the first 12-h Winter Weather Forecast and the 24-h Day Two Winter Weather Forecast. SPC forecasters used the output for their Mesoscale Discussion product. The evaluations also indicated that forecasters used the algorithm output based on the Eta solution more often than output from the RUC. Most (> 95 percent) of the forecaster evaluations commented that the output was presented in a useful way.

3 May 1999 Tornado Outbreak

Forecasting the Event

Despite the relatively successful long-lead forecasts of the storms during the 3 May 1999 tornadic outbreak in Oklahoma and Kansas, considerable uncertainty among forecasters with regards to the timing, location, and mode of convection persisted through the time of convective initiation. Despite this uncertainty, forecasters identified three crucial elements that they monitored for clues as to how the event would unfold. These elements include (a) the absence of strong surface convergence along a weak dryline in western Oklahoma and the Texas panhandle; (b) the presence of a cirrus shield that was hypothesized to limit surface heating (except under holes in the cloud deck); and (c) the arrival of an upper-level wind-speed maximum into

Oklahoma that was responsible for favorable synoptic-scale ascent and the cirrus shield. The MM5 model was used to explore the sensitivity of the outbreak to these features using simulations down to 2-km horizontal grid spacing. A 30-hour control simulation reproduced the observed long-lived, long-track nature of the supercell outbreak, although errors in timing, location and longevity existed. Convective initiation occurred along the leading edge of the cirrus shield and within holes in the shield, suggesting the importance of incoming solar radiation to the development of the storms. Consequently, the simulation was deemed adequate for evaluating the importance of the above processes identified by forecasters.

Two processes were evaluated using factor-separation techniques: the opaqueness of the clouds to solar radiation and the upper-level wind-speed maximum associated with a potential-vorticity (PV) filament. Synoptic regulation of the 3 May 1999 event was imposed by the effects of the PV filament. Two pulses of convective activity occurred, the first tied to initiation within holes in the cirrus shield, and the second with the passage of the PV filament. The PV filament was responsible for forcing the upper-level synoptic-scale ascent that produced the cirrus shield and for enhancing boundary layer convergence well to the east of the dryline, where convection initiated. The joint effects of the PV filament and cloud-radiative processes acted to focus the convection in particular locales, associated with holes in the cirrus shield. Although the presence of the PV filament inhibited rather than enhanced deep-layer shear, through interactions with a stronger PV anomaly in the northern stream, sufficient shear and storm-relative helicity existed to produce supercell storms for PV filaments of 0, 1 and 2 times the magnitude of the analyzed feature at 0000 UTC 3 May.

The potential usefulness of high-resolution mesoscale modeling was also assessed. In particular, it was found that the forecast data would have provided useful guidance that could have assisted forecasters in formulating and evaluating conceptual models of the event, enhancing situation awareness, and reducing forecast uncertainty.

Comparison of WSR-88D Data to the 3 May 1999 Oklahoma City Tornado Damage Path

CIMMS scientists were instrumental in developing a highly detailed damage survey of the 3 May 1999 F-5 tornado that struck the Oklahoma City metropolitan area. The survey maps, developed using ground and aerial surveys, include contours of the Fujita-scale damage intensity rating. These F-scale contours were digitized into shape files for use within ArcView GIS. WSR-88D radar data from Twin Lakes, OK (KTLX) were also digitized as ArcView shapefiles, and overlaid with the F-scale damage contours to compare the radar observations with the actual damage path of the tornado. Furthermore, output from the NSSL Mesocyclone Detection Algorithm at the 0.5-degree elevation angle was digitized and compared with the actual damage path location. Findings indicated that the WSR-88D observed vortex detections were of about the same diameter as the tornado in rural Grady County (0.75 mile wide), but larger than the damage path width in Cleveland and Oklahoma Counties (radar 0.75 mile wide, tornado 0.33 mile wide). These findings indicated that the WSR-88D does not detect the actual tornadic vortex except for the most rare very large tornado cases ("wedge" tornadoes), and only when the storm is close to the radar. The distance between the radar-detected vortex and the damage path was typically no more than 0.5 km.

3. Climatic Effects of/Controls on Mesoscale Processes

Tropical Studies

Sea Surface Temperature Anomalies

Most investigations of relationships between tropical Pacific sea surface temperature anomaly (SSTA) events and regional climate patterns have assumed teleconnections to be linear, whereby the climate patterns associated with cold SSTA events are considered to be similar in structure and morphology but opposite in sign to those linked to warm SSTA events. In contrast, and motivated by early evidence of nonlinearity in the above regard, this study identified characteristic (i.e., composite) calendar monthly central and eastern North American precipitation patterns separately for warm and cold SSTA events in different regions of the tropical Pacific (central, eastern, west-central "horseshoe", far western) identified through principal component analysis. The precipitation anomaly patterns were computed from an approximately 1° latitude/longitude set of monthly station data for 1950-92. Their robustness and nonlinearity were established using local, regional, and field statistical tests and a variance analysis. This combination of unique SSTA analyses, the composite selection that followed, and characteristic precipitation anomaly determination from a fine resolution data set increased our understanding of tropical Pacific-North American precipitation teleconnections in several respects. First, significant linkages to the two SSTA modes related to traditional warm and cold events (central and eastern tropical Pacific) were identified for all months except September and October, with all exhibiting some nonlinear characteristics. Conversely, several regions/seasons were confirmed to have essentially linear associations with traditional warm and cold events. However, only nonlinear precipitation teleconnections were associated with SSTAs in tropical Pacific regions largely unrelated to ENSO. The results also demonstrated the sensitivity of central and eastern North American precipitation teleconnections to the location and extent of tropical Pacific SSTAs.

Tropical Variability

A project was undertaken to study climate variations and trends associated with tropical variability is underway. Notable milestones included enhanced documentation of the tropical-wide height mode at numerous geopotential height levels in both the NCEP reanalysis data and the ECHAM4 GCM. The GCM work enabled documentation of how a small change in SST in the central tropical Pacific Ocean, co-located where observed SST has increased over the past 40 years, generates a height rise through the equatorial zone around the globe with a spatial structure similar to that observed. Moreover, the GCM runs have enabled the testing of hypotheses on the generation and maintenance of the height rise.

Tropical Western Pacific Solar Radiation

An historical database of daily solar radiation values for all of the reporting stations (212 possible) in the tropical western Pacific (100°E-170°E, 10°S-10°N) was constructed. The daily solar radiation values were generated using a sophisticated semi-physical model that has been under development since the mid-1970s. This model estimates the instantaneous radiant flux density received at the Earth's surface, which is a product of the incoming solar radiation at a location on the Earth's surface and the attenuation of this radiation from clouds, aerosols, Rayleigh scattering, and absorption by water vapor and permanent gases. This unique tropical dataset, which gives long-term representative information of the Sun's radiant heat energy, should be of wide utility to the climate, agricultural, hydrological and engineering communities.

The Surface Reference Data Center of the Global Precipitation Climatology Project

The Surface Reference Data Center (SRDC) was successfully transferred to the Environmental Verification and Analysis Center (EVAC) at OU. The importance of validation of GPCP satellite rainfall products necessitated a sharpening of the role of SRDC. As a consequence of this need a meeting among GPCP principals and SRDC personnel was held during January 1999. An important result of this meeting was the recognition of the need for a medium through which comments and suggestions could be solicited from the research community at large as to how the SRDC might meet the community's verification requirements. It was decided to experiment with a newsletter and to develop a web page that includes a bulletin board. Both the newsletter and the web page were designed to publish researcher comments and preliminary research related to GPCP activities, particularly verification activities. An added benefit of the newsletter was an increased awareness of GPCP activities among the research community at large. During the January meeting, specific objectives were set out and ultimately met for the SRDC to accomplish before May 1999. These objectives were:

- Conduct validation exercises using Dr. George Huffman's daily satellite rainfall product over Oklahoma using the Oklahoma Mesonetwork;
- Produce and publish the 'Validator' newsletter;
- Set up a data conduit for U.S. cooperative network data from the National Climate Data Center (NCDC) to the SRDC;
- Solicit suggestions for the functionality of the SRDC from GPCP data producers, and
- Start up routine validation of GPCP products.

OU scientists completed an error analysis of the tropical rainfall database and the results are now on-line at: http://www.evac.ou.edu/srdc. Based on conversations at the Sea Level Rise/Climate Change meeting held in Rarotonga, Cook Islands, a new collaborative effort between the Surface Reference Data Center (SRDC) with Pacific regional meteorological directors was organized. The collaboration also involved the sharing of information on long-term forecasting, data, and education between the SRDC and the meteorological directors. The effort was initiated due to the long-term decline in the climate observation network in the Pacific and the need to reverse this decline. A trip to Apia, Western Samoa was taken to increase the number of participants in this collaboration. Success was made with the Kiribati Meteorological Service in establishing 15 new raingauge sites on different low-lying atolls.

Expansion and Analysis of the Comprehensive Pacific Rainfall Data Base

Taylor's Atlas of rainfall data was combined with the Comprehensive Pacific Rainfall Database (CPRDB), totaling 72 stations of combined data. An exploratory data analysis was done on this dataset of monthly rainfall. Data from these station records goes back in most instances prior to 1950, and in a few instances prior to 1900. We first investigated simple least-squares regression analyses with the data for 20 year time periods (a minimum of 20 years was chosen due to the 2-5 year ENSO cycle), a 50-year period (1947-1996), and for long station records with a sufficient amount of data. Trend results for the 72 stations were also analyzed spatially. We also explored techniques in filtering (mostly in the frequency domain with relatively long, unbroken datasets) to better assess rainfall trends. Also explored were Neural Network techniques for time series prediction and cluster analysis. The Taylor's Atlas data were also digitized for distribution to users. Basic and thorough data quality checking was performed. Included in the quality checking analysis was (1) neighboring station data with significant discrepancies; (2) high/low percentage of zero rainfall amounts; (3) unusually high rainfall amounts; (4) comparison of rainfall to ENSO events and season; and (5) identification of possible rainfall errors due to the specific instrument used.

We also compiled a database of Pacific hurricane data that was used to study unusually high rainfall amounts (as well as suspicious low/zero rainfall amounts during a tropical storm) to establish a physical basis for the amounts. It was discovered that observers commonly report zero rainfall on weekends, when in fact the data are missing. This tends to create biases on weekend values and on Monday, as the Monday value is often recorded as a daily value when in fact it is an accumulation.

Moroccan Precipitation Studies

Precipitation Variability and Seasonal Prediction

Over the last five years, there has been a strong collaborative effort between CIMMS and the Kingdom of Morocco to increase our understanding of the interannual-to-decadal variability of Moroccan winter precipitation within the North Atlantic climate system, as well as within the global climate system as it relates to the late rainy season (tropical Pacific sea surface temperatures). This understanding was used to develop a seasonal prediction capability for Morocco. This project was motivated by the predominance of extremely poor Moroccan winter precipitation since the late 1970's. During the 1997-98 Moroccan precipitation season, CIMMS issued an Experimental Prediction Statement plus three updates/verifications to officials in the Moroccan government. These long-term predictions were based exclusively on CIMMS research findings over the last four years. During the first half of FY 1997, five presentations were made at international meetings to present our findings. These included: Dr. Peter Lamb presented *Prediction and Decadal-Scale Ocean Climate* at the International Council of the Exploration of the Sea (ICES) Workshop in Copenhagen, Denmark and *On the North Atlantic Oscillation and the Seasonal Prediction of Moroccan Precipitation* at the First Regional Training Course on Practical Applications of Seasonal-to-Interannual Climate Prediction to Decision-Making in Agriculture and Water Resources Management in Africa in Niamey, Niger; Dr. Neil Ward gave an invited presentation on *Blending of Modeling and Statistical Approaches* to the WMO Workshop on Dynamical Extended Range Forecasting in Toulouse, France; Diane Portis presented a poster at the 22nd Annual Climatic Diagnostics Workshop detailing the research basis for, the nature of, and verification of our Prediction Statements; and Mostafa El Hamly, a Moroccan engineer from the Direction de la Météorologie Nationale in Casablanca, gave a paper to the Annual Meeting of the AGU on the oceanic and climatic signature of the North Atlantic Oscillation. During the spring of 1998, our group co-authored a book chapter, *North African*

Climate Variability, which will appear in "Beyond El Niño: Decadal Variability in the Climate System" to be published by Springer Verlag. This book chapter features research on the climate variability of the Sahel and Maghreb.

The development and issuance to Moroccan government officials of "Experimental Precipitation Predictions for Morocco" continued with the prediction for 1998-99 verifying extremely well. Also, a book chapter, "Climate Variability in Northern Africa: Understanding Droughts in the Sahel and the Maghreb", was published in "Beyond El Nino: Decadal and Interdecadal Climate Variability" (Antonio Navarra, Ed., Springer Verlag, 1999). This chapter features research on the climate variability of the Sahel and Maghreb.

Weather Systems Analysis

For the documentation of the weather systems affecting Morocco, a cyclone-tracking algorithm was obtained from Colorado State University and was used to track the intensity and the path of weather systems in the North Atlantic since 1958 using four per day NCEP/NCAR reanalysis data. From this algorithm, the following ten variables were outputted with daily resolution on a 2.5 by 2.5 degree grid from 1958 through 1997: total cyclone events, number of cyclone days, total system events, number of system days, cyclone central pressure, cyclone intensity, cyclone translation velocity (all cyclones and no-stationary as well), maximum deepening, and cyclogenesis and cyclolysis events. Software was developed to plot the storm tracks of each storm over a month's time. On these plots, an identification number and the time of each observation of position document the storms. The sea level pressure anomaly maps using the NCEP reanalysis data were produced for the 17 months identified as extreme precipitation cases for one of the North Atlantic Oscillation (NAO) control and non-control categories for both coastal and central Morocco. These results were binned in boxes that span 30°W-0° in longitude and either 1.0, 2.0 or 2.5° in latitude. These two basic datasets were used to create seven different "running domain" data sets. The motivation behind these data sets is to have smoother latitudinal profiles of the variables mentioned above. The running domain data sets differ in the number of bins that are included for each latitude estimate of a variable and in the latitude resolution of the estimates. As an illustration, if the "running domain" is moved one degree for every estimation, then the latitudinal resolution of the estimates will be one degree. The latitude estimate is made at the mean latitude of the area covered by the bins. With each of these datasets, the annual cycle of the latitudinal profiles of each of these variables was plotted. Monthly latitudinal profile plots were produced showing the composite profile for each of the four categories chosen to show NAO control and non-control. Each of these composite profiles also had climatology as a background. The running domain dataset with 10 bins (at 2.0°/bin) per latitudinal estimate yielded the best results.

Rainfall Event Analysis

An eighteen-year (1979-1996) daily Moroccan rainfall dataset was obtained for 25 reasonably well-distributed stations. A monthly dataset was created for each station to quantify the rainfall events. The parameters included the number of rainfall events/month, the total precipitation from all of these events, the mean precipitation/event, and the mean length/event. This monthly dataset has been used in conjunction with the monthly cyclone data described above to analyze the relationship between weather systems and Moroccan precipitation patterns.

Annual cycles for each of these parameters at each station (which were grouped by region) were plotted. Contour plots were made showing the spatial scale of the monthly climatologies. Composites of these variables for the four categories representing NAO control and non-control were completed.

North Atlantic Climate Variability on Different Timescales

The North Atlantic Oscillation (NAO) is a robust regional circulation pattern with a very important location in the climate system. It occurs over major oceanic gyres that are linked to the thermohaline circulation that affects global climate. There is evidence that the NAO plays a significant role in capping or intensifying the convection within these gyres through advection of Arctic sea ice, the advection of waters into the gyres of different salinity and temperature, or in-situ precipitation. The NAO also has a significant impact on regional precipitation patterns over northern Europe and northwest Africa. Since 1994, our research group has investigated in depth the NAO control on Moroccan precipitation that maximizes over the northwest and southwest regions of the country during winter. One of our primary objectives was to generate seasonal precipitation forecasts for Moroccan officials so that they could make better socioeconomic decisions (described previously). Understanding the temporal and timescale behavior of the NAO signal is essential for developing its predictive capability. We have investigated the NAO signal over seasonal, intraseasonal, decadal and century timescales. Since there is a seasonal migration of the centers of actions of the NAO, we developed a “mobile” index. As measured by the new “mobile” index (NAOm), the NAO maintains its intensity from winter-to-summer to a greater degree than has been indicated by traditional NAO indices based on fixed stations in the eastern North Atlantic. Monthly hemispheric teleconnection maps show that the broader associations of the NAO, particularly over the western North Atlantic and eastern North America, are more apparent during spring-summer-autumn when the new NAOm index is used. This NAOm has enabled us to study the coupling between the seasons in the evolution of the NAO on intraseasonal and decadal timescales. We believe that this is an important key to understanding the climatic forces behind the NAO on different timescales and to developing predictive capability.

North Atlantic Storm Track Variability and Associations with Monthly Regional Climate Variations

Fifty-two years (1948-99) of reanalysis products and other data (e.g., NAO) was used to document North Atlantic winter storm track variability (October-March) and its associations with monthly regional climate variations. Cyclone counts were estimated by Serreze’s cyclone detection and tracking algorithm using 6-hourly NCEP/NCAR reanalysis sea level pressure (SLP) fields. The study domain extended over the Atlantic basin from 20°N to 72°N, and from 80°W to 0°. The first step in our analysis was the construction of a cyclone track density field (CDF) for the study domain. The CDF field was designed to provide a description of the storm tracks on time scales of two weeks and longer, rather than to describe the movement of individual cyclones. The principal modes of North Atlantic winter storm track variability were identified from a rotated principal component analysis of the CDF field. The cyclone behavior over the North Atlantic can be classified into six major regime patterns; corresponding to the positive and negative amplitude excursions of each of the first three rotated principal components. These patterns were found to be dynamically consistent with the anomaly fields of SLP and 500hPa height. The centers of action for the first rotated principal component (RPC1) have the closest location to the Icelandic low and the Azores high. RPC1-based composite differences of SLPA and CDFA resemble a strong positive NAO. RPC2-based composite differences of SLPA and CDFA resemble a negative phase of the NAO with the southward migration of the NAO centers. It is the positive pattern of this regime that brings the most cyclones into the Iberian Peninsula and Morocco. RPC3-based composite differences of SLPA and CDFA show that this is a very dry pattern for Europe. The linkage between the NAO and these CDF patterns was further investigated by spatial correlation of these patterns with the NAO index and composites of the CDF patterns during extreme phases of the NAO.

African Studies

East African Rains

Almost all facets of societal and economic activities in East Africa are critically dependent on the variability of seasonal rainfall that mostly occurs during the boreal spring (Long Rains, March-May) and autumn (Short Rains, September/October-December). However, the societies are often unprepared to adjust quickly to dramatic deviations from normal rainfall regimes (both seasonal total and frequency of extended wet/dry spells within the season), and valuable resources are often wasted. The fundamental goal of this CIMMS study was to understand the mechanisms that govern the intraseasonal and interannual rainfall variability and hence improve existing climate monitoring and forecasting in East Africa. This research first assessed the representativeness of the predictability of the large-scale rainfall at smaller spatial scales within East Africa. In addition, the validity of using outgoing longwave radiation anomalies as a proxy for rainfall anomalies was evaluated. Diagnostic analyses were also made of the relationship between East African rainfall and ocean-atmosphere structures associated with El Niño/Southern Oscillation (ENSO) and non-ENSO variability, with a view to establishing the physical basis for remote teleconnections with sea surface temperature (SST) and therefore improving reliability and confidence in SST-based prediction schemes for East Africa. Having defined the teleconnection structures for the seasonal mean, this study then took a first look at the role of extended wet spells over East Africa in the October-November rainfall anomalies and associated teleconnection structures that, in addition to enhancing understanding, sheds light on the potential for anticipating intraseasonal rainfall events. Finally, the research looked at the large-scale boundary layer moisture relative to rainfall variability, which also leads to a better understanding of the evolutions of wet spells. The results of the study have provided insight into rainfall variability in East Africa, in view of global tropics ocean-atmosphere climate patterns and underlying mechanisms. These results should feed into real-time monitoring and forecasting at intraseasonal to interannual time scales to enhance early warning and disaster preparedness activities and minimize the climate-related catastrophes that are prevalent in the region. This work was performed and completed at OU by a doctoral student from the University of Nairobi in Kenya.

Contribution to International Climate Outlook Forums

Scientists at CIMMS contributed strongly to Climate Outlook Forums in West, East and Southern Africa (and one in the Caribbean). Verification of all the first round of African forums was supervised by CIMMS and results were presented at the forums, demonstrating that the levels of skill achieved by all forum map forecast products was well above the level expected by a random forecast strategy, and quite consistent with the levels of skill achieved by forecast models (empirical and numerical) on past data. CIMMS continued to contribute to further regional training workshops in Africa for National Meteorological Service personnel. These included a further workshop for West Africa and first workshops for East and Southern Africa, such that almost every National Meteorological Service south of the Sahara now has a member of staff conversant with regional climate prediction and a set of seasonal rainfall prediction models for regions within their country based on sea-surface temperature predictors. The training included verification methods as well as prediction methods. CIMMS also undertook collaborative work with the South African Drought Monitoring Center to develop the first system for verifying regional climate outlook forum seasonal outlook maps.

Regional Climate Impacts: Information and Forecasting for Users - The Case of Malawi

As part of the Malawi Environmental Management Project (a World Bank sponsored initiative), scientists at CIMMS visited the Malawi Meteorological Department headquarters to develop capacity for user-tailored regional climate prediction systems. Meetings were held with users in Malawi including the Tea Association, the National Insurance Company, the Regional Water Board, and World Vision International. Impacts of climate anomalies on their activities were discussed and pilot climate services, incorporating climate predictions and real-time monitoring through the season, were defined for each of these customers. This experiment with the commercial sector provided the perfect complement to a RANET project aimed at the small-scale farmer.

Variability of West African Disturbance Lines

A large set of historical daily rainfall data from the West African Sahel was used to document the role that variations in the characteristics of individual rainfall disturbances have played in the long-term decline and the large interannual variability of seasonal rainfall totals in that region. The existing rainfall data set was updated through 1998. Analysis of these data suggested that a long-term decrease in both the size and intensity of disturbance lines has contributed to the decline in seasonal rainfall totals in the Sahel. Large, well-organized disturbance lines have become less frequent, and small, weak disturbances have become more common. The seasonal average size and intensity of disturbance lines decreased from the 1950s until the mid-1980s throughout the Sahel. Since then, the trends in seasonal average disturbance line characteristics have varied according to location within the study area. On the intraseasonal time scale, composites of extremely dry and extremely wet years showed that throughout the entire rainy season, disturbance lines tend to be larger and more intense during wet years and smaller and less intense during dry years. In collaboration with the TAMSAT group at the University of Reading, satellite rainfall estimation techniques were applied (for those years when both satellite and raingauge data are available) to verify sections of the raingauge based rainfall indices used to obtain the results summarized above.

Characteristics of the Kiremt (June-September) Rainy Season in Ethiopia

One of the most important steps in investigating the characteristics of the primary rainy season of Ethiopia is developing a unique research-quality database. Starting with a trip to Ethiopia in June 2000, we collected and computerized daily rainfall data for 120 stations that have 13 to 50 years of observations, and 25 years of daily upper-air soundings for Addis Ababa. This database, the first of its kind for Ethiopia, was extensively quality controlled through visual inspections and computerized program checks. The next major accomplishment was the objective determination of the start and end times of the rainy season of Ethiopia based on daily rainfall of 120 stations. In addition, we have objectively determined the 'breaks' of the summer rains. These objective analyses have provided not only the climatology of onset, cessation and breaks, but also enabled us to investigate the interannual variability of rainfall, and specifically the characteristics and causes of droughts in Ethiopia. In this regard we made a preliminary investigation to understand the causes of the extreme drought of 1984, one of the most severe droughts of Ethiopia.

South and Central American Studies

A Special Atmospheric Sounding Network for Studies of Climate and its Variability in the Tropical Americas

A special network of pilot balloon sounding stations was operated and expanded to include ten countries ranging from Paraguay to Mexico. Daily observations from approximately 15 sites was used by NSSL to monitor lower tropospheric wind variations associated with the annual cycle and with climate anomalies over the region. Of special interest were observations in Bolivia to describe the major low-level jet east of the Andes and twice-daily observations at several sites in Mexico around the Gulf of California to better describe the annual cycle of winds associated with the Mexican monsoon. The data from the network have been used to describe wet and dry periods both in Central America and in Peru during the recent 1997-98 El Niño event. A major thrust was to convert the network observations from a strictly research mode to one where the observations arrive in real-time for use by the forecasting communities throughout the region.

U.S. Studies

GCIP

Land-atmosphere interactions are central to the natural environment, involving and affecting individual weather systems, regional climate, the hydrological cycle, soil and vegetation status, and agricultural production. This importance is manifest in several long-term, international, biological and geophysical programs, including GEWEX. The first major GEWEX activity, GCIP, focused on the land-atmosphere interactions of the greater Mississippi River basin during the second half of the 1990s. A land-atmosphere interaction suite of pervasive environmental importance involves the classical issue of the relative contributions to regional precipitation of locally evapotranspired (i.e., recycled) moisture versus externally advected atmospheric water vapor. Using a new but simple formulation, we obtained the first comprehensive estimation of the intraseasonal and interannual variability of those moisture sources for the growing season precipitation of arguably the World's most productive, largely unirrigated, agricultural region – the Corn Belt and surrounding areas of the midwestern United States – which also occupies about 35 percent of the GCIP domain. Consistent with its GCIP co-location, this region is considered representative of the mid-latitude, mid-continent, land-atmosphere interactions that are vital for global water resources and hence food production. For four highly contrasting growing seasons, we found the contribution of the locally evapotranspired moisture to this precipitation to be relatively small and remarkably consistent (largely 19-24 percent) on a monthly and seasonal mean basis, despite large precipitation and crop yield variations, and to decrease markedly (from a 28 percent to 15 percent average) with increasing precipitation on a daily basis. Our approach and results yielded considerable physical insight into the complex land-atmosphere interactions involved, including into plant behavior and the apparent paradox between the above monthly/seasonal and daily time-scale results.

Moisture budget components and related parameters were evaluated for a large area (about 10^6 km^2) in the midwestern United States for all 24-hour (12-12 UT) periods during the highly (contrasting) May-August periods of 1975, 1976, 1979, and 1988. Relationships among the budget components were obtained by first stratifying them in different ways, and then by using linear correlation and cross-spectral analysis. The results showed that the calculation of evaporation as a residual of the moisture budget equation yielded values close to the (few) existing observations, especially for periods on the order of one month or longer. The evaporation showed a clear bimodal distribution with respect to precipitation, with high evaporation associated with low and high precipitation amounts, and with a minimum of 3.1 mmd^{-1} for a precipitation rate of about 4-5 mmd^{-1}. The interannual and intraseasonal variation in precipitation was mostly accounted for by the fluctuations of the moisture flux divergence (and chiefly by its velocity divergence component). An extremely high negative correlation (in the 24-hour moisture budget) was found between the horizontal moisture advection and the time change of precipitable water. A high correlation was also found between rainfall and the vertically integrated vertical moist advection. Rainfall and total precipitable water were also positively correlated. In addition there is a low, but significant positive correlation between precipitation and horizontal advection and a negative correlation between precipitation and the time change of precipitable water. Precipitation correlated with evaporation on a monthly time scale (but not on shorter time scales) indicating a possible feedback between the two variables on that time scale. Power spectrum analysis of the 12-hour moisture budget components revealed peaks in three major frequency bands, located at 2-4, 5-6, and 8-12 days. Several pairs of budget terms exhibited a high coherence squared with a nearly constant phase difference within a broad frequency band in all four summers. The most outstanding results were that maximum precipitation follows the maximum horizontal convergence term by 15 degrees and the moist advection maximum by 120 degrees. Another finding was that the time change of precipitable water and moist advection have a very high coherence squared, and are in-phase over a wide frequency band. Finally, the maximum in precipitation follows maximum precipitable water by about 20 degrees and the maximum time change of precipitable water by 110 degrees.

Southwestern U.S. Precipitation

A new "monsoon" index was developed that better identifies the region of southwest North America that experiences a climatically distinct summer rainy period. The index focuses both on the precipitation during July and August and on the lack of precipitation during the prior two months. Historically, the characteristic dry period has not been incorporated into such indices. This new index illustrated that the summer monsoon is most distinct from northwestern Mexico and southeastern Arizona west northwestward into the California deserts and extreme southern Nevada. Prior indices have indicated the dominant monsoon affects to extend from northwest Mexico across southeastern Arizona and most of New Mexico. The synoptic patterns that actually lead to the inverse correlation of summer precipitation between the central Plains and northwestern Mexico were investigated for several years where the wet/dry and dry/wet signals were very strong for climate zones in eastern Nebraska and southeastern Arizona.

Implementation of the U.S. Climate Reference Network (CRN)

The purpose of this project was to provide advice on station design and development in connection with implementation of the U.S. Climate Reference Network (CRN). The work included recommendations on selection of instrumentation for measuring temperature, precipitation, global solar radiation, and wind speed and procedures for (a) calibrating the various sensors and documenting the results, (b) verifying system performance in the "System Field Comparison" phase among co-located stations, and (c) analyzing the data from the "Validation Phase" which leads to station commissioning. Work was conducted with the National Climatic Data Center to develop real-time quality control measures applied to CRN data. To date the principal accomplishments have been an investigation of windscreens for reducing under catch of rain and snow (especially the latter), and the design of calibration procedures of a vibrating-wire type all-weather precipitation gage. Both efforts are ongoing and are being carried out with personnel at the Atmospheric Technology Division of NCAR through the Frozen Precipitation Research Project.

Atmospheric Radiation Measurement (ARM) Program

Soil Moisture Measurements

The ARM Program deployed a rugged, automated, and affordable soil water sensor in an attempt to meet the soil water data needs of ARM and GCIP investigators. This system, devised by CIMMS scientist, is called the soil water and temperature system (SWATS). Various factors required that an approach different from traditional efforts within the soil science and hydrologic communities be devised, requiring selection of the best sensor available given logistical and fiscal constraints. The implementation of this network was completed during 1997. Data collection and analysis continue.

Coordination with the USDA/ARS and Oklahoma Mesonet soil moisture measurement networks to achieve similarity in calibration and validation procedures was undertaken. This effort was facilitated by an "Oklahoma Soil Moisture Summit" held at the USDA/ARS Grazinglands Research Laboratory in March 1999. The development of a second-generation calibration technique to address sensor limitations under wet conditions led to a major reprocessing effort of the archived ARM soil moisture data.

Research on the spatiotemporal variations in soil water looked at representative time series from the first three years of operation. Of special interest were periods of drying in spring and summer and subsequent cool season recharge of soil water.

Broadband Surface Albedo

Knowledge of the broadband surface albedo, defined as the ratio of the hemispherical reflected solar flux to the hemispherical incoming solar flux, is important in modeling the surface energy budget because the quantity (1-albedo) is the proportion of the incoming solar flux available for sensible and latent heating at the land-atmosphere interface. Clear sky albedo varies with time of day, day of year, vegetation type and health, soil type and moisture, and presence or absence of early morning dew or frost.

ARM SGP extended facilities (EF) were visited to document the uniformity of vegetation and landform in and around each facility. The purpose was to establish the degree to which site measurements of downward and reflected solar radiation, particularly the latter, are representative of the size of satellite footprints; i.e., at least a few square kilometers. Each of the 21 EF sites visited was classified as "good", "fair", or "poor" with regard to the extent of vegetation and landform uniformity. Six sites were classified as "good". These are Plevna, KS; Coldwater, KS; Pawhuska, OK, Morris, OK; El Reno, OK; and Cordell, OK. Solar and Infrared Radiation Stations (SIRS) data for 1998 and 1999 for these six sites were extracted from the ARM Data Archive and each day was classified into one of six cloud cover indices: clear entire day; continuous clear portion(s) ≥ 3 h; continuous clear portion(s) < 3 h; significant periods of cloudiness; overcast; and indeterminate. Surface albedos were calculated for days of little or no detectable cloud cover using data obtained from these six sites. Plots were prepared showing the diurnal variations of clear-sky albedo for the six sites over the 2-year period of study. Additional plots were prepared showing seasonal variations of clear-sky albedo. Dependence of clear-sky albedo on antecedent rainfall was also studied. A climatological study of daily surface albedo for all radiometer-equipped EFs was underway.

Low-Level Jet

A long-term project examining the low-level jet (LLJ) over the ARM SGP site concluded during this period. Thirty days of LLJ activity were examined, using both ARM and NWS observations and model simulations using the NCAR/PSU mesoscale model, and twelve cases were identified for intensive study. Of the twelve cases, six involved strong LLJs and six involved weak LLJs. Results indicated that the model simulations of the strong LLJs were more accurate than those of the weaker LLJs. Yet, importantly, observations indicated that weak LLJs form more often over the SGP, indicating model simulations of the northward flux of water vapor in low-levels may under predict the true flux amounts.

A case of enhanced LLJs owing to the development and evolution of a persistent region of mesoscale convection also was explored. Over a two and half day period, 15 mesoscale convective complexes (MCSs) developed and moved eastward across a moist axis located over the SGP region. While the 6-18 hour lifetimes of each of these individual MCSs was not sufficiently long to influence the large-scale environment greatly, it is possible that the cumulative effects of the entire group of MCSs produced significant changes in the large-scale flow patterns. This hypothesis was investigated using output from two runs of a sophisticated mesoscale model. One run included the effects of convection, and the other did not. Results indicated that in low levels, the inflow of warm, moist air into the convective region increased when convection was allowed in the model, enhancing the likelihood that convection will continue and thereby act as a positive feedback mechanism. In upper levels, the convection acted as a Rossby wave source region and produced significant upper-level perturbations that covered at least a 50*f*-longitude spread. Convective effects also influenced cyclogenesis, as the MCSs strengthened the low-level baroclinicity and modified the phase relationship between pressure and thermal waves in mid levels. Thus, it is clear that the effects of a persistent, mesoscale region of convection on the large-scale environment are substantial.

A review article on the importance of LLJs to climate was published in the *Journal of Climate* in July 1996. This work summarized many studies showing that LLJs occur frequently in many parts of the world. These low-level wind speed maxima are important for both the horizontal and vertical fluxes of temperature and moisture, and have been found to be associated with the development and evolution of deep convection. Since deep convective activity produces a significant amount of upper-level cloudiness and is responsible for a large fraction of the warm season rainfall in the U.S., the relationship between LLJs and deep convection suggests that LLJs are important contributors to regional climate. Results from a number of past studies were reviewed, and the potential for data from the ARM Program to augment our understanding of LLJs was discussed.

An exploratory study on the ability to simulate nocturnal planetary boundary layers, important to the simulations of LLJs, was undertaken using a simple one-dimensional boundary layer model. Results from both one- and three-dimensional numerical simulations indicated that the nocturnal boundary layer often is too shallow when compared with observations from the ARM SGP Lamont site. Since many complex interactions occur within the nocturnal boundary layer (e.g., gravity waves, drainage flows, mechanically induced turbulence), a procedure to use a statistical mixing approach was developed. In this approach, the amount of mixing that occurs at a given grid point is related to the wind shear in the layer. The greater the wind shear, the more often stronger mixing occurs in the model simulation. This statistical approach replicates the behavior seen in observations of nocturnal boundary layers, and results from 20 cases showed that the depth of the nocturnal boundary layer was better simulated with the statistical intermittent mixing model than with the Blackadar implicit K-theory scheme used in the NCAR/PSU mesoscale model. Initial three-dimensional testing of this approach indicated that while the depth of the nocturnal planetary boundary layer was improved by using the intermittent mixing model, the model simulations of wind speed were slightly less accurate. This suggests refinements in the intermittent mixing approach are needed before further testing is pursued.

Measurements of Water Vapor

Work was done to combine laboratory intercomparisons and calibrations with field tests of ARM surface water vapor measurements before and after an intensive three-week study of water vapor in September 1996 in northern Oklahoma. Laboratory work was performed in the calibration facility of the Oklahoma Mesonet. This work was instrumental in producing high quality and consistent water vapor measurements during the field study. Temperature and relative humidity errors that resulted from large temperature fluctuations were analyzed. These errors occurred because of the filter that is required in the typical probes that measure relative humidity. A new system was designed and used during the September 1996 study to remove these errors. In general, these errors are small and are not a large problem. However, if one-minute data are obtained from these probes, then the errors can be significant when air temperature is changing rapidly.

Research was also performed to compare state-of-the-art chilled mirror hygrometers with standard Vaisala relative humidity probes to assess the accuracy of the standard probes and the feasibility of using the chilled mirror sensors for a long period of time in a field situation. It was found that the standard relative humidity probe performed remarkably similar to the chilled mirror standard during a follow-up intensive study of water vapor conducted at the ARM site in September 1997. In fact, it was recommended that the Vaisala probes are sufficient for such purposes, and that the chilled mirrors can be reserved for special field projects. The assessment of the durability of the chilled mirror hygrometers for long-term deployment is ongoing.

CIMMS scientists also installed chilled mirror dewpoint sensors at the ARM SGP Central Facility (Lamont) to provide NIST traceable moisture measurement capabilities. These sensors act as calibration standards for other moisture measurements made in ARM and should provide a high level of confidence and accuracy. These chilled mirror dewpoint sensors, installed at the surface and on a 60-m tower during the September 1997 study, provided surface and low-level measurements necessary to complete the Raman lidar moisture profile (the lidar usually has a lowest range gate of approximately 60-m). This deployment made it possible to compare precipitable water vapor measurements made with microwave radiometers and a GPS system with those obtained from the Raman lidar. Although the shape of the Raman lidar moisture profile is correct, the absolute calibration may drift. Therefore, the 60-m tower observations were used to scale the lidar profile so that the two agree at the 60-m level. Great care was taken to ensure that the 60-m tower observations were correct; thus, the tower observations were treated as correct and the lidar profile was adjusted to agree with it. Comparisons at the Central Facility showed that microwave radiometer and Raman lidar measurements were extremely stable throughout the intensive period with respect to one another (slope = 1.01 ± 0.01 with a 3 sigma standard deviation), but that there was a pure bias of about 0.18 cm between the two. The comparison to the GPS values with processing provided by the Scripps Institute of Oceanography showed a fractional difference of about 5 percent and only a small offset. Comparisons to NOAA ERL processing of the GPS data showed similar results, but with precipitable water vapor values that were only about 2 percent drier than the tower values. Similar chilled mirror systems were also developed to support field projects requiring highly accurate, NIST traceable measurements of dewpoint. The University of Wisconsin used one system on Andros Island in 1998 as part of CAMEX-III.

A temperature and relative humidity calibration chamber was purchased by the ARM Program and operates at the SGP Central Facility through the efforts of scientists at CIMMS. The chamber has proven useful in testing sensors and has detected instrumentation errors that otherwise would have gone undetected or would have required manufacturer testing to find. A calibration schedule was developed to test field sensors, which are calibrated every two weeks in the chamber. This ensures that accurate field tests are performed, with the ultimate goal of improving data quality. Calibration of individual radiosondes is feasible using the calibration chamber.

Radiosonde calibrations were performed in the Oklahoma Mesonet laboratory and compared to the results provided by the sonde manufacturer (Vaisala). This experiment was designed partly in response to work done at the University of Wisconsin for the ARM Program that involved scaling the radiosonde output to a single humidity measurement on a 60-m tower in order to improve the estimate of sonde integrated water vapor. Thus, in order to determine if a single point comparison can increase sonde accuracy, several radiosondes were recalibrated in the laboratory. If the calibration results showed that a significant portion of the error is because of an offset, then comparison of sondes with an accurate moisture measurement prior to sonde launch could lead to improvements in the accuracy of the moisture profiles obtained by the sondes.

A contamination correction developed by sonde vendor Vaisala was applied to radiosondes launched by the ARM Program in 1997 and 1998. Over 1,000 sondes were launched from the Central Facility in 1998, and the magnitude of the correction and its impact on precipitable water vapor and the radiative fluxes were examined in collaboration with scientists at NCAR. Preliminary results indicate a large seasonal variability in the magnitude of the correction (weaker in the winter and fall and larger in the spring and summer). Surface longwave fluxes were modified by as much as 7 W/m^2 in the spring and summer. The relative impact of the water vapor correction on the radiative fluxes appears to be larger when the correction to precipitable water vapor is smaller. These results are similar to those obtained in the re-analysis of TOGA COARE sondes, except that the seasonal variability was not evident. Seasonal variability could have important implications from a climatic point of view and will be examined further.

ARM Southern Great Plains Site Observations of the Smoke Pall Associated with the 1998 Central American Fires

Drought-stricken areas of Central America and Mexico were victimized in 1998 by forest and brush fires that burned out of control during much of the first half of the year. Wind trajectories at various times during the episode helped transport smoke from these fires over the Gulf of Mexico and into portions of the U.S. Visibilities were greatly reduced during these favorable flow periods from New Mexico to south Florida and northward to Wisconsin as a result of this smoke and haze. Public health advisories and public information statements were issued by agencies such as the NWS in May in Oklahoma. This event was also detected by the unique array of instrumentation deployed at ARM's SGP CART and by sensors of the Oklahoma Department of Environmental Quality/Air Quality Division. Observations from these measurement devices suggested elevated levels of aerosol loading and ozone concentration over the CART during May 1998 when flow conditions were favorable for the transport of the Central American smoke pall into Oklahoma and Kansas. Trajectories ending at the CART Central Facility in May indicated that May 13-15 and May 17-19 should have been particularly good days for observing the smoke pall in Oklahoma and Kansas. Indeed, analyses from the ARM aerosol observing system, Raman lidar, solar and infrared radiation stations, multi-filter rotating shadowband radiometer, Cimel sunphotometer, micropulse lidar, a University of Utah polarization diversity lidar, and condensation nuclei counters on the North Dakota Citation aircraft showed elevated levels of aerosols. Additionally, ozone monitors of the Oklahoma Air Quality Division showed concentrations on May 11 in excess of EPA clean air limits of 0.080 parts per million, although the weather conditions that day (not excessively hot or stagnant) were not conducive to producing ozone, suggesting transport into the region. Interestingly, the smoke pall intrusion of May 13-15 was generally limited to the lowest two kilometers of the atmosphere, while the later intrusion, which occurred after a strong cold front had cleaned the atmosphere late on May 15, showed elevated aerosols up to six kilometers. This multi-collaborator observational study, coordinated by a CIMMS scientist, particularly showcased a new capability for retrieving aerosol extinction profiles from Raman lidar data. A manuscript describing this work was featured on the cover of the November 2000 issue of the *Bulletin of the American Meteorological Society*.

ARM Program Data Quality Office

The ARM Data Quality Office was established at CIMMS in July 2000 with staff hired in July 2000 and January 2001, respectively. The office has the responsibility to:

- Develop and implement a process to systematically inspect and assess all ARM datastreams, including those from the Southern Great Plains, Tropical Western Pacific, and North Slope of Alaska sites;
- Comprehensively inspect and assess ARM datastreams for quality (this activity is done in coordination with ARM Program instrument mentors and site scientists);
- Transmit quality assessment results to site operators in a timely manner so that corrective maintenance and troubleshooting can be accomplished quickly, reducing the amount of unacceptable data collected (done in coordination with instrument mentors and site scientists);
- Transmit quality assessment results to data users in a reasonable fashion so that they may make informed decisions when using ARM data in their research;
- Ensure that web-based documentation about ARM data quality is available and useful to all; and
- Participate in discussions relevant to furthering the ARM data quality program.

Activity has occurred to date in all six categories, though the prime thrust of the first year of the project has involved creation of the process (system) with which to inspect and assess ARM datastreams. It is web-based and can be seen at http://dq.arm.gov.

SuomiNet Efforts in the U.S. Southern Great Plains

SuomiNet is a university-based, real-time, national network of Global Positioning System (GPS) installations established in 2000 for geosciences research and education, with funding from the National Science Foundation and cost sharing from collaborating universities. The network exploits the ability of ground-based GPS receivers to make atmospheric measurements, particularly slant-path integrated water vapor. OU and CIMMS, in partnership with the ARM Program, participated in the establishment of geodetic quality SuomiNet receivers at 15 ARM SGP locations throughout Oklahoma and Kansas and at the Oklahoma Mesonet weather station in Norman. Data collection and analysis continues.

Application of WSR-88D Data Toward Developing Four-Dimensional Wind and Cloud Fields

WSR-88D Level II radar data provide an additional external data set for research directed toward achieving the scientific goals of the ARM Program. This project involved efforts in two unique but related areas. The first area entailed the creation of vertical profiles of the horizontal wind and divergence at radar locations within the ARM SGP site. Preliminary work demonstrated that the radar-derived velocities and divergence signatures can be used to verify the large-scale vertical motion fields provided in the ARM Single-Column Model (SCM) data sets (or from models such as that of the ECMWF). The second area of interest involved the integration of the radar data into 4-D analyses of the cloud field within the SCM box. Algorithms, developed at CAPS, which integrate a variety of observational sources (e.g., radar, satellite, and surface data), were used to generate cloud fields and associated products. Evaluation of the advective tendencies of hydrometeors (which are not currently well estimated) was an anticipated output of this work. The performance of the cloud analysis package was evaluated via an intercomparison of ARM observations (e.g., millimeter cloud radar) with the analysis cloud fields. Both research thrusts have contributed to the development and testing of SCMs. This work involved collaboration with scientists at the University of Utah and the U.S. Department of Energy.

Aerosols

Anthropogenic Sulfate Aerosols

A simple and computationally efficient method that allows a multitude of sensitivity tests for evaluation of the indirect effect of anthropogenic sulfate aerosols was developed. The tests performed focused on the effects of marine stratiform cloud types and amounts, as well as on the seasonality of the indirect forcing. Indirect forcing was found to be -1.1 Wm^{-2}, with a hemispheric difference of 0.4 Wm^{-2}. Hemispheric forcing had a strong seasonal cycle, with Northern Hemisphere (NH) forcing exceeding that of the Southern Hemisphere (SH) during the NH spring and summer and the SH forcing prevailing during the SH spring and summer. The contribution to the forcing by different cloud types was also estimated. The estimate of indirect forcing depends on the climatological mean value of transmittance for different cloud types. The transmittance of the clouds, however, may vary widely, resulting in large regional and seasonal variability of the aerosol indirect forcing.

4. Socioeconomic Impacts of Mesoscale Weather Systems and Regional Scale Climate Variations

Farm Level Decision Model

A whole-farm level decision model was used to examine the impact of the type of decisions producers make on the value of seasonal climate forecasts for east central Texas. Results suggested precipitation forecasts directed toward crop mix and applied nitrogen level decisions would have the largest economic value. Further, the results showed that the economic value of climate forecasts could not be obtained by examining only a small set of decision types. Rather, all decision types must be modeled to correctly value seasonal precipitation forecasts. This occurs because, in response to seasonal climate forecasts, changes in one type of decision may override the need to change other decision types. Finally, forecasts of precipitation during the crop tasseling and grain filling stages may be more valuable than precipitation forecasts for earlier crop growth periods.

Economic Decision Models

Economic decision models incorporating biophysical simulation models were used to examine the impact of the use of Southern Oscillation (SO) information on sorghum production in Texas. Production for 18 sites was aggregated to examine the impact of the use of SO information on the aggregate supply curve and other economic variables. Two information scenarios were examined. The first scenario assumed producers do not use SO information in making their production decisions. This scenario was contrasted to a scenario in which producers use information concerning the SO in making their production decisions. For all expected prices, the use of SO information increased producers' net returns. The expected Texas aggregate sorghum supply curve using SO information shifted both left and right of the "without information" supply curve depending on the price. Changes in nitrogen use based on the SO information were a major factor causing the shift in the supply curves. Further, the use of SO information decreased aggregate expected costs of production. Changes associated with the use of SO information can be summarized as follows -- the use of SO information provides producers a method to use inputs more efficiently. This more efficient use has implications for both the environment and for the agricultural sector. Time series models were used to examine the impact of Southern Oscillation (SO) extreme events in estimating and forecasting Texas sorghum and winter wheat yields. Results were both crop and period specific. Including SO events in forecasting yields decreases the forecast mean square error for winter wheat but had no significant impact on sorghum forecasts. Further, it was shown that a significant correlation between SO events and yields does not necessarily translate into better yield forecasts.

Pipe Bursting due to Freezing

Research was completed on an investigation of the occurrence of freezing temperatures in the southeastern U.S. and their relationship with insurance claims and losses due to pipe bursting. The arrival of a proprietary set of insurance claim data in May 1996 initiated the study of claim occurrence in relation to earlier ongoing analyses of the freezing temperature variability in the Southeast. It included results of each of the following: 1) analysis of the climatology of freeze occurrence in the southeastern United States -- mean occurrence, standard deviations, linear and parabolic trends in occurrence, and analysis of spatial variability; 2) analysis of the spatial and temporal variability of pipe-bursting-related insurance claims; 3) daily analysis and comparison of two catastrophic pipe-freezing events; 4) derivation of alert indicator temperature thresholds for pipe-freezing for distinct multi-county regions; and 5) application of the indicator temperature thresholds in economic analyses, a study of the climatology of severe-freezing temperatures, and the development of a loss-prediction method based on predicted monthly temperatures. Beginning in May 1997, the above research results were formulated into a set of reports to the Institute for Business and Home Safety (IBHS). New data were received in May 1997, which were added to the existing results, and a revision process was initiated based on comments from IBHS and insurance-industry representatives. A final report to the IBHS on the investigation of freezing temperatures and their relationship with insurance claims and losses due to pipe bursting was completed and submitted in February 1998.

El Nino and its Impacts on Society

In cooperation with the Institute for Business and Home Safety (IBHS), a "white paper" on the subject of El Niño and its possible effects on the property insurance industry was prepared. The paper addressed long-term relationships with El Niño and the occurrence of floods, wildfires, hurricanes, severe weather, and nor'easters. For each weather phenomenon, the known relationships with El Niño were examined, examples of previous insurance losses were listed, confidence levels in the year-to-year occurrence of the El Niño-related anomalies were discussed, and current predictions were outlined. A one-day workshop on the same topic was held in Washington, D.C., on 3 November 1997 for approximately 80 executives from various components of the insurance industry. Presentations were made by Dr. Peter J. Lamb (CIMMS), Dr. Michael B. Richman (University of Oklahoma), Dr. Thomas R. Karl (NCDC), Dr. James D. Laver (CPC), and Dr. Roger S. Pulwarty (CIRES).

Climate Prediction, Information, and Policy Response: A Retrospective Assessment of Drought Management in Oklahoma

Work began on documenting prior drought and forecast information through conventional organizational and institutional channels. A regular schedule for team meetings was set, scheduling of interview trips was started, and information collection strategies were developed. A bibliographic record, including a comprehensive newspaper collection and news video coverage, was developed and materials continue to be collected. By the end of June 1998, 29 hour-long, sector-specific interviews had been conducted by the research team to profile information use and drought response. Information was gathered through telephone and personal interviews with members of the Oklahoma Governor's Drought Management Task Force. A daylong meeting was convened by the Oklahoma Department of Civil Emergency Management, and a detailed set of information was acquired. A statewide economic impact assessment of the drought was given to the team by an agricultural economics professor from Oklahoma State University. The team began identifying environmental, economic, and social impacts associated with sector-specific impacts to estimate the value of forecast information. The Oklahoma Mesonet database was used to create a "virtual" drought scenario for the state, and used to identify more accurately the geographic locations of the most severe impacts over the time period of the 1995-96 drought event. In addition, the drought team developed a wheat-growing simulation model based on the drought year to help determine the risks/benefit options available to wheat farmers in the most severely impacted areas. The modeling exercise was developed with the use of the CERES wheat model. Oklahoma Climatological Survey research staff completed the task of characterizing the distribution of temperature and precipitation variables associated with long-range forecasts normalized for Oklahoma. The research team was represented at a drought-related research conference, "Planning for the Next Drought," in Albuquerque, New Mexico. The conference was organized by the National Drought Mitigation Center, and convened drought experts from southwestern states, including Oklahoma and Texas.

Mitigating Severe Weather Impacts on Society and the Civil Infrastructure

Over the last 35 years, the costs of weather-related disasters have doubled or tripled each decade. Weather-related natural disasters alone have taken lives, damaged property, and produced other costs averaging at least $50 billion per year. The mid-continental U.S. from the Gulf coastal plains to Canada experience natural hazards related to severe storms every year. The 3 May 1999 tornado outbreaks in Oklahoma and Kansas, and numerous flood events, are potent examples of the hazards that severe storms pose to communities. The reported costs of such disasters are just a fraction of the actual costs, which include damages to natural resources, loss of landfill capacity, loss of wages, productivity, and threats to public health. The costs of natural hazards are projected to increase if steps are not taken to help communities reduce their vulnerability and prevent natural hazards from becoming natural disasters. These increasing costs are of great concern to government agencies, the private sector, and the public.

In response to a multitude of natural hazards and disasters, national focus is changing from reactive to proactive efforts to reduce impacts to society. For efforts ranging from learning the best methods of response to developing of mitigation measures, a venue was needed to bring together the diversity of stakeholder organizations, both public and private, to formulate strategies for improving the safety and well being of society so that a natural hazard does not become a disaster. Mitigation planning is an emerging industry requiring expertise ranging across scientific and engineering disciplines. As a start to research on these subjects, a symposium was held in spring 2001 in Tulsa, Oklahoma. It focused on weather-related disasters, bridging engineering and meteorological disciplines, to reduce societal impacts, loss of life, and property loss. This symposium addressed the issues of severe weather impacts on the civil infrastructure, best methods to mitigate disasters, and new technologies for prediction and dissemination of information and warnings. The ultimate goals of this symposium were to develop intervention strategies, identify challenges for the future, and determine how to proceed. Topics included floods, wind, drought and other severe impacts of weather and storms. Groups who planned this event include the Oklahoma Weather Center (of which CIMMS is part), the OU International Center for Natural Hazards and Disaster Research, and the OU School of Civil Engineering and Environmental Sciences, in collaboration with FEMA Project Impact, Tulsa Project Impact, the Oklahoma Department of Civil Emergency Management, the NWS, NSSL, and other local, state and federal agencies.

5. Doppler Weather Radar Research and Development

Warning Support

Warning Decision Support System

CIMMS helped design a visualization system that can interactively process, in real-time, 3D radar data from multiple sources, and integrate them together. It is known as the Warning Decision Support System (WDSS). The WDSS display software was modified from its early prototype and has been used to display reflectivity data mosaics from multiple radars, lightning data, and new algorithm outputs (including the Hail Detection Algorithm implementation with neural network output and the dual polarization Hydrometeor Classification Algorithm from the

Cimarron radar). The display uses an earth-centric coordinate system and an automatically updating simulation time to manage the display. The 3-dimensional displays allow the user to interact with the radar data to display cross sections or CAPPIs from a volume of radar data. The ability to rapidly update the algorithm displays (after each elevation angle) was designed and developed. The algorithm outputs from each radar volume were also ingested and organized into a table that may be used to generate trends of each detection characteristic. These tables allow the user or algorithm developer to access to the time-varying characteristics for use in other applications. The WDSS visualization system also integrates maps and other Geographical Information Systems information such as Digital Elevation Maps (DEMs). We tested this system at the National Weather Service Forecast Office in Norman.

The NSSL deployed the WDSS for real-time testing at the Pleasant Hill, MO forecast office during the 1998 convective season. Although there was a general lack of convective storms compared to other years, feedback from the forecasters was positive regarding the use of WDSS in the warning decision making process. Of particular note, the forecasters continue to be impressed by the organization of information within the WDSS and the ease at which the information can be accessed. The Pleasant Hill environment was a unique test site for the WDSS since the WDSS was displayable on the AWIPS workstations as a complimentary warning decision tool. As a result, the staff was able to conduct sectored warning operations where forecast staff was assigned warning responsibilities for specific portions of the county warning area (CWA).

A winter version of the WDSS was deployed in the Reno NWS forecast office in November 1998 for testing of the USBR Snow Accumulation Algorithm (SAA). The Reno staff was impressed with the SAA performance as snow depth verification closely matches that of the SAA's depth estimates. The WDSS is capable of displaying the SAA output in a similar fashion as the precipitation estimates. This test continued through April 1999.

CIMMS and NSSL personnel worked closely with the Techniques Development Laboratory to implement WDSS functionality in the NWS AWIPS. Many of the best features of WDSS were implemented into AWIPS.

An algorithm was developed to segment radar data to identify storms cells for use in WDSS. The segmentation uses a novel hierarchical K-Means clustering algorithm developed at CIMMS to segment images.

Warning Decision Support System - Integrated Information (WDSS-II)

The NSSL deployed a prototype next-generation WDSS (WDSS-Integrated Information) in the Jackson, MS, forecast office. CIMMS scientists designed this visualization system to interactively process, in real-time, 3-dimensional radar data from multiple sources, and integrate them together, resulting in WDSS-II.

Work was done with the Australian Bureau of Meteorology (BOM) to support WDSS operations in Sydney during the 2000 Olympics by deploying a WDSS-II system.

A real-time testing facility, sometimes referred to as the Warning Applications Research room (WARROOM), was implemented during spring 2000. A real-time algorithm evaluation exercise involving the WDSS-II started at that time, and lasted until the end of June. Over 30 participants from NSSL were recruited for the exercise, and teams of 2-4 worked on individual storm days. The teams made comments on various aspects of the WDSS-II, and these were used to make improvements in the system.

Advanced Weather Interactive Processing System (AWIPS)

The NWS, as part of its modernization activities, deployed the Advanced Weather Interactive Processing System (AWIPS) to all forecast offices. This new system allows an integrated sensor approach to detection and warning for severe thunderstorms and tornadoes, including radar, satellite, lightning and other sensor data. These data are blended to help arrive at warning decisions. This represents a shift in NWS use of radar in warnings (which had been used more as a stand-alone sensor) and in the type of training previously provided by the ROC (the PUP). CIMMS, working with ROC, was involved in new efforts with AWIPS in two ways: first, development of AWIPS capabilities, and second, development of training associated with new integrated sensor applications. For the first objective, AWIPS software was ported to ROC UNIX workstations and optimized to run on a network of applications and training development systems. Multiple data types and complete data sets were prepared to run on the UNIX network in the same manner in which the data will be processed in field-office AWIPS units. For the second objective, stand-alone radar signatures and algorithm outputs were integrated into multi-sensor applications (particularly, joint use of radar and satellite information) and tested on storm and tornado cases from 1997 and 1998. Important activities included:

- Development of a better understanding of TVS evolution
- Development of a better understanding of how WSR-88D radars see tornadogenesis
- Use of radar and satellite to reveal tornadic storm updraft evolution
- Use of radar and satellite to better estimate thunderstorm rainfall
- Development of joint radar and satellite methods for determination thunderstorm equilibrium level.
- Analysis of the Jarrell, TX tornado of 27 May 1997
- Analysis of the Hall-White Counties, Georgia, tornado of 20 March 1998
- Work with NSSL, as part of SCAN, to design and test next-generation AWIPS software

Radar continues to be the primary tool that NWS forecasters use in the AWIPS era to interrogate convective phenomena for severe potential. Radar training as such became the primary focus of the WDTB. CIMMS personnel supported radar-use training in AWIPS, advanced velocity interpretation, and new radar-based warning decision tools. Support for radar use training in AWIPS included converting the primary ROC training course, *Distance Learning Operations Course* (DLOC), to an AWIPS format. Support for more advanced training of radar fundamentals included developing a CD-ROM module, *Velocity Explorer*, which uses dual-Doppler analysis and 3D-imagery of severe storms to illustrate single Doppler sampling limitations. Other advanced radar applications included understanding reflectivity and velocity characteristics of tornadic storms using close-range radar data. CIMMS scientists also supported the development of training for WDSS SCAN 2.0, which was scheduled to be integrated into AWIPS in 2001.

Tornado Warning Guidance

Scientists at NSSL and OSF began working together in 1997 to generate new, supplemental Tornado Warning Guidance (TWG) for the NWS based on the latest ideas about and understanding of tornado prediction. Tornado probability diagrams based on numerous radar-based parameters were generated.

CIMMS, in collaboration with the ROC Applications Branch and the WTDB developed the 1999 NWS Tornado Warning Guidance document (TWG99). In anticipation of updating this document, the TWG database was greatly expanded from 43 to 123 cases. Eighty-three of these cases have associated NSE algorithm data, and all 123 cases have associated BWER data. During 2000-2001, CIMMS completed a statistical analysis of this expanded database in preparation for an update to the Tornado Warning Guidance document to be issued in 2002.

WATADS Development

NSSL and CIMMS, in cooperation with the ROC, continued support of the WSR-88D Algorithm Testing and Display System (WATADS) during the period. WATADS software makes it possible to play back high-resolution WSR-88D data tapes to test and compare baseline and experimental algorithms to improve forecasts/warnings. For example, during the FY01 reporting year, there were 2,950 hits on the WATADS Homepage; 482 direct communications with users; 254 different users; and 125 problems identified, 97 percent of which were resolved. A list of WATADS users during the reporting year included the NWS (79 Offices) - 131 (52%); universities - 62 (24%); Department of Defense - 14 (6%); ROC/Other Government - 24 (9%); and Other - 23 (9%).

County Warning Area

NWS personnel are sometimes deluged with radar information on storms within their County Warning Area (CWA). Some offices have several WSR-88Ds available for inspection of storms. In warning operations it can become overwhelming to sort through all of the data and choose the radar with the "best" view of the storm. Scientists at NSSL developed the Multi-Radar Ingest and Analysis System (MuRIAS) to provide a means of ingesting and sorting the WSR-88Ds across a given CWA. This algorithm ranks storms based on severity and alerts the meteorologist to the particular radar it found that provides the best view.

Severe Weather Training Applications

To help reduce the false-alarm rate and increase the probability of detection and lead times for severe weather warnings, development continued at ROC on how to most effectively integrate current observational data into the warning process. Important activities included:

- Participation in the development of current tornado warning guidance for operational forecasters,
- Evaluation of the WSR-88D's ability to detect tornadogenesis features and the limitations of its viewing angle,
- Development of more web-based tutorials on issuing warnings for pulse storms, downburst prediction, and other types of severe weather,
- Development of joint radar and satellite methods for determining thunderstorm characteristics such as updraft evolution and the thunderstorm equilibrium level,

- Documentation of the importance of boundary and updraft evolution as seen by radar and satellite on significant events such as the Jarrell, TX, tornado on 27 May 1997, and
- Investigation of mesocyclone and tornado evolution and algorithm performance for close-range events such as the 3 May 1999 tornado outbreak in Oklahoma.

WSR-88D Open Systems Development

ORPG

NSSL was tasked by the NWS to perform the software development for "re-hosting" the WSR-88D Radar Product Generator (RPG) to an open systems environment. The NWS and ERL signed a Memorandum of Understanding in August 1995 for undertaking this task. Work began shortly thereafter, which included gaining an understanding of the current RPG, initiating the design and development of the Open Systems RPG (ORPG) software infrastructure, determining the best techniques and developing the support software to port the legacy RPG algorithms and product generators to the ORPG environment, and the development of a new Graphical User Interface (GUI) Unit Control Position (UCP).

A total of five Incremental Software Builds were planned for the completion of the ORPG. Reviews and demonstrations of the ORPG were conducted in July 1997 (Incremental Build 2) and January 1998 (Incremental Build 3). Both reviews were well attended by WSR-88D experts and stakeholders. Consensus continued to affirm significant progress continues to be made with the project and that the ORPG will serve the growing operational demands of "tri-agency" users (Department of Commerce, Department of Defense, and Department of Transportation) quite well. Official software and documentation releases of each incremental build were delivered to the OSF for testing and review. Engineering software drops of near-Build 4 functionality were provided to the OSF through June 1998 to support ORPG hardware selection. ORPG team members accessed data from the WSR-88D for ORPG development and testing purposes. The ORPG was able to perform most of the control and monitoring functions of the legacy system. The Product Distribution function was considered to be one of the more complicated components of the legacy system. Considerable effort went into simplifying its design to increase the level of maintainability as well as enhance the flexibility and extensibility of its function. All legacy algorithms and products (51 in all) were eventually ported and integrated into the ORPG. These applications represented the only software ported from the legacy system. The remainder of the ORPG, including the supporting software infrastructure and system applications, represented entirely new development. A very critical enhancement to the ORPG was the development of a new Human/Computer Interface (HCI) to replace the Unit Control Position (UCP). The UCP was an alphanumeric, nested menu interface that was not intuitive and required significant training. The HCI took advantage of an intuitive, graphical interface to display system status and control.

Early in 2000, the manufacturer of the communication server for the ORPG went out of business. A replacement server was identified and software adjustments and extensive testing were required to incorporate the new hardware into the ORPG. Working closely with the NWS, extensive testing (integration and system level) was conducted. Software defects detected during testing and selected enhancements requested by the NWS were addressed. Documentation of the software design and implementation went into full swing later in the period. Advanced technical training in operating systems, interconnectivity, and related areas required for ORPG deployment support readiness was completed as well. Development and implementation of a unique training program was completed that systematically prepares ROC hotline operations personnel to support worldwide fielding of the advanced open architecture radar product generator ORPG throughout the NEXRAD network.

OPUP

NSSL was tasked to develop an Open Systems Principal User Processor (OPUP) for Department of Defense users of the WSR-88D system. The Principal User Processor was a dedicated weather radar display system that was deployed as part of the WSR-88D equipment. NSSL began development activities for the OPUP system, including a review of requirements, a review of available ORPG software infrastructure and support services, and development of prototype applications. Several of the early display prototypes were redesigned to provide more functionality and ease of use. Prototype applications were developed for communicating with the WSR-88D RPG, product storage, graphical product display and control, and configuration functions.

OPUP was designed to implement NEXRAD display functionality in the context of the Air Force Weather Agency (AFWA) centralized forecast Hub concept. The Hub operational scenario established four regional hubs that collect weather data and disseminate them to weather data customers (i.e., Air Force and Army bases). This allowed base weather units to concentrate on providing mission-unique weather support. While the old PUP had only one workstation and could have just one dedicated telecom connection to one radar, the OPUP has dedicated connections to up to 20 radars and products can be displayed on multiple workstations over a local area network. It enables Air Force forecasters at the hubs to issue forecasts and severe weather warnings for Air Force and Army bases in their geographic region of responsibility. In order to establish an OPUP presence early, a staged approach was established, deploying limited functionality versions of OPUP, followed by releases of increased functionality at incremental times.

This project began in late 1997 and is scheduled to conclude in October 2003. In January 2000, the project shifted from a “waterfall” to a “spiral” development model to satisfy AFWA’s requirement for earlier deployment. The OPUP was to be deployed in two phases, called Spiral I and Spiral II. Spiral I included the deployment of four Large OPUP systems to AFWA’s four regional weather hubs at Scott AFB, IL, Barksdale AFB, LA, Davis-Monthan AFB, AZ, and Shaw AFB, SC. Spiral I was completed 31 July 2000, on schedule. From July through March 2001, the OPUP project developed and then deployed an interim software release that added critical functionality to the OPUP system. The additional functionality included the ability to display radar cross-section products, improvements to alert processing, and the ability to dial multiple radars simultaneously. In January 2001, AFWA requested an additional Spiral I deployment to Yokota AB, Japan, by 31 August 2001. Deployment preparations were on schedule at the end of the cooperative agreement period.

ORDA

The objective of this NSSL work was to design and develop signal processing and automatic calibration algorithms for the WSR-88D radar. Activities included analyzing and documenting signal processing functions currently operational in the WSR-88D legacy system, and designing, implementing, and testing the basic set of signal processing functions on the new Open Systems Radar Data Acquisition (ORDA) system. The latter included most of the signal processing functions performed in the legacy Hardwired Signal Processor (HSP) and Programmable Signal Processor (PSP). Code was developed for the new WSR-88D host computer running the real-time operating system VxWorks (WindRiver Systems) and the array of signal processors (SHARCs) running on the Mercury Computer Systems operating system (MCOS).

CODE

The planned transition from legacy hardware and software to a more open environment offered numerous opportunities for improvements to the WSR-88D radar system. One such improvement is the Common Operations and Development Environment (CODE). Still under development, CODE is a process for facilitating introduction of new and improved algorithms and products into the WSR-88D system. In recent years as many as 60 algorithms have been developed for inclusion in the WSR-88D baseline. In addition, more than 70 NWS forecast offices, universities, and DoD organizations use the WSR-88D Algorithm Testing and Display System (WATADS) to improve existing algorithms through post-event studies. CODE also promises to open the algorithm development process to more researchers.

The objectives of CODE center on standardization, reuse of software, ease of including new software in the baseline, ease of data transfer, and common functionality. CODE will be a software system and a development environment running on a workstation separate from the ORPG. It will behave much like the current WATADS with notable additions, namely, the ability to add an algorithm to the baseline, enhance existing algorithms and products, and develop new algorithms with minimal software re-engineering using modular common functionality. With CODE, it will be possible to test algorithms using archived or real-time data. When applications are created in CODE, both the developer and the ROC will be able to run the applications on a common system during initial testing and validation. Applications thus introduced can be integrated into the ORPG much faster because the need for re-engineering is limited. Work locally involves ROC and NSSL scientists.

Severe Weather Application Algorithms

Severe Storms Analysis Package

The Severe Weather Warning Applications and Technology Transfer (SWAT) Team at NSSL continued its primary mission of developing severe weather applications, primarily for the WSR-88D, and transferring technology and knowledge to the NWS and FAA. The team is comprised of two sub-teams – one devoted to the development of tornado warning applications and the other to severe storm warning applications. The SWAT Team's Severe Storms Analysis Package (SSAP) includes the following meteorological algorithms that have been tested off-line and in real-time at WFOs:

- Tornado warning applications
    - Mesoscale Detection Algorithm – MDA
    - Tornado Detection Algorithm – TDA
    - Vortex Detection and Diagnosis Algorithm – VDDA)

- Severe storm warning applications
    - Storm Cell Identification and Tracking Algorithm – SCIT
    - Hail Detection Algorithm – HDA
    - Damaging Downburst Prediction and Detection Algorithm – DDPDA
- Applications related to both sets of applications
    - Near-Storm Environmental Algorithm – NSE

Work on these algorithms is described below in more detail.

Rapid Update Software

One drawback of the original WSR-88D system was that algorithm processing was not done until after the completion of each volume scan of data. Thus, vital algorithm information such as circulation position updates and detections that may have existed at the lower radar elevation angles were not available until the radar finished scanning through the higher elevation angles. This lag time could be as long as several minutes. Through funding from the FAA, software was developed that updates algorithm output after every sweep enabling new severe weather detections to be immediately relayed to the user.

The MDA, TDA, SCIT algorithm, and HDA were incorporated into NSSL's SSAP with rapid update capability, allowing detections and warnings generated by these algorithms to be output at the end of each radar tilt (about every 30 seconds) as opposed to at the end of each volume scan (every 5-6 minutes). This output is also displayed in WDSS-II for all data tilts, and in RADS for the current of latest data tilt. An evaluation of the output indicated that the software functions properly and is of great utility to forecasters.

Mesoscale Detection Algorithm (MDA)

The MDA allows for the detection of storm-scale vortices of various sizes and strengths and classifies them into a number of different vortex types. Trends of vortex attributes are also computed. Each vortex is also diagnosed using a Neural Network (NN) to determine the probability of tornadoes or severe weather associated with each detection.

CIMMS scientists tested the MDA on an ever-expanding database consisting of a variety of tornadic and non-tornadic supercell cases. These scientists also developed a special web-based case study collection of a variety of storm types collected nationwide. This web page depicts a wide range of the types of tornadic storms that have been observed with the WSR-88Ds, and provides detailed discussions, images, and algorithm output evaluations.

Enhancements made to the MDA included the addition of Near-Storm Environmental (NSE) algorithm parameters (as derived from RUC mesoscale model grids). Over 100 NSE parameters were incorporated into the MDA (and TDA). Work was completed to statistically analyze the integrated data. Although individual NSE parameters showed little skill by themselves to discriminate tornadic from non-tornadic detections, a prototype NN trained on a small potion of the integrated data set (14 events) showed nearly a doubling in the skill (using Heidke Skill Statistic as a measure) in diagnosing the probability of a tornado for each detection (from about 35 to 60 percent). A more robust NN was developed that was trained on the Tornado Warning Guidance data set. Web-based tornado warning guidance truthing software was evaluated to aid CIMMS scientists and NWS field forecasters in the development of local MDA and TDA data sets, suitable for local adaptable parameters studies, and for the incorporation of field data into the nationwide database to be collected at NSSL. The software guides forecasters by using the same truthing, association, and scoring methods employed by the NSSL and ROC so that there is consistency in validation efforts.

Tornado Detection Algorithm (TDA)

The TDA underwent extensive WSR-88D implementation during 1997 and was recoded to comply with current WSR-88D computing architecture. New techniques added to the TDA included the computation of azimuthal and radial shear using a linear least-squares method. The TDA was amended to include a rapid update of TVS locations after the first low-altitude elevation. This algorithm continues to be used by WFOs and continues to be favored over the current WSR-88D TVS algorithm.

In cooperation with the ROC Applications Branch, the Tornado Detection Algorithm (TDA) was implemented into the WSR-88D Build 10 Radar Products Generator (RPG) in the fall of 1998.

The TDA was also modified so that it can detect clockwise storm-scale vortices. These modifications were developed in part to support real-time algorithm testing in Sydney, Australia, in the Southern Hemisphere. An "Anti-MDA" was also tested on a few Northern Hemisphere left-moving supercell cases.

Vortex Detection and Diagnosis Algorithm (VDDA)

The VDDA represents a merging of the MDA and TDA into a single algorithm, with some new techniques added. This combined algorithm was needed for several reasons. First, from the analysis of many past supercell cases, it was discovered that there are a variety of storm-scale vortices that can be tornadic in supercells, and they range in size from TVS-like to mesocyclones. Second, it is important to share the analysis techniques of the MDA and TDA, such as the vertical and time association techniques. Also, the integration of data from other radar-based algorithms and other sensors provide a more thorough analysis of the vortices. A new technique featured in the VDDA is an integrated method for diagnosing rotation and divergence within detected vortices.

A pilot study was completed regarding the identification of azimuthal and radial shear regions within WSR-88D data using a least squares derivative technique. This technique was envisioned to be useful in the identification of vortices associated with tornadoes and mesocyclones, as well as identification of divergence associated with downbursts. Also, the technique should be able to differentiate false detections due to linear shear phenomenon (e.g., gust fronts) and true vortex detections. A least squares derivative technique for the identification of azimuthal and radial shear regions was incorporated into a new version of the VDDA. Also, simulated WSR-88D data were created for analytical Rankine vortices with varying diameters, rotational velocities, range from the radar, and beam center-to-vortex offsets. These data were used to test the MDA and TDA for analytical difference, and algorithm strengths and weaknesses. The least-squares derivative technique was also tested on these simulated data. Also, special data sets of simulated mesocyclones with embedded TVSs, mesocyclones with associated rear-flank downdraft gust fronts, and pure linear gust fronts, all with varying strengths, sizes, ranges, and orientations, were developed for testing. The goal of the testing was development of a new two-dimensional vortex feature detector that detects all scales of thunderstorm-scale vortices (mesocyclone and TVSs) for the VDDA.

Neural Networks and Statistical Analyses

Three Neural Networks (NN) were developed - one for MDA, one for TDA, and another for circulations detected by MDA and TDA, jointly. All three NNs had two output nodes, corresponding to the probability of tornado, and the probability of damaging wind, respectively. These were trained and validated on a data set consisting of 29 storm days, and as many as 56 attributes. All three NNs had sufficiently matured for incorporation into SSAP. Reliability diagrams showed that all of the probabilities produced by the NNs were highly reliable. A new data set then became available for analysis. It consisted of 43 storm days, incorporates BWER attributes, and has as many as 85 attributes. As a result of the introduction of BWER attributes it was necessary to develop 6 different NNs (each with two output nodes, for the probability of tornado, and damaging wind):

- NN_I: for circulations detected by MDA, only.
- NN_II: for circulations detected by TDA, only.
- NN_III: for circulations detected by MDA and TDA, jointly.
- NN_IV: for circulations detected by MDA and BWER, jointly.
- NN_V: for circulations detected by TDA and BWER, jointly.
- NN_VI: for circulations detected by MDA, TDA, and BWER, jointly.

Upon preprocessing the data, it was found that if all of the available attributes are input into the NN, some of the resulting NNs tend to over fit the data. This occurs when the sample size is small in comparison to the number of parameters of the NN, the latter being proportional to the number of input nodes. As a result, the optimal NNs do not necessarily require all of the attributes as inputs. The reliability diagrams indicated that the produced probabilities are completely reliable within the statistical error bars.

The aforementioned 43-day data set was utilized for a determination of the best predictors of tornadoes. In spite of the numerous subtleties in the analysis, it was found that it is possible to isolate a few of the many predictors as being the “best” predictors. Several methods were employed; each designed to address a different facet of the problem.

The original set of MDA/TDA NNs was updated with some revisions. In addition to the inclusion of NSE variables as inputs into the NNs, the inputs were transformed to principle components. In order to avoid overfitting, only a subset of the principal components were employed as inputs. A brute force, bootstrapping approach was employed to determine the optimal number of principal components employed as inputs into the NNs. The data were preprocessed in a number of ways for the purpose of extracting information that may be useful for producing tornado warning guidance. This information, however, was not released in order to provide a larger database.

Given the success of NNs in the prediction/detection of tornadoes, work was extended to include the HDA. The development of such a NN was broken into two tasks - a NN developed to detect/predict the existence of hail, and a NN to predict the size of the forecasted hail. The latter was developed first. In fact, two NNs were developed for the prediction of hail size - one that predicts hail size in some physical unit, and another that assesses the probability of belonging to one of three classes of hail size (coin size, golf ball size, and baseball size). Due to the small sample size, Bayesian inference was employed to estimate some of the parameters of the NNs. The first NN produced size estimates that were approximately 30 percent improved over the estimates of the existing rule-base. The latter NN produced probabilities that are highly reliable and discriminatory, with the exception of forecasts of golf ball size hail.

Three neural networks for the HDA were updated, completed, and implemented into WDSS. These are: one for producing a Probability of Severe Hail (POSH); another for estimating Maximum Expected Hail Size (MEHS) in some physical unit; and a third for estimating the hail size in terms of three size classes (> .75", >1.5", >2.25"). A number of statistical techniques were applied to an 83-event data set for the purpose of extracting Tornado Warning Guidance. Also, a preliminary MDA/TDA/BWER/NSE neural network was developed based on the 83-event data set. Work on a Markov chain for tornadic activity was completed as well.

Storm Cell Identification and Tracking (SCIT)

The goals of the SCIT algorithm are to accurately identify the complete depth (volume) of each storm cell and to correctly match cells between volume scans so as to provide reliable trend and forecast movement information. Numerous deficiencies in the tracking routines were identified, and many traced back to errors in the vertical association routines. A multiple-year project with the ROC Applications Branch took place to identify methods to improve the vertical association within the SCIT algorithm.

The SCIT algorithm was modified to produce intermediate output before the end of the volume scan. Expanding on the "rapid update" feature, storm cell information can now be displayed as each elevation angle is completed. After data from the first elevation angle are received, two-dimensional storm cell components at the lowest elevation are matched with cells from the previous volume scan, and their positions are updated. The "new" 2-D components inherit the attributes of the associated "old" storm cell until a new 3-D cell is built and new attributes are computed. Above the first elevation angle, two-dimensional storm cell components at adjacent elevations angles are vertically associated and combined into new 3-D features, according to standard algorithm criteria, as each elevation scan is completed. When a storm cell ceases to have new 2-D components added, it is considered "topped." Topped 3-D cells are matched with 3-D cells from the previous volume scan and feature attributes are calculated. Associations with past 3-D cells allow for tracking information (previous and forecasted locations) as well as a feature identifier to be assigned. Topped 3-D features are then identified on the radar display as each elevation angle is completed.

Hail Detection Algorithm (HDA)

The HDA was analyzed in response to the perception of users that the algorithm was over-warning in summertime storm situations. A total of 78 storm days (hail and non-hail) from locations in Florida, Texas, Virginia, and Illinois were analyzed to determine the bias. The analysis concluded that the over-warning perception could be improved by altering the Probability of Severe Hail (POSH) parameter.

A substantial amount of time was spent investigating the utility of a volumetric severe hail index (VSHI). Although the VSHI was found to have a higher correlation with hail size for isolated storm cells compared to the simple 1-D severe hail index (SHI) parameter, testing on squall-lines showed relatively poorer performance for VSHI at predicting hail size. Test results also showed identical discrimination skill (for severe hail) for both VSHI and SHI. It was concluded that the VSHI parameter offers limited potential for improving the performance of the HAD.

Due to the lack of significant positive test results associated with development of the VSHI, emphasis was shifted to increasing the amount of NSE data used by the HDA. This involved the addition of four new parameters:

- Height of the wet-bulb zero
- Vertically-integrated wet-bulb temperature
- Wind speed at the equilibrium level (EL)
- Storm-relative flow at the -20º C level

A program was written to calculate these parameters from sounding data, and output was generated for all the storm days in the HDA database.

Conditional probability functions for different hail size categories were developed for users of HDA output. A graph and table relating the maximum expected hail size (MEHS) parameter to probabilities of hail size ≥ 1.5 and 2.5 inches, respectively, were created, and this information was disseminated to the operational community via a report on NSSL's web page and with announcements on the SOO-TALK and WX-TALK mailing lists, and in an article in the ROC publication *NEXRAD Now*.

Damaging Downburst Prediction and Detection Algorithm (DDPDA)

This DDPDA algorithm was developed to provide the capability to both predict and detect damaging wind events using Doppler radar reflectivity and velocity data. The DDPDA scans through radar data to locate downburst precursors - events detectable in the middle and upper levels of a storm that may precede the onset of strong winds at the surface. Early versions of the algorithm focused mostly on predicting damaging wind events from short-lived "pulse" thunderstorms. A prediction equation was developed by analyzing approximately 50 convective cells that produced outflows of varying strengths.

The DDPDA was completely rewritten in the C programming language. Additional methods and programs were developed to help better assess the performance of the algorithm and to facilitate easier data collection. The primary events examined were high reflectivity cells that were observed either close to a radar, where the strength of the outflow can be accurately measured, over a wind sensor, or over a highly populated area (where damaging winds are most likely to be reported). The DDPDA was evaluated using a data set of 226 cells located over populated areas, 30 of which were severe. The algorithm yielded 20 hits, 10 missed events, 21 false alarms, and 175 correct non-forecasts of non-events. The probability of detection was 0.617, while the false alarm ratio was 0.512 and the critical success index was 0.392. On average, the algorithm gave an 8.5-minute lead-time for events in this data set. CIMMS scientists at NSSL facilitated agreements between the TDWR Program Support Facility (PSF) and the Low Level Windshear Alert System (LLWAS) Program Office to acquire TDWR and LLWAS microburst/downburst algorithm output (in and around 10 major U.S. airports), data that were necessary for verification. Additional agreements were initiated for obtaining various mesonet data for detecting possible strong microburst/downburst events. Linear multivariate discriminate analysis was used on the available data to determine which WSR-88D derived parameters are useful for detecting damaging events.

The Damaging Wind Events Database was further expanded by 48 severe downburst-producing storm cells and 1137 cells that did not produce severe winds. These storms are classified as "pulse" cells that formed in an environment of moderate-to-high convective available potential energy (CAPE) and weak vertical wind shear. This brings the total number of cells in the database to 148 severe and 2445 non-severe cells, from 76 different event days. Approximately one half of these events are from the U.S. Desert Southwest region. One quarter of the remaining events are from the Florida/Georgia region, while the remaining events are scattered across the Midwest and Central Atlantic states.

Near-Storm Environment (NSE) Algorithm

The goal of the NSE algorithm is to integrate Doppler radar and mesoscale model data to provide the SSAP algorithms with information about the environment of each storm cell, such as shear and stability parameters. Currently, NSE uses output from the Rapid Update Cycle-2 (RUC2) model to help determine the environment of storm cells.

CIMMS scientists completed a statistical study of integrated MDA, TDA, and NSE data for the Tornado Warning Guidance. NSE gridded data are bilinearly interpolated to the location of the MDA and TDA centroids to determine values for each vortex detection. Initial results looked at bivariate distributions of the data, and this suggested that only a few NSE variables offer some diagnostic value for determining whether or not an algorithm-detected storm-scale vortex is tornadic or non-tornadic. Later, a NN was developed on the data set. An early NN using a subset of the data showed nearly a doubling in the skill (using Heidke Skill Statistic as a measure) in diagnosing the probability of a tornado for each detection (from about 32 percent for a NN with no NSE data to 60 percent for a NN that included NSE data). A more robust NN using the NSE data was under development. NSE data were also used to improve the HDA and the DDPDA. The NSE algorithm also supplies real-time data to several of NSSL/SWAT WDSS real-time data sites.

Multiple Pulse Repetition Frequency Dealiasing Algorithm

The Multiple Pulse Repetition Frequency Dealiasing Algorithm (MPDA) involves the mitigation of range and velocity ambiguities inherent in the collection of Doppler radar velocity data. MPDA is a scanning strategy and processing package that collects and merges data at different Nyquist velocities. This is done to create a better representation of the final velocity field than is possible by collecting data at only a single Nyquist velocity. During spring 1997, NSSL successfully tested the package in real-time at the Norman NWS forecast office. Fault mitigation continued through the remainder of 1997, and the final code was delivered to the ROC in 1998.

One interesting case of MPDA data collection occurred during the 3 May 1999 tornadic event. This data set provided a wealth of analysis with respect to strong tornadic signatures. It had been hypothesized that the MPDA would not perform well in an environment such as that on 3 May. To the contrary, it performed exceptionally well in this situation and handled the tornadic signatures well, and in many cases, performed better than the operational KTLX data collection. This was a joint effort between the ROC Applications Branch and the NSSL and represents part of a broader effort to improve overall NEXRAD data quality. An artifact of Doppler radar data is uncertainty in position of a return echo at certain distances from the radar antenna. There are hardware improvements that are possible; the MPDA is a low-cost, interim software solution. We anticipate the MPDA will be recommended for implementation in an early software build under Open Systems.

Bounded Weak Echo Region Algorithm

A Bounded Weak Echo Region (BWER) algorithm was developed in 1998 to detect and classify (using probabilistic "confidence" factors) weak-echo vaults within severe thunderstorms using WSR-88D reflectivity data. The BWER data was integrated with the MDA and TDA data for the entire 123-event Tornado Warning Guidance data set.

Multiple-Radar Algorithm Comparison Study

A study was conducted to determine the amount of variation in severe storm detection algorithm output that occurs when a storm is viewed simultaneously by more than one WSR-88D radar. This work was done as part of an effort to expand the WDSS to integrate information from multiple WSR-88Ds. Two storms were analyzed. Primary conclusions indicated that large differences were found between algorithm output from the two radars. Also, for ranges less than 130 km, storm-top divergence observations were sensitive to the VCP being used and can be highly degraded when the radar is scanning in VCP21. In supercells, velocity dealiasing errors occurred more frequently in VCP11 than in VCP21, thus producing more errors in the output of velocity-based algorithms. Integration of algorithm output from multiple WSR-88Ds into the WDSS was determined to require accurate "error filtering" to avoid propagating incorrect guidance information.

Vertical and Time Association Failure Analysis

NSSL conducted a failure analysis of vertical association (VA) techniques of algorithms within the SSAP. A range of vertical association failures were identified for MDA, TDA, and SCIT for several different storm types including:

- Warm-season/high-shear/supercell (KTLX, 3 May 1999)
- Squall-line (KLSX, 15 April 1994)
- Cool-season/high-shear/supercell (KMPX, 26 October 1996)
- Southwest-monsoon/weak-shear/pulse (KIWA, 14 August 1996)
- Hurricane (KLWX, 13 July 1996)

Failures in the VA code are similar for all schemes when more than one 2D algorithm feature is identified at a given elevation angle, forcing the 3D code to choose between the multiple 2D features. TDA also had an added VA feature that created problems when two TVS signatures were correctly diagnosed within 4 km of one another. Problems outside the 3D code also caused VA failures such as dealiasing problems and an improper setting of the reflectivity threshold below which velocity data are set to missing. Failures occurred in less than 10 percent of all volume scans studied in all cases except for the high shear/fast moving case of 3 May 1999. The cyclic nature of the supercells in that case created conditions in which the VA code often failed (nearly 50 percent of the time). Based on VA code failures, it appeared the most logical solution to this problem could be found by examining all elevation angles at one time rather than examining just two elevation angles at a time. The results from this study suggested that the most appropriate 2D feature at each elevation angle should be identified according to location rather than strength rank (MDA) or gate-to-gate velocity difference (TDA).

As part of an effort to improve the time association (TA) process of several algorithms in the SSAP (SCIT, MDA and TDA), a failure analysis was conducted to identify the primary causes of TA errors. Algorithm output was generated using Level II data from several storm days representing different storm types (see list above). The analysis results indicated that the most common cause of TA failure was due to multiple detections in close proximity to one another, where the TA process chose the wrong candidate for time association. Often, multiple detections were produced because of VA failures. At other times, the algorithm was simply detecting weaker, secondary features. To a lesser extent, bad first-guess locations caused by bad motion vectors also led to TA failures. This study points toward two primary areas for improving time association. First, the algorithm detection/identification process needs to be optimized, including the minimization of VA failures. Then, the TA process should be expanded to utilize additional storm/feature characteristics versus simply selecting the candidate that is closest to the first-guess location. This would involve developing a "cost" function that would compare various algorithm parameter values for all available TA candidates, thereby leading to a more robust TA procedure.

Analysis of TDA Performance

The ROC Applications Branch sought to determine the frequency of TVS (Tornado Vortex Signature) and ETVS (Elevated TVS) false alarms when storms pass directly over a WSR-88D. A random selection of 20 cases from NSSL Level II archives was used for this analysis. All cases have at least one occurrence of a tornado, recorded within or slighter greater than 25 km of the radar vicinity. The analysis compared the TDA performance in WATADS 10.0 with respect to the deactivation of WATADS 9.0's Build 10 dealiasing algorithm. Results were tabulated, and it was observed that TDA performance in WATADS 10.0 is more sensitive to detections. But, the tradeoff is a higher false alarm rate (FAR) for ETVS of 9.38 percent and TVS of 10.36 percent, as compared to WATADS 9.0 FARs for ETVS of 3.83 percent and TVS of 3.31 percent. In addition, the WATADS 10.0 dealiasing algorithm enhanced its former WATADS 9.0 dealiasing algorithm by filling “good” gates/bins to accurately reflect a shear.

Scoring Detection Algorithms

The ROC Applications Branch coded, debugged, and developed a data structure leading to an automated process for scoring output of Doppler radar algorithms, called the Scoring Algorithm Detections program. The program provides comparative scoring and will be used to evaluate candidate algorithms for inclusion in the WSR-88D program. This is an important step in developing a structured algorithm improvement process. During the prototyping stage, candidate WSR-88D severe weather algorithms developed through technology transfer by the NSSL were compared with baseline WSR-88D algorithms. Algorithm data files were obtained from WATADS Version 10.1. The new program compared the number of hits and misses of each selected case, and calculated several established scoring parameters (POD, FAR, CSI, and HSS).

Verification Studies

Synthetic Tornado Climatology

NSSL developed a study to determine whether radar-observed storm-scale vortex signatures (e.g., mesocyclones and TVSs) can be used as a proxy to synthesize tornado climatologies where verification is problematic. Tornado verification can be problematic in certain locations, such as those with low population density, in mountainous and forested regions, and where storm verification is not as actively pursued (such as in Europe and other countries).

Starting with a database of "well-verified" tornado events (43 cases with about 207 tornado reports), and the associated output from both mesocyclone and TVS detection algorithms, we determined the likelihood that particular detections are tornadic based on a variety of detection attributes (such as rotational velocity, depth, etc.). We then applied the posterior probabilities of the well-verified dataset to a test data set that is assumed to be poorly verified (the poorly-verified data set is actually a three-year nearly-conclusive set of all the storm-scale vortex detections collected from the Pittsburgh radar during 1996-1998). The resulting synthetic climatological values for number of tornadoes are quite similar to the actual number of reported tornadoes within the domain of the radar for the poorly verified data set.

Warning Verification Project

NSSL initiated a data collection effort aimed at severe thunderstorm ground-truthing. This project emphasized quality over quantity for the observations it is trying to collect. While *Storm Data* provides a large, nationwide set of ground-truth data, many instances remain when NSSL needs more detailed and precise information. The Verification Project set out to build this type of database with three specific efforts: 1) a WWW-based tool was created for interested observers to deposit storm reports, 2) volunteer storm chasers were asked to accurately log weather observations using GPS equipment and laptop computers purchased during VORTEX, and 3) NSSL continued to perform damage surveys, particularly for those events not surveyed by the NWS.

Precipitation Algorithms

QPE-SUMS

QPE-SUMS is an improved precipitation algorithm that utilizes data from multiple sources. Its functionality includes ground clutter removal, convective/stratiform separation, radar data mosaicing, and flexible Z-R equations. Since its inception, it has been redesigned as an operational, real-time algorithm. Precipitation products are generated every 5 minutes on a grid covering the state of Arizona. Users may display products in a workstation environment, or on a PC via a web-based client developed by the Oklahoma Climatological Survey. Water and power managers have the option to view algorithm output with several important overlays, such as power lines, canal locations, gauge sites, or watershed boundaries.

Generation of Terrain Hybrid Scan and Occultation Data Files in Preparation for the Snow Accumulation Algorithm

In preparation for implementation of the Snow Accumulation Algorithm (SAA), it was necessary for the ROC Applications Branch to generate site-specific terrain hybrid scan and occultation data files. These files account for and remove local terrain that otherwise would cause unrealistically high returns at low elevation angles. UNIX batch processing was used to deal with such a large volume of data sets. All data files were annotated, resized, and compressed for future reference.

Hydrometeor Classification Algorithm Using Polarimetric Radar Data

In collaboration with scientists from the National Center for Atmospheric Research (NCAR), work was completed on a real-time polarimetric radar algorithm to identify and classify hydrometeor types. The algorithm classifies eleven hydrometeor types: light rain (LR), moderate rain (MR), heavy rain (HR), large drops (with low concentration) (LD), rain/hail mixture (R/H), graupel/small hail (GSH), hail (HA), dry snow (DS), wet snow (WS), and horizontally- and vertically-oriented ice crystals (IH and IV). It uses fuzzy logic to weight and combine polarimetric radar measurements of reflectivity (Z), differential reflectivity (Z_{DR}), specific differential phase (K_{DP}), cross correlation coefficient (rhv (0)), and linear depolarization ratio (L_{DR}). The algorithm also identifies radar signatures associated with anomalous propagation, birds, and insects. NSSL and CIMMS scientists participated in the TExas/FLorida Underflight (TEFLUN-B) Experiment near Melbourne, Florida. Though some fine-tuning of the algorithm was needed, an evaluation of its performance on the NCAR S-POL radar during that experiment indicates that the algorithm effectively determined hydrometeor types.

A new version of a polarimetric rainfall algorithm based on the joint use of the specific differential phase K_{DP} and differential reflectivity Z_{DR} was developed and tested for several "outlier" rain events in Oklahoma for which the operationally used WSR-88D precipitation algorithm failed. The new algorithm, which takes into account variations in the drop median volume diameter D_0, showed substantial improvement.

A real-time version of the hydrometeor classification algorithm based on polarimetric radar data was developed and tested during the spring/summer convective season of 2001. It allows us to distinguish between different types of rain, rain/hail mixture, biological scatterers (insects and birds), and ground clutter (including anomalous propagation echoes). The output products (fields of different polarimetric variables and results of classification) were delivered on the regular basis to the Norman NWS forecast office.

Polarimetric Radar Developments

Observations of Rain

Regular observations of rain with the Cimarron polarimetric radar combined with observations from conventional KTLX (central Oklahoma) NEXRAD radar, 2D-video-disdrometer, the ARS raingage micronetwork, and the Oklahoma Mesonet were initiated and continued through the period. Analysis of simultaneous data showed that the polarimetric rainfall algorithm gives about 1.5 to 2 times the reduction in the standard deviation of the estimate of the one-hour areal rain accumulation for the micronetwork region (40 by 30 km area). As documented by the 2D-video disdrometer, the polarimetric rainfall estimation algorithm clearly outperformed the conventional method in the cases of hail contamination. Polarimetric data from the testbed WSR-88D radar were collected for the first time. Some engineering and performance characteristics of the polarimetrically upgraded WSR-88D were evaluated using observational data.

Winter Storms

Long-term statistics of polarimetric observations in winter storms in central Oklahoma were examined to develop a procedure for rain/snow discrimination as a part of a general classification algorithm. The zones of negative specific differential phase K_{DP} near the tops of clouds were also identified and examined as possible indicators of vertically aligned crystals due to the presence of strong vertical electric fields.

Polarization Diversity

A comparative study of different schemes for implementation of polarization diversity on the WSR-88D radar was performed.

Atmospheric Electricity

A relation between negative K_{DP} signatures and tilted crystals with a high degree of common alignment in electrically charged zones of the cloud was further clarified using data from the National Lightning Detection Network and new polarimetric variables from the NCAR S-POL radar.

Full Polarimetric Matrix Measurements

An analysis of full polarimetric matrix measurements made with the NCAR SPOL and Colorado State University CHILL dual-polarization radars in Colorado, Florida, and Brazil was performed. The results revealed the tremendous power of multi-parameter radar measurements for hydrometeor classification. A study of a new polarimetric parameter, co-cross-polar correlation coefficient, revealed its possible use for particle orientation determination.

Joint Polarization Experiment Planning (JPOLE)

Work has progressed on planning for the Joint Polarization Experiment (JPOLE), which will serve as the first operational test of weather radar polarimetry. In preparation for the operational demonstration, which will be conducted as a multi-seasonal test and evaluation period (to begin in the spring of 2002) and an intensive observational period that will utilize the addition of numerous field facilities for the collection of verification data sets (to begin in the spring of 2003), prototype real-time polarimetric algorithms were developed and supplied to operational forecasters at the Norman NWS forecast office since the spring of 2001.

In addition to the operational demonstration, JPOLE will provide an opportunity to investigate many complementary hydrological and meteorological scientific objectives. As such, input on science objectives has been gathered from potential project PIs and work has begun on initial drafts of project operational and science overview documents.

C-Band (5.5 cm) Dual Linear Polarimetric/Doppler Radars for Weather and Weather Engineering Research – SMART-R

Most of the fabrication of the Shared Mobile Atmospheric Research and Teaching (SMART) radars was completed. Parts were obtained to construct the radar systems and the truck assemblies. A design upgrade replaced the older combination of high voltage power supply, pulse forming network, and vacuum relay with the newer integrated solid state modulator assembly, which will be required to ultimately add polarization. The radar parts included stabilized local oscillators (STALO), the SIGMET digital antenna controllers, and solid-state modulator assemblies for two radars. As of 30 June 2001, we and the other collaborating institutions completed two radar systems and two truck assemblies. Pedestals, transmitter cabinets, and generators were integrated to both trucks, and one of the radar systems was fully integrated to one of the truck assemblies.

Radar Usability Improvements

Volume Coverage Pattern (VCP) Development and Testing

NSSL developed a set of volume coverage patterns (VCPs) that satisfy the WSR-88D users' needs for improved vertical and temporal resolution. Capabilities of the existing and proposed VCPs were compared by using simulated datasets based on a composite time-height cross section of maximum reflectivity within the typical cell of a multicell hailstorm. Vertically integrated liquid and downburst lead times were computed from the reflectivity cross-section. Evaluations of these quantities indicate that the types of new VCPs proposed here provide improved vertical and temporal resolution. Archive Level II data for experimental VCPs were collected using the OSF KCRI radar on 11 separate events during spring 1999, including the 3 May 1999 tornado outbreak. Archive Level II data for experimental VCPs were collected data using KCRI on seven separate events during spring 2000.

CIMMS worked with NSSL to analyze six new optimized VCPs. Three of these replaced the four operational VCPs (11, 21, 31, and 32). The three new VCPs were developed with an angle selection that allows for less uncertainty of echo height measurement between adjacent elevation scans. By selecting a slightly faster antenna rotation, the new VCPs also include more elevation angles for the entire volume scan, including much more dense coverage at the lowest elevation scans (3 or 4 elevations scans between 0.5 and 1.5 degrees, when there used to be only 2). A brand new "Fast-VCP" was developed that is a "half" VCP – it updates at 2.3-minute intervals to allow for the observation of quickly evolving low-altitude phenomena such as tornadoes and downbursts. Two more VCPs, which incorporate the MPDA, have also been developed. The experimental KCRI WSR-88D in Norman was used to collect experimental data using all six new VCPs. CIMMS helped NSSL scientists identify radar coverage problems by simulating "cone of silence" problems with the six experimental VCPs throughout the contiguous US. Terrain blockage was taken into account at WSR-88D sites near mountains. CIMMS worked with NSSL to simulate the spatial coverage provided within the three composite layers (0-24,000 ft, 24-33,000 ft, 33-60,000 ft) and the spatial coverage that would be available to detect storms that extend to heights of 30,000 ft and 60,000 ft. The findings were used to address how well they provided the data needed to produce the WSR-88D composite layer products and the echo top product. Working with NSSL, CIMMS also continued to research optimal scanning strategies for mountaintop radar sites. These strategies employ the use of elevation angles below 0.5 degrees such that the lowest elevation angles skim the valley surfaces and maximize full volume coverage for the densest population centers. Since elevation angles below 0.5 degrees are currently not authorized, these new mountaintop VCPs are not expected to be implemented until this restriction is lifted.

Mitigation of Radar Velocity and Range Ambiguities

CIMMS continued investigation of schemes to mitigate range and velocity ambiguities. Four different phase-coding methods for the recovery of spectral moments of overlaid weather signals were evaluated. Three of these, random phase coding, $\pi/4$ phase coding, and $\pi/2$ phase coding were previously published. The fourth is a set of codes for which henceforth we use the abbreviation SZ (n/M), where M is the code length and n is an integer that defines the spectral properties of the code. To evaluate the performance of the phase-coding methods, simulated weather signals were used in a versatile program that generates any desired spectral parameters and coding scheme. Simulations included practical effects of noise, data window, phase uncertainty, quantization, code synchronization, and presence of ground clutter. The simulation studies indicated that the proposed SZ (n/M) phase coding scheme performs better than any of the other coding schemes, and is the best candidate for implementation on the WSR-88D. The uniform PRT used in the phase-coding scheme allows effective filtering of the ground clutter. A decoding algorithm has been developed to estimate all spectral parameters of two overlaid weather signals. The algorithm uses processing in the spectral domain and, hence, needs a powerful radar signal processor.

Radar Data Quality Improvements

This work investigated and implemented procedures to improve the quality of WSR-88D radar data. Activities included the investigation of regression filters as ground clutter filters in the context of variable PRT, and comparison of the performance of regression filters used as ground cancellers with the performance of WSR-88D ground clutter filter algorithms.

Scale Filtering of Radar Data

Two ways to speed up the identification of large-scale features in radar images were developed at NSSL using 1) a Fast Fourier Transform (FFT), and 2) a computationally efficient spatial filtering technique.

Radar Research

Comparison of Lightning Ground Flash Rates to Radar-Derived Characteristics

A study was completed that compared maximum ground flash rates with radar-derived characteristics (relative isolation of cells, maximum reflectivity, VIL, and thickness of regions with ≥ 30 dBZ at temperatures ≤ 0°C) of storm cells identified by the real-time WDSS. It was found that low ground flash rates were produced by many of the cells having almost any combination of radar characteristics. However, the proportion of cells with higher ground flash rates and the maximum ground flash rates produced by cells within a particular category of radar characteristics tended to increase as some radar-derived parameters increased. The strongest relationship was found with the degree of cell isolation. Maximum ground flash rates increased considerably as the storm-cell embedded reflectivity increased and as cells occurred closer together. There also was a fairly strong tendency for a cell’s maximum ground flash rate to increase as the 30-dBZ thickness of the cell increased. Maximum ground flash rates depended less on VIL and maximum reflectivity. Storm cells with large ground flash rates had larger values of 30 dBZ thickness and almost all were either embedded in larger reflectivities or were close to other cells identified by the WDSS algorithms.

Clear-Air Adjoint Method Wind Retrievals from the WSR-88D Radar

A Clear-Air Adjoint-Method (CAAM) of wind retrieval from WSR-88D radars was completed at NSSL. The CAAM is utilized primarily in clear-air or precipitation-free regimes using WSR-88D radars for several reasons: 1) to reduce the complexity of the equation set used in the retrieval process; 2) because past wind retrieval studies have primarily examined precipitation events only; and 3) retrieval studies from WSR-88D radars have only just recently been carried out. CAAM is based upon the equation set used in Xu's simple adjoint wind-retrieval method. This technique uses predictive equations for reflectivity and radial wind while utilizing a cost function containing least-squared differences of observed and estimated variables including radial wind, reflectivity, time-mean radial wind, and divergence. Because of CAAM's application to precipitation-free events using WSR-88D radars, additional improvements over Xu's simple adjoint system were needed.

These improvements were examined using both idealized and real-data cases. Within the idealized experiments, various configurations of atmospheric structures, including constant wind flow and a propagating boundary regime, were investigated. The idealized cases revealed the dependence of accurate retrieval solution on the existence of gradients within the observation fields. Whenever the gradients were of insufficient magnitude across any portion of the radar domain, then the non-zero first guess field and the utilization of two fitting terms (time-mean radial wind and divergence terms) within the cost function became very important in producing accurate retrievals. This importance was also underscored in the real-data cases as well and points to the fact that regions of diffuse reflectivity gradients can exist often in precipitation-free environments.

Overall, results indicated a strong importance on the first-guess provided for the retrieval technique. Instead of using a zero first-guess as in past retrieval studies, an initial wind field was provided using either the Velocity-Azimuth Display (VAD) or Volume-Velocity Processing (VVP) techniques. In addition, the use of divergence calculations from the VVP method improved the accuracy of CAAM. Model produced divergence calculations were constrained toward the VVP-provided divergence calculations through the cost function.

Airborne Doppler Data Analysis and System Development

MEaPRS

From 15 May to 15 June 1998 during MEaPRS, NSSL operated the radar onboard the NOAA P-3 aircraft. Just before the MEaPRS experiment began, the NOAA Aircraft Operations Center upgraded this radar system to enable it to operate in a dual PRF mode. The first experimental mission of the MEaPRS experiment was performed to test the new radar system. Analysis of the data from the test flight showed that the new system affords a Nyquist velocity of about 51 ms^{-1} as compared to a previous value of about 13 ms^{-1}. This radar upgrade will significantly reduce the amount of time required to edit and analyze airborne Doppler radar data. The new system was used routinely on all subsequent P-3 flight during MEaPRS.

FASTEX

Work continued on the P-3 airborne Doppler radar data collected during the Fronts and Atlantic Storm Track EXperiment (FASTEX). The field portion of the experiment, which included four aircraft (one NOAA P-3 and one NOAA Gulfstream IV) and numerous surface vessels (one or more of which was NOAA ships), was conducted out of Shannon, Ireland, during January-February 1997. A total of 18 experimental missions were conducted. Work continued on these data sets, including both individual P-3 data sets and a combination of NOAA P-3 and NCAR ELDORA data sets.

Caljet

From 15 January to 30 March 1998, the Caljet experiment was conducted from a base in Monterey, California. It included NSSL staff operating the radar onboard the NOAA P-3 aircraft. The experiment was initially conducted to study land falling low-level jets that strike the western coast of the United States. The experiment was scheduled to last six weeks, from 15 January-28 February. As the scheduled ending time approached, a request was made to extend the project for another 65 hours of NOAA P-3 flight time. The extension was requested because the real-time dropwindsonde data provided by the aircraft had enhanced the forecast models significantly during the then ongoing El Niño event.

Convection and Precipitation Identification with Radar

Severe Thunderstorms in the Southwestern U.S.

The NSSL WISH group continued to work directly with the staff of a number of NWS forecast offices, the SPC and the ROC to improve the use of WSR-88D data to identify and warn for severe thunderstorms in the western United States. Efforts were made to evaluate the performance of the SCIT and HDA algorithms in the West and numerous workshops were held to convey the results to field forecasters. Results of this effort have affected the evolution of several WSR-88D algorithms and helped lead to a real time evaluation of the NSSL WDSS system at the Tucson forecast office during summer 1999. Problems with clutter filtering were also identified; work was done directly with the ROC and the Phoenix NWS forecast office to both improve the local clutter filter tables and to identify causes for apparent failure of the clutter filter at ranges less than 50 km. This work also led to interactions with NWS Operations Headquarters regarding the concurrent failure of the ground echo filter and the PPS system, leading to non-real, huge precipitation accumulations from the Phoenix radar. These kinds of failures affect long-term research since the false precipitation is archived and not flagged, and thus resides in the databases as if real rain events occurred. The impacts of military chaff releases and their false echoes have also been documented and discussed at a number of Department of Defense meetings.

High-Resolution Convection Climatology for Central Arizona

During the monsoon season (roughly July-September), central Arizona receives a significant portion of its yearly rainfall. Storms that develop over this area can produce flooding, severe weather, and lightning. Hence, a better knowledge of areas favorable and unfavorable for storm development would be useful for forecasters, utilities, and fire managers. The goal of this NSSL SRAD WISH team study was to create a high-resolution convection climatology, and examine the role of terrain forcing and synoptic-scale effects on convective initiation, modes, and movement.

Toward this goal, volumetric reflectivity mosaics with 1-km resolution were created using Level II radar reflectivity data collected from Phoenix (KIWA) and Flagstaff (KFSX) radars during July and August of 1996-2000. Also, diurnal reflectivity frequencies above a selected threshold were created to document areas of persistent convective initiation. These fields were spatially analyzed with respect to the mountainous terrain and synoptic conditions to understand better the role of terrain forcing and synoptic regime in producing convective initiation over central Arizona. This work was fruitful because it 1) illustrated a new method for improving the resolution of convection climatologies applicable to most regions in the U.S. (especially mountainous regions), and 2) attempted to identify better ways to forecast convective initiation areas of mountainous terrain.

Three-Dimensional Multiple Radar Reflectivity Mosaics

A real-time 3D multiple radar reflectivity mosaic scheme was developed by the NSSL WISH team. The multi-scheme can remap and mosaic reflectivity fields from up to 10 radars for any given 3D Cartesian grid. Applications of the scheme to winter and summer cases have shown that the mosaic fields provide more complete depictions of storm and precipitation events than products from single radars. Gridded data would allow various WSR-88D users to benefit from a wide-variety of products and displays (flexible horizontal or vertical cross-sections and regional rainfall are examples) that could be extracted easily from multiple radar analysis grids. Gridded radar data could also be easily combined with information from other data sources (e.g., satellite, gridded model analyses, or forecast fields), increasing their value in the overall forecast and warning process.

Major improvements were subsequently made to the 3D multiple radar reflectivity mosaic scheme. A gap-filling scheme was developed for removing ring-shaped discontinuities on horizontal cross sections of the interpolated reflectivity fields. The discontinuities are due to the large elevation gaps in WSR-88D data samplings. The mosaic algorithm was optimized and computational efficiency has greatly increased. The optimizations were realized through 1) using lookup tables for the polar-to-Cartesian and Cartesian-to-polar coordinates transformation; and 2) better handling of large 3D data arrays. A data compression scheme was developed for the mosaic products. The compression procedure saved the disk storage resources and speeded up archive processes significantly. The mosaic algorithm was documented in detail using a well-organized format. The documentation includes functional descriptions, variable tables, pseudo code and computational formulas. Extensive in-code documentation was also added to the mosaic programs to improve readability of the code. These documentation efforts can help users to better understand the algorithm logic, and they can serve as useful references for further development/improvement.

Vertically Pointing Radar for Precipitation Monitoring

During the winter of 2000, a 10-cm vertically pointing radar was deployed in Utah and Arizona by the NSSL WISH team to study the vertical structure and temporal evolution of precipitating clouds. Snow, graupel, melting layer, and rainfall were observed in concert with many other observational platforms during the IPEX field campaign. Observational periods spanned over 26 days from February through April. After the data were collected, a program was written to process and display the results for ongoing analysis. The time-height cross sections were able to show reflectivity from heavy snow. The 45-m height resolution of the radar captured unprecedented detail in wintertime precipitating clouds affecting the southwestern U.S.

Radar Data Access and Distribution

Collaborative Radar Acquisition Field Test (CRAFT): A Prototype for Accessing and Distributing WSR-88D Base Data in Real Time

In order to provide real time base (Level II) WSR-88D data for evaluation in storm-scale numerical weather prediction, and to begin addressing the long-term base data archival problem at the NCDC, the CAPS joined forces in 1998 with UCAR, the University of Washington, the NSSL, and the ROC to establish the Collaborative Radar Acquisition Field Test (CRAFT). Funded initially by a grant from the Oklahoma State Regents for Higher Education, CRAFT is an experiment in the real time compression and Internet-based transmission of NEXRAD base data from multiple radars. The initial test bed of radars at Oklahoma City, Tulsa, Fort Smith, Fort Worth, Lubbock, and Amarillo delivered data continuously for over a year with virtually no outages. Funds received from the ROC were used to pay the communications costs of the data lines for the six radars listed above, for maintaining the data ingest computers, and for archiving the data at OU. CRAFT data also are received in real time by the NSSL and used in development of the WDSS-II. In early June 2000, the NCDC began receiving compressed base data in real time from the six CRAFT radars via the commodity Internet. These data are now ingested directly onto the NCDC mass storage system.

The CRAFT was expanded from 6 to 21 radars, with 18 more radars to be added by the end of calendar year 2001. The NCDC now receives and directly archives Level II data from these 21 radars, thus completely bypassing the legacy 8mm tape recording methodology. Indeed, CRAFT has been so successful as a prototype that 8 mm recording has been discontinued at 13 sites. The data archival rate at NCDC, which was approximately 65 percent based upon the 8 mm recording technology, is well above 95 percent under Project CRAFT.

Attention was also given to data dissemination via collaborative research partnerships with universities (UCLA, Washington, Penn State, Illinois), NOAA laboratories/operational centers (FSL, NCEP), and private companies (WeatherData, Baron Services). Initial work in data mining also has begun, with emphasis on establishing climatologies of and interrelationships among convective storm attributes (e.g., VIL, echo top, echo mass and area, motion). These early results are being used as a foundation for follow-on proposals to the National Science Foundation.

III. Outreach

ARM Program Educational Outreach

During the past eight years, the Oklahoma Climatological Survey (OCS) has established a solid infrastructure for atmospheric science education, primarily at the pre-college (K-12) level, with the support of the U.S. DOE ARM Program. Environmental data, including those from the ARM Southern Great Plains site in Oklahoma and Kansas and the Oklahoma Mesonet, are available to educators who have web access (http://outreach.ocs.ou.edu/arm/). Unique display software has been developed to provide student interactivity with the data. Reference materials and lessons are online and in printed form to aid the educator in the application of the data in the classroom. And, most importantly, master teachers have been educated to understand and use the data in their activities. These master teachers represent a significant resource to provide workshop instruction to additional K-12 teachers.

Workshops on Regional Climate Prediction and Applications

This workshop series was initiated by CIMMS in 1999-2000 and has continued. The workshops are intended to improve the capabilities of national meteorological services (NMS) in developing nations in the following respects – to understand the behavior of the global climate system; to use such understanding to develop or adapt seasonal climate (especially rainfall) prediction schemes for their countries; and to work with other professionals in their countries to apply the prediction schemes in the management of agricultural production, water resources, energy generation and consumption, and public health. The need for these Workshops emerged from NMS leaders of many developing nations recognizing that their organizations did not possess the expertise to capitalize on the seasonal prediction and application opportunities offered by the 1997-98 El Niño. Workshops are held at the OU College of Continuing Education, with the primary financial sponsorship of the International Activities Office of the U.S. National Weather Service, and additional support from NOAA's Office of Global Programs, the World Meteorological Organization, and other U.S. and international agencies.

Each Workshop extends, on a full-time basis, for 6 weeks and has 12-20 participants. The CIMMS Director, one or two additional Course Lecturers, and several Guest Lecturers give the course lectures. The participants develop small research projects using data from their country. The series is intended primarily for young NMS personnel who have received excellent training in basic meteorology at a University (B.Sc. level) or World Meteorological Organization

Training School (Class II level), but who have limited exposure to the fundamental principles of modern climate dynamics and their application to economic management and other environmental and societal issues. Meteorologists who work outside their NMS (e.g., in regional meteorological centers like ACMAD and the DMCs, universities, other government agencies, or NGO's), but who have strong working relationships with the NMS, may also be accepted. Applications are particularly encouraged from meteorologists who have attended preliminary training workshops in climate prediction (e.g., the African Centre of Meteorological Applications for Development, ACMAD) or had other opportunities to acquire some basic knowledge of climate dynamics and its applications. These Workshops further develop the skills of such individuals, especially since substantial material is presented from the University of Oklahoma M.Sc. module in Climate Dynamics. The First Workshop (late 1999) and Second Workshop (mid-2000) both focused on the Tropical Atlantic Basin and trained 25 meteorologists from the following nations in Africa, Central and South America, and the Caribbean – Mexico, El Salvador, Costa Rica (2), Barbados, Netherlands Antilles, Venezuela, Brazil (4), Paraguay, Argentina, Algeria, Morocco, Senegal, Ghana, Burkina Faso, Niger, Bénin, Nigeria, Chad, Cameroon, Congo, and Tanzania. The Third Workshop in mid-2001 dealt with the Tropical Pacific Islands and Rim, and had approximately 20 participants from Malaysia and Vietnam in the west, across the Pacific Islands to Ecuador and Chile in the east. Subsequent workshops in 2002 and later years will deal with the Circum-Indian Ocean Region and then return to the Tropical Atlantic Basin.

NSF Research Experiences for Undergraduates

A new proposal, with funding through 2003, was awarded to OU for the Research Experiences for Undergraduates (REU) program, funded by the National Science Foundation. Successful 10-week REU programs were conducted during the summers of 1998-2001 involving ten undergraduate students each from across the U.S. Each student worked on a research project with an OU or NOAA investigator, wrote a substantial final paper, and made a conference-style presentation on his/her findings in early August. The REU search committee includes several CIMMS scientists. A large number of our REU alumni have received American Meteorological Society awards and fellowships and have gone on to graduate studies at major universities.

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