

Cooperative Institute for Mesoscale Meteorological Studies - CIMMS

Final Report on Cooperative Agreement NA37RJ0203

Covering the Period July 1, 1993-June 30, 1996

Peter J. Lamb, Director

INTRODUCTION

NOAA and the University of Oklahoma (OU) established the Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) in 1978. CIMMS promotes cooperation and collaboration on problems of mutual interest among research scientists at the NOAA Environmental Research Laboratories' National Severe Storms Laboratory (NSSL) and the OU School of Meteorology (and other academic departments at OU). Through CIMMS, NSSL scientists and OU faculty and researchers also collaborate on research supported by other NOAA programs and laboratories and by other agencies such as the National Science Foundation (NSF), the U.S. Department of Energy (DOE), and the Federal Aviation Administration (FAA).

A 3-year cooperative agreement between OU and NOAA for CIMMS funding took effect on July 1, 1993, and continued through June 30, 1996. Under this agreement, CIMMS concentrated its efforts and resources on four principal research themes: (1) basic convective and mesoscale research, (2) forecast improvements, (3) climate effects of and controls on mesoscale processes, and (4) socioeconomic effects of mesoscale weather systems and regional scale climate variations. This report summarizes research activities and findings during this three-year cooperative agreement period.

BASIC CONVECTIVE AND MESOSCALE RESEARCH

VORTEX

The Verification of the Origin of Rotation in Tornadoes Experiment (VORTEX) was successfully planned, coordinated, and executed in 1994 and 1995. This effort involved participants from five universities, NOAA, and NSF, and was described in a journal article. Data were gathered for numerous nontornadic and tornadic supercells, as well as for several days with no convection or nontornadic convection. Research on the voluminous dataset collected is anticipated to last several years. These results will be published once they are available. Many will involve case studies of the various events sampled.

CIMMS, NSSL, the University of Mississippi, and the New Mexico Institute of Mining and Technology collaborated in the field work of VORTEX '94 to measure electrical properties of storms to complement the other measurements of supercell storms and their environments. Electrical measurements included vertical profiles of electric fields and particle charge inside supercell storms, electric fields at the ground, and the location and polarity of lightning strikes to ground.

Collaborative research was conducted with scientists from OU on supercell morphology across the supercell spectrum. The leading cause of variation across the spectrum was discovered to be the storm-relative airflow in the layer bearing the anvil (i.e., the region above the -40°C isotherm level). In the process of this climatological and modeling analysis, it was also determined that isolated high-precipitation supercells do not form in high-humidity environments, as was previously suspected, nor do low-precipitation storms form in uniquely dry environments. Storm type was found to be a function of the redistribution of hydrometers by the storm-relative flow, not the amount of water available in the updraft.

Regional Weather Processes

The Mexican monsoon is a significant feature in the climate of the southwestern United States and Mexico during the summer months. Past numerical simulations frequently have been unable to reproduce the widespread, heavy rains over Mexico and southwestern United States associated with the monsoon.

Collaborative fieldwork, data gathering, and experimental forecasting were accomplished during July-August 1993 in southwestern North America. Groups participating in the work were CIMMS, NSSL, NWS, Arizona State University, several Mexican institutions, and the Salt River Project (private power company). Field centers were at Phoenix, Arizona, and Obregon, Mexico. Data sets gathered allowed examination of conditions during onset of the Mexican monsoon and further documented the severe storm environments in central Arizona. Formal publications were made of studies of Arizona severe storms and nighttime rains.

In collaboration with scientists at the National Center for Atmospheric Research (NCAR) and the University of Arizona, the Pennsylvania State University (Penn State)/NCAR mesoscale model was used to simulate 32 successive 24-h periods during the monsoon season. Mean fields produced by the model simulations were compared with observations to validate the ability of the model to reproduce many of the observed features, including the large-scale midtropospheric wind field, southerly low-level winds over the Gulf of California, and heavy rains over western Mexico. Preliminary analysis of the mean model fields suggested that the Gulf of California is the dominant moisture source for deep convection over Mexico and the southwestern United States. Upslope flow along the Sierra Madre Occidental advects low-level Gulf moisture into western Mexico during the daytime, and southerly flow at the northern end of the Gulf advects Gulf moisture into Arizona on most days.

Analyses will be continued of the mesoscale model simulations of the Mexican monsoon with an emphasis on understanding the dynamics of the northward surges of warm and moist air from the Gulf of California into Arizona.

Storm Electricity

A research program begun in FY 1992 in collaboration with scientists from the University of Mississippi and NSSL involved the electrical aspects of mesoscale convective systems (MCSs). Electric field soundings in the stratiform and transition zone regions were analyzed. A paper was published in the November 1993 issue of the *Bulletin of the American Meteorological Society* described our finding that most soundings fit into one of two repeatable types. One has four charge regions inside the cloud including substantial positive charge at 0°C, and the other has five or six charge regions inside the cloud. In both, the lowest charge is negative and the polarity of the regions alternates from bottom to top of the cloud. Maximum electric fields in stratiform regions were found to be of the order of 100,000 V m⁻¹.

As part of collaboration between CIMMS, NSSL, and the University of Mississippi, an analysis was completed and published of a large case study from Cooperative Oklahoma Profiler Studies (COPS)--91. Five soundings of the electric field and thermodynamic properties were made in a mesoscale convective system (MCS) that occurred in Oklahoma and Texas on 2-3 June 1991. Airborne Doppler radar data were obtained from three passes through the stratiform echo. From these electrical, kinematic, and reflectivity measurements, a conceptual model of the electrical structure of an MCS was developed, and several other conclusions were reached:

- Profiles of the vertical electric field are similar over approximately 3 hours and 100 km in this region, and the electrical charge regions inside this stratiform cloud are horizontally extensive and layered
- There was direct evidence for more positive charge below 4 km within regions of locally heavier stratiform precipitation
- Results from a line-source model of diffusion suggested that advection of charge from the MCS convective region is a viable charging mechanism

The COPS-91 case study was supplemented by an investigation of the effect on electric field profiles of penetrating uniform and non-uniform charge regions of varying size at varying distances from their center. A three-dimensional model, not restricted by any assumptions about the geometry or symmetry of the charge regions, was developed. Charge locations were based on the 2-3 June 1991 electric field soundings and the one-dimensional approximation to Gauss's law. Results from the study include the following:

- Vertical electric fields from the model are not significantly different from the observed fields and are also nearly identical to fields resulting from infinitely extensive charge layers.
- For a vertical path 90% of the way toward the model edge, the calculated vertical electric field is reduced by less than 10% from its value through the center of the model domain.
- Large changes in charge density (of a factor of 5) over relatively short horizontal distances (of less than 2 km) are needed to produce the observed magnitudes of horizontal electric fields.

In related research, a M.S. thesis by a CIMMS/NSSL student provided the first systematic documentation of the large electric field and charge density that we now believe are commonly located around 0°C in the stratiform region of MCSs. This finding was unexpected based on knowledge of thunderstorm charge structure and is likely tied with the kinematics and repeatable electrical structure of MCSs.

A CIMMS graduate student supported by NSF received his Ph.D. for research on precipitation particle charge and size measurements inside thunderstorms and MCSs. A number of new findings were made. It was discovered that 20-80% of the precipitation was uncharged (i.e., below our detection threshold of 5×10^{-12} Coulombs). Both polarities of charge were found to coexist at all altitudes. The precipitation charge density turned out to be 0.5 to 0.01 of the total charge density (the rest was presumably on smaller cloud particles). Particle charge and size were uncorrelated with any environmental variables including the electric field magnitude, and particle charge and size were found independent of each other. A paper describing the design, calibration, and flight of the novel balloon-borne particle sensor was published.

Data were analyzed from a 1992 field program in Orlando, Florida, of coordinated observations of lightning radiation sources. These sources were obtained with a two dimensional interferometric system operated by the New Mexico Institute of Mining and Technology, lightning images yielded by a high speed and sensitivity motion analysis system, and electrical measurements obtained by CIMMS and NSSL scientists. Analysis included the novel interpretation of lightning processes during the continuous current phase in flashes to the ground. The research also presented for the first time the ground truth for interferometric lightning data, and revealed the nature and novel interpretation of long and highly branched horizontally propagating lightning flashes during the decaying stages of storms.

CIMMS scientists and collaborators from the New Mexico Institute of Mining and Technology completed research on correlated high-speed video and radio interferometric observations of a cloud-to-ground lightning flash. The resulting published paper provided new interpretation of transient radiation and luminous processes during the continuing current phase in lightning flashes to ground.

A cooperative program with the Massachusetts Institute of Technology (MIT)/Lincoln Laboratories was conducted by CIMMS and NSSL scientists in Orlando, Florida, during July-August of 1993. This program collected data on electric field variation on the ground, rate, and types of lightning flashes, and the specific features of radar reflectivity during storm evolution. The result was the development of an algorithm to predict the end of the lightning threat to ground operations at airports.

New research was funded through NSF for in situ observations of the electric field and x-rays in thunderstorms. This research supports a Ph.D. student and is a collaborative effort by CIMMS, the School of Meteorology and the Department of Physics and Astronomy at OU, and NSSL. This research will test a hypothesis that high ambient electric fields accelerate electrons to runaway and cause the emission of x-rays.

A study investigated unusual lightning in a heavy-precipitation tornadic storm. During some periods in this storm, cloud-to-ground lightning strike activity was dominated by flashes that lowered the positive charge to the ground instead of the normal negative charge. A few previous studies have found relationships between positive flashes and large hail or tornadoes. This study was the first for which digital data from the WSR-88D were available, enabling more detailed analysis of storm relationships.

A collaborative study with the Oklahoma Climatological Survey and NSSL developed a thunderstorm climatology for Oklahoma based on five years of lightning strike data. Geographic and diurnal variations in lightning occurrence each year were analyzed by season and for 12 categories of synoptic conditions.

Gufmex

A Master's thesis was completed on the subject of "Equilibrium thermodynamics over the Gulf of Mexico and its use in severe storm tracking". A paper from this study was published in a journal. In addition, proposals were funded by the Global Energy and Water Cycle Experiment (GEWEX) to focus on the evaluation of National Meteorological Center models using data sets from GUFMEX field programs in 1988 and 1991.

Research with a Southern Region office of the National Weather Service, (Slidell, Louisiana) and NSSL under the Cooperative Program for Operational Meteorology, Education and Training (COMET) was completed. This research involved use of Special Sensor Microwave/Imager (SSM/I) data in the evaluation of moisture return from the Gulf of Mexico over a three-year period. The research was published.

In an extended dynamical study, generalized C-vector formulations were applied to the cold-front case in the Gulf of Mexico on 21 February 1988. This work defined the ageostrophic circulation more accurately than its quasigeostrophic counterpart. Incorporating the latent heating into the C-vector improved the diagnosis of the mesoscale substructures associated with the frontal rainbands.

Data Assimilation

Research on the parallel processing coding of a deterministic prediction model was completed. This model, a barotropic hurricane track model, was tested on the difficult case of Hurricane Elena in 1985. The model exhibited skill in forecasting the place and time of landfall, and the model execution time was cut by a factor of four when the eight-processor Alliant computer was used instead of the serial mode version of the code. This research was a joint project between NSSL, the OU Department of Computer Science, and the National Hurricane Center.

Study of Rain Initiation in Warm Convective Clouds

A study of warm rain initiation using a 3-D convective cloud model with an explicit microphysics formulation revealed that rain formation may be facilitated by the filtering of cloud droplets with different sizes. It was shown that droplets of different sizes move along different trajectories. During the in-cloud recycling process, cloud droplets of different sizes enter the cloud at different spatial locations and mix with the droplet-free air brought from the upper levels of the cloud. This results in a decrease of the total concentration, as well as in the concentration of larger droplets, thus facilitating rain formation through enhanced condensational growth.

It was also found that the notion of an air parcel as an entity containing various constituents (water vapor, aerosol particles, cloud droplets, etc.), all evolving under the same dynamical conditions, may be rather limited. Our results indicate that these elements may have quite different histories resulting in inhomogeneities in cloud microstructure. The findings are described in a 1993 *Journal of Atmospheric Sciences* paper.

A new 3D convective cloud model with explicit formulation of ice-phase and warm rain microphysical processes was developed. The present version of the model includes three modes of ice initiation: deposition and condensation-freezing nucleation combined, contact freezing, and immersion freezing. A set of numerical experiments was conducted to reveal the sensitivity of the model's dynamics and microphysics to parameters of various ice nucleation modes. Comparison of production rates and determination of predominant spatial locations for each mode of primary ice initiation was made based on the numerical simulation results.

Development of a Cloud Model that Explicitly Formulates Ice and Liquid Phase Microphysics

The development of the algorithm and code for the ice-phase module was completed. The work was a collaborative effort with a scientist from the Central Aerological Observatory in Moscow and two scientists from the Hebrew University in Jerusalem.

Mesoscale Dynamics, Physical Processes, and Modeling

A completed observational study of squall evolution provided the most comprehensive investigation of the structure, and the first study of the evolution, of a certain class of squall lines that occur most commonly in the tropics but that can also occur in middle latitudes. It was found that a sloping zone of large negative vorticity can characterize the flow in

this type of squall line, and that the evolution can be characterized by this vorticity zone becoming more horizontally oriented with time. This work was published in a journal.

Frontal Rainbands

The interaction between frontal forcing, potential vorticity (PV) anomalies, latent heating, eddy viscosity, and the boundary PV flux were examined through viscous, semi-geostrophic (VSG) diagnostic model simulations and diagnoses. Two types of feedback mechanisms between rainbands and frontal forcing were identified. The strong feedback explains the growth of stable rainbands, while the weak feedback explains the self-maintenance of existing bands.

Density Currents in Shear Flows

Theoretical models were developed to improve understanding of the interaction between the environmental shear and a density current produced by a thunderstorm. It was found that the environmental shear plays an important role in controlling the depth and propagation speed of the density current and producing long-lived squall lines, while the effect of the cold pool circulation is secondary or insignificant. This work involved collaboration with scientists in the Mesoscale and Microscale Meteorology Division at the National Center for Atmospheric Research (NCAR/MMM).

Cold-Air Damming

The theoretical model of cold air damming was further refined and analytical approximate solutions were obtained. From the analytical solutions, the scale and intensity of cold air damming can be quantified as functions of the external parameters that characterize the environmental flow. The theoretical results were tested with three cases of cold-air damming and found to be useful for diagnoses or local forecasts of cold air damming, provided the external parameters are properly estimated from the operational analyses or predictions.

Numerical simulations were performed to verify earlier theoretical results and improve understanding of the interaction between the environmental shear and density current produced by a thunderstorm. It was found that, regardless of the initial setting (dynamically balanced or highly unbalanced), the density current front can reach nearly the same quasi-steady state and the quasi-steadiness can be well maintained as long as the cold-pool air mass is sufficient. The propagation speed, depth, and gross shape of the quasi-steady density current head were found to agree closely with previously published theoretical results. Physical insight was gained on the basis of theoretical analysis and numerical diagnosis. The work was done in collaboration with scientists at CAPS and NCAR.

More general types of cold air damming were studied with both analytical and numerical models. The new analytical model considers not only the cold mountain-parallel jet but also the upstream stratification, because in the atmospheric events of cold-air damming both the mountain-parallel (northerly) cold advection and the up-sliding mountain-normal advection (that produces adiabatic cooling) can produce the cooling effect. With this new feature, the range of the upstream wind direction for the persistence of cold-air damming was relaxed in the new analytic model, and performed better in comparison with observations.

In addition to the upstream stratification, the impact of thermal wind shear was also examined numerically by using the mesoscale model developed by CAPS. It was found that the temperature gradient associated with the thermal wind shear can enhance the cold advection of the mountain-parallel jet during the developmental stage of cold-air damming, while the middle-level flow above the cold dome and below the critical level can produce warm advection, causing the later decay of the cold-air damming after the mature stage.

Diagnosis of Ageostrophic Circulation

The completeness of the solution for a three-dimensional ageostrophic circulation solved from the psi-equations and the admissible boundary conditions was further studied for quasigeostrophic and semigeostrophic systems with complex terrain. The C-vector formulations were generalized to the semigeostrophic and primitive equation systems. The research was conducted in collaboration with scientists at the State University of New York at Albany and at NSSL.

Semi-Balance Model

A new type of intermediate model (IM) -- the semi-balance (SB) model, was derived for slowly evolving nonlinear flows (such as vortices and fronts over a wide range of Rossby numbers). The SB model combines the major advantages of the semigeostrophic model and balance equation model. Diagnostic equations were derived for the secondary circulation in the SB model. The associated initial-boundary value problem is well posed in iterative form, provided the leading order potential vorticity is positive so that the flow is inertially and convectively stable.

The previously derived SB model was further extended to include the effect of diabatic sources. Both flow-dependent conditions and flow-independent conditions were examined for the diabatic semi-balance system. It was found that the leading outflow could be affected by the diabatic forcing under the flow-dependent conditions.

The 6-7 May 1985 Mesoscale Convective System (MCS)

The 6-7 May 1985 MCS is a difficult case to numerically simulate because it occurred under a weak large-scale forcing. Using PRE-STORM mesonet soundings to enhance the initial field obtained through four-dimensional data assimilation, a successful simulation was made with the NCAR MM4 model. Subsequent PRE-STORM soundings, hourly mesonet surface data, high-resolution rainfall data, and satellite and radar data were used for the validation of the simulation. Several convective schemes were tested and the Fritsch-Chappell scheme was found to give the best performance. The vorticity budget based on the simulated high-resolution data showed that both the downdraft and updraft were important for the mesovortex intensification.

The simulation of the 6-7 May 1985 MCS was further improved in terms of accuracy of predictions of pressure and rainfall fields. A modified version of the Fritsch-Chappell convective scheme was used to extend the reliable simulation period from 12 hours to 18 hours. The important model output variables (rainfall and sea level pressure) were verified quantitatively with high-resolution observational data. The vorticity dynamics were examined in detail and compared with the observational analysis. The work was done in collaboration with scientists at NSSL and NCAR.

Analysis of the structure of precipitation fields in MCSs continued. Clear signatures of the melting layer location and thickness were observed in the polarimetric variables. In the stratiform region of one MCS, a significant descent of the melting zone with respect to the location of the environmental zero degree isotherm was found. The cause of this anomaly is being investigated. In another case, after the stratiform rain had begun to decrease, undular formations were seen that are reminiscent of mammatus clouds above the precipitation.

Polarimetric Radar Measurements of Precipitation

Observations were analyzed of the co-polar correlation coefficient $|\text{rhv}(0)|$ made with ground based and airborne weather radars at nearly vertical incidence. A sharp decrease of $|\text{rhv}(0)|$ occurred at the bright band bottom, and is attributed to a varying mixture of hydrometeors with diverse shape, size, and thermodynamic phase. The largest contribution to this decorrelation seemed to come from wet aggregates; this was substantiated by consideration of two simple models. One consists of randomly oriented wet prolate spheroids and the other considers an ensemble of distorted spheres. Prolates with axis ratios of 3 or distorted spheres with root mean square roughness equal to 15 percent of the diameter decreased the correlation to 0.8 at a 10-cm wavelength. At a 2.2 cm wavelength, and for the size range encountered in the bright band, the decrease was a function of equivalent diameter because the scattering was in the Mie regime.

The $|\text{rhv}(0)|$ measurements at 13.8 GHz and from aircraft were the first ever of their type. Also, the differential phase and differential reflectivity measurements at a 10° off nadir were the first of their kind. These last two variables showed a distinct signature in the bright band. This is significant because it might lead to applications on airborne or spaceborne platforms.

FORECAST IMPROVEMENTS

Profiler Applications

A Profiler Triangle Analysis Package (PTAP) was implemented in the Experimental Forecast Facility (EFF). The PTAP is an algorithm that derives kinematic and thermodynamic variables (displayed on time-height cross-sections) from a triad of wind profilers. Quality control and objective analysis procedures are performed on each dataset prior to the triangular calculations. The PTAP is useful for diagnosing mesoscale troughs and ridges that are important for forecasting severe convection.

Terminal Doppler Weather Radar (TDWR)

Research examined the causes of false alarms in the TDWR Gust Front Detection Algorithm (GFA). During 1989 field tests in Kansas City, and subsequent field testing in Oklahoma City and Memphis, a high number of false alarms caused by the vertical wind shear associated with low-level jets was observed. Using a radar-derived vertical wind profile, a technique was developed that attempts to remove these vertical wind shear-induced false alarms.

Work has begun to evaluate the microburst detection capability of the Unisys Microburst Prediction Radar (MPR). MPR data collected during the summer of 1994 at the Memphis International Airport are compared with TDWR data and other independent data sources at the airport.

Mesocyclone Detection Algorithm

CIMMS and NSSL scientists completed a test of three different mesocyclone detection algorithms (MDA) on a large Doppler radar database containing numerous tornadic and non-tornadic mesocyclones. Results showed that the algorithms performed adequately but require further improvements.

The MDA went through a major modification during FY 1994 in an attempt to improve detection performance and to provide information about circulations that are below typically defined mesocyclone strengths. These modifications move the algorithm closer to a circulation detector than a mesocyclone detector.

Work has also started to enhance the MDA by adding an anticyclonic circulation detection algorithm, a three-dimensional storm convergence profile computation (useful for determining the low-altitude convergence precursors to tornadic mesocyclones), depth criteria and helicity input (based on sounding data), and mesocyclone classification (using trend data).

Tornado Detection Algorithm

The tornado detection algorithm (TDA) was tested using recorded data from tornado cases during an 18 month period that were within 150 km of a Level II WSR-88D site. Summary files from the runs of the TDA were created and are being used to improve the algorithm's performance.

Gust Front Detection Algorithm

A study is being completed that shows that gustfront detection algorithm (GFDA) false alarms are not likely to occur in the vicinity (within 10 km) of an airport. A second study found that the GFDA's Wind Shear Hazard estimation is typically low, but no easy solutions to the underwarning problem were found.

Real-Time Severe Weather Warning Prototype Displays

The Real-time Analysis and Display System (RADS) allows operational meteorologists ready access to information necessary to make timely warning decisions, and also serves as a useful postanalysis tool in manipulation of radar data and algorithm output. Many improvements have been made to RADS, including a redesign of the user interface (in collaboration with human factors specialists); augmentation with 1-h and storm-total precipitation; and the addition of graphical overlays for downburst, gust front, and prisms algorithm output.

The RADS was greatly enhanced to produce valuable "trend" information, which shows the decay/growth of a given severe cell. Enhancements were made to algorithms for Mesocyclone Detection (MDA), Tornado Detection (TDA), Hail Detection (HDA), and Storm Cell Identification and Tracking (SCIT) to provide this trend information. Real-time tests of this display system and the algorithms were conducted at Orlando and Boulder. The initial reaction from a user group of NWS Scientific Operations Officers (SOO) was that the display system and the algorithms will be valuable tools when implemented operationally.

Work has begun on using NSSL's RADS in a postanalysis mode to examine correlations of lightning trends with trends in radar-derived parameters in different geographical locations.

Weather Impacted Airspace

NSSL collaborated with the Federal Aviation Administration and other research organizations on the development of a new weather information product known as Weather Impacted Airspace (WIA). The WIA product is issued to pilots and air traffic controllers as an alert for hazardous aviation weather conditions. CIMMS contributed to the WIA through development of convective weather detection and prediction algorithms that will one day be integrated into the WSR-88D radar system. Initial testing of the product took place during the summer of 1993 in Orlando and Boulder in cooperation with Massachusetts Institute of Technology/Lincoln Laboratories and the National Center for Atmospheric Research.

Microburst Outflow Strength Variability Investigation

Work was completed on an investigation of the variability of outflow strength from Florida microburst producing storms. Eight such storms during the 1990 test of the TDWR radar in Orlando were investigated to explain the observed variability in outflow strength. Results indicated that when storm outflows impacted a cool stable layer (i.e., outflow from a previous thunderstorm), this resulted in a decrease in their strength. This suggested that an assessment of the near surface conditions is necessary for predicting the strength of an impending microburst outflow, and should be incorporated into the automatic prediction algorithms under development.

Storm Cell Identification and Tracking Algorithm

Work continued to develop an enhanced Storm Cell Identification and Tracking (SCIT) algorithm that uses seven reflectivity thresholds (30-60 dBZ in 5 dBZ increments). The current WSR-88D SCIT algorithm does a poor job of identifying and tracking individual cells in clusters (areas) and lines because it only uses one reflectivity threshold of 30 dBZ. The new algorithm was tested on WSR-88D data from Florida and Oklahoma and had a much higher probability of detection (95%) than the standard WSR-88D algorithm (33%) applied to the same dataset.

Testing and development continued on NSSL's SCIT algorithm, including interpreting Doppler radar data to develop "ground truth" information. This information was then used as a basis for evaluating the performance of the algorithm, which was then implemented into the WSR-88D system in early 1996.

WSR-88D Velocity Dealiasing

A study was completed showing that the WSR-88D velocity dealiasing algorithm incorrectly dealias velocities in circulation regions. Some errors have caused missed tornadic circulations. The study has suggested corrective measures that virtually eliminate errors in the cases examined.

Single-Doppler Wind Analyses

Simple-adjoint (SA) methods were developed for retrieving wind fields from single-Doppler measurements. The methods were tested on Phoenix II field experimental data and Denver Airport microburst data. The results were very encouraging. Extensive comparisons were also made between the SA methods and other existing methods of the same category, with the SA methods being found to be the best. Because of their low computational cost and high accuracy, the SA methods seem the most promising for near-future operational uses with the WSR-88D and TDWR radar networks. The SA method also can be used for retrieving sea-surface currents from satellite infrared images.

The previously developed simple-adjoint (SA) methods for single-Doppler wind retrievals were further developed and tested with more cases. The cases include additional Phoenix-II cases, a Denver Airport microburst case (11 July 1988), an Orlando Airport gust-front case (27 August 1990), and an Orlando Airport wet-microburst case (18 August 1990). The NOAA/ERL Environmental Technology Laboratory (ETL), Massachusetts Institute of Technology/Lincoln Laboratories, and the NCAR Research Applications Program provided Doppler data. The SA methods were also tested and compared with other methods in an algorithm intercomparison project organized by the Center for Analysis and Prediction of Storms (CAPS) at OU.

Generalized VAD Methods for Radar Data Analyses

Efforts were made in generalizing the conventional VAD method to retrieve not only the mean horizontal wind and divergence, but also vorticity and associated advection from Doppler-radar data. This method is a combination of the conventional VAD method and SA method. The method was tested with artificial data and real data; the preliminary

results indicated that the generalized method could improve the retrieval in comparison with the conventional VAD method.

Hail-Producing Thunderstorms

The evolution and morphology of hail-producing thunderstorms was studied using single Doppler analysis techniques. The focus has been on two hailstorms that occurred on 11 July 1989 during the North Dakota Thunderstorm Project. On that day, individual updrafts (interpreted from ascending reflectivity maxima) were observed to form and grow on the west edge of the storms. As the associated reflectivity maxima descended, they moved either to the left or to the right of the environmental flow as descending precipitation. This behavior was responsible for the characteristic "V" shape of these storms. Topics investigated thus far include updraft evolution, mid-altitude wake flow behavior, and hail spike characteristics.

Mesoscale Model Output Interpretation

Because mesoscale model predictions will soon become a standard product in operational forecasting, the ability to interrogate and assess the model forecasts intelligently will become one of the most important aspects of operational forecasting. An approach to interpreting mesoscale model output in a forecasting environment was developed and applied to a case study of a severe-weather outbreak. This approach relies on knowledge of the model parameterization schemes typically included in any operationally usable mesoscale model, and for this case, would likely have assisted forecasters.

CLIMATE EFFECTS OF AND CONTROLS ON MESOSCALE PROCESSES RESEARCH

Cloud Modeling with Detailed Microphysics

The development of a model of a cloud-topped marine boundary layer (CTMBL) was completed. The model includes a 3-D large-eddy simulation dynamical framework, the explicit formulation of cloud microphysics, and representation of long and short wave radiation processes. The simulations performed with the new model included studies that investigated the role of CCN regeneration processes in the evolution of the CTMBL, examined the effect of cloud layer inhomogeneity on its radiative properties, and compared the radiative parameterizations that are most commonly used in GCN and climate models. The results obtained were presented at a number of conferences and published in two scientific journal papers.

The CIMMS large-eddy simulation (LES) cloud model (CM-XMP) with explicit microphysics (to represent warm rain processes) was employed to simulate the observed evolution of a stratocumulus-topped marine boundary layer (SMBL). The model predictions were in good agreement with both the observed gross dynamical properties and the microphysical parameters of the SMBL case study.

The CIMMS CM-XMP was also used to investigate the effects of ambient aerosol on the radiative and microphysical properties of stratocumulus cloud layers. It was shown that in environments with low cloud condensation nucleus (CCN) counts, the released latent heat was overestimated by the moist saturation parameterization, resulting in large errors in SMBL parameters.

A study of the drizzle process revealed that both ambient aerosol and the surface moisture flux substantially affected drizzle production from marine stratocumulus. The latter may be responsible for drizzle from very polluted stratocumulus clouds, which was often observed during the Atlantic Stratocumulus Transition Experiment (ASTEX) field program.

Numerical simulations have been performed of marine stratocumulus cloud layers with CCN concentrations typical for clean and polluted marine clouds. The study was aimed at the effects of atmospheric aerosols on stratocumulus cloud layer radiative properties (the Twomey effect). The "independent pixel approximation" approach was used to evaluate the performance of cloud radiative parameterizations most commonly used in general circulation models (GCMs), and the sensitivity of cloud optical depth to various microphysical parameters was investigated.

Climate Diagnostics Dataset Development

Datasets for the Lamb-Richman 1° grid for eastern North America were completed for the period 1949-92 for daily values of maximum temperature, minimum temperature, and precipitation. These data are being used to quantify the relative importance of several kinematic and thermodynamic processes and parameters (lifting condensation level, and tropospheric vertical motion, precipitable water, and lower and mid-upper tropospheric water vapor flux convergence) for central North American noon-midnight rainfall amounts during May-August. Strong regional (e.g., Great Plains versus Upper Midwest) and diurnal (e.g., noon-6 p.m., 6 p.m.-midnight) variations are characterizing the results. These results have implications concerning our need and ability to model regional climate.

Relationship between El Niño-Southern Oscillation and North American Precipitation

Important ENSO research findings to date have included the identification of different modes of tropical Pacific sea-surface temperature (SST) anomalies associated with warm events and cold events. For example, at least two separate and nearly uncorrelated anomaly patterns (emphasizing the central Pacific and eastern Pacific) are required to explain the ENSO phenomenon.

Further research has revealed that warm and cold ENSO events appear to be nonlinearly related to North American precipitation. Individual ENSO events have a broad range of ocean SST patterns, suggesting the inter-ENSO variability may be related to or caused by deviations from the "average" idealized ENSO picture. The research suggests such an idealized picture is artificial, and specific warm and cold anomalies in the tropical Pacific Ocean may be the key characteristics.

North American Storm Track Precipitation Signatures

The characteristic precipitation patterns associated with three well-documented North American winter storm tracks (Alberta, Midwestern, and East Coast) were identified. Four-dimensional analyses of the evolution of divergence and vorticity patterns were calculated from several days prior to the onset of each storm to several days after the storm left the track. The vorticity at low levels (880 hPa) closely followed the low-level (750 h-Pa) pressure patterns, whereas the 250-hPa vorticity patterns closely resembled patterns expected for planetary long waves.

Atmospheric Moisture Budget of Central North America

Quantitatively investigation continued of the atmospheric moisture budget of a 106-km² rectangular area that extends from eastern Nebraska-Kansas to eastern Ohio and from central Wisconsin-Michigan to the southern borders of Missouri and Kentucky. This work focused on the contrasting growing seasons (May-August) of 1975, 1976, 1979, and 1988. It examined the interrelations between the moisture budget components, and assessed the relative importance of imported versus locally evaporated moisture for the growing season rainfall.

Diagnostic Studies of Growing Season Rainfall Fluctuations in Central North America

This project sought to identify the large-scale tropospheric conditions that provide the most favorable environment for the development of rain-producing mesoscale weather systems. Attention was focused on the large-scale vertical motion, static stability, and water vapor flux convergence. Pronounced differences in the relation between 12-hour rainfall amount and the above processes/parameters emerged between the northern Great Plains and the southeastern U.S.

Climate Modeling

A CIMMS scientist worked closely with the Geophysical Fluid Dynamics Laboratory (GFDL) to archive their full arrays of daily data from key R-30 runs. These are the only full archives of such runs now available. This was completed for both the 1x and 2x CO₂. A CIMMS scientist visited Max-Planck Institut für Meteorologie (MPIM) to present seminars and discuss collaborative research. This resulted in a verbal agreement to share MPIM model output and the statistical expertise of CIMMS scientists. Research comparing the MPIM T21 model's geopotential height fields to observed data for the period 1970-1988 was undertaken.

The MPIM climate model called ECHAM2 was used to examine how well the model portrayed the low-frequency modes of variability in the observed atmosphere. A technique new to meteorology, orthogonal Procrustes Target Analysis (PTA) was used to compare the winter and summer low frequency patterns in four-dimensional geopotential

height data. The major finding was a tropic-wide geopotential pattern in both seasons. This pattern had a sharp discontinuity in the 1970s and appears to be strongly related to ENSO events. The new methodology allowed a 20 percent variance improvement in discovering how well a climate model could capture observed variability.

Multivariate Statistics

A large paper that reviewed the meteorological applications of cluster analysis, and extended that field through the comprehensive analysis of North American daily precipitation data, was completed and published in a major journal. Another large paper was published on the effects of domain shape, orthogonality, and maximum variance property on Principal Component Analysis. In another paper, Procrustes Target Analysis programs were used to analyze patterns of sulfur emission in the western United States.

Research on the optimum tests to determine data set dimensionality continued. A major finding was that standard eigenvalue tests showed little potential for determining the dimensionality of atmospheric parameters. Another area of work attempted to determine the hyperplane width that yielded the most accurate portrayal of climate fields in Principal Component and Empirical Orthogonal Function Analysis. This statistical parameter was found to be a strong function of sample size and a weak function of the scale of the phenomenon.

Research in cluster analysis continued, using several fuzzy cluster analysis algorithms in an attempt to regionalize North American precipitation. Research also continued to determine the hyperplane width for two-sided (both positive and negative correlations) data to complement work on one-sided data.

A joint CIMMS/NSSL/OU project was initiated on a CM-5 massively parallel (MPP) computer to determine the size limit for a dataset to be analyzed for regional climate or severe weather outbreak applications. A CIMMS scientist is working closely with an OU computer scientist in this effort. Preliminary results suggest that judicious use of the MPP algorithms could enable an 8K x 8K matrix to be eigen-decomposed in less than 4,800 seconds using a parallel bisection method. This substantially exceeds the capabilities of the best CRAY machine currently in existence.

Atmospheric Radiation Measurement (ARM) Program Site Scientist Team

CIMMS continued to perform its "Site Scientist" role for the Southern Great Plains portion of this international program operated by the U.S. Department of Energy. This involved participating in many planning and review meetings, assisting with the establishment and early operation of the central observing facility near Lamont, Oklahoma, and the further development of a broad-based research program. Our site operations activities center on monitoring the accuracy of the data flows from the increasing number of instruments at the central facility. The research program is investigating atmospheric radiative transfer and the surface radiation balance, cloud-radiation interactions, convective and stratiform cloud processes, lower tropospheric studies, and spatial and temporal analyses of cloudiness and soil moisture. This work is providing the basis for two M.S. theses that are nearing completion, two Ph.D. dissertation projects that are well underway, and a recently initiated M.S. thesis project.

Low Level Jets over the ARM Domain

In support of the Atmospheric Radiation Measurement (ARM) program, an observational and modeling study of the Great Plains low-level jet (LLJ) was begun. Data from the 915-MHz radar wind profiler at the ARM central facility were examined for June through August 1994. A preliminary analysis of these data yielded 33 LLJs with maximum wind speeds in excess of 12 ms^{-1} . Of these, 21 had the level of maximum wind speed at or below 500 m, which is the lowest range gate of the NOAA 404-MHz wind profilers located along the ARM domain boundaries. Several cases have been chosen for further study, including several events in which the LLJ persisted after sunrise, and appeared to be lifted higher into the atmosphere as the planetary boundary layer deepened, owing to the effects of sensible heating. These cases will be investigated using both the special ARM datasets and model results from the Penn State/NCAR mesoscale model.

Single-Column Model for ARM data

Efforts have started to construct and test single-column climate models. This work has involved the extraction of the physical subroutines from the NCAR community climate model (CCM1). This single column model is designed to perform diagnostic studies of radiation and cloud parameterizations by using the observational data obtained from the Oklahoma/Kansas ARM site and the National Weather Service. It also can be used to investigate the effect of an

individual physical process. In addition to the single-column model extracted from CCM-1, another single column model called COLAID (from Maryland State University) was installed and tested in our local computer. This model is featured by its advanced subroutines for biospheric processes.

An SCM constructed by extracting the physical subroutines from the NCAR community climate model (CCM-I) was used to examine the large-scale representativeness and accuracy of the lateral boundary flux measurements and calculations at the ARM Southern Great Plains sites. The preliminary results can be summarized as follows: (1) the SCM can produce nearly the same results as the CCM-1 if the lateral boundary fluxes are precisely given; (2) the results of the single column model are moderately sensitive to noise in the lateral boundary conditions; (3) the SCM simulated temperature can (or cannot) closely follow the CCM-1 global run if the noise in the lateral boundary fluxes is below (or above) 10 percent of the signal level; and (4) when the advection term is calculated by using the central finite difference scheme from the gridded (instead of spectral) data produced by the CCM-1 run, the SCM simulated temperature can significantly differ from that of the CCM-1 global run. The representativeness of the lateral boundary conditions was found to be crucial for the SCM simulations and accurate methods need to be developed for calculating the boundary fluxes.

Three methods were developed for calculating the SCM boundary flux and divergence: (1) the finite difference method; (2) the truncated spectral method; and (3) the two-dimensional B-spline fitting method. The later two methods use extended ARM data (beyond the site coverage). The first two methods were tested with the simulated ARM data (by the NCAR CCM-1, T42 version) for the intensive observing period of 16-25 June 1993. It was found that the truncated spectral method produced better results than the finite difference method. The high-resolution (60-km) analysis data, from the Mesoscale Analysis and Prediction System (MAPS) model at the NOAA/ERL Forecast Systems Laboratory, were recently obtained from NCAR for the same observing period and will be used to test the three schemes.

Insolation over the Midwest and the Southern Great Plains

Through collaboration with scientists at the Illinois State Water Survey, a semi-physical model was implemented to generate a new historical (1945-91) daily solar radiation (SR) database for 53 locations in nine Midwestern and six adjacent states. The model validated strongly against sets of daily SR measurements from three contrasting parts of the study region. Basic analyses of the dataset documented the midwestern spatial and temporal SR variability since the mid-to-late 1940s.

Substantial progress was made on a Great Plains counterpart to the aforementioned Midwestern SR study. In this case, the documentation of the spatial and temporal SR variability was complemented by analyses of the associated variation of cloud type and amount. Particular attention was focused on the analyses for Oklahoma and Kansas to provide background climatology for the southern Great Plains (SGP) locale of the ARM Program.

A technique was developed whereby the standard error of a simple spatial average can be computed given any spatial configuration of measuring sites. The equation was applied to the Oklahoma Mesonet pyranometer data network, and the statistics generated were then used to estimate the optimal temporal averaging interval (6 hours) for the pyranometer network being established over the SGP by the ARM Program.

Investigations of Rainfall Variations in Subsaharan West Africa

This work investigated both the mesoscale character of the rainfall during several contrasting rainy seasons since 1968, and the tropospheric wind regimes that accompanied the rainfall variations. The rainfall analyses used daily and monthly rainfall data to identify the size, frequency, and magnitude of individual mesoscale systems, and assess their integration to regional climate. The tropospheric analyses were based on individual rawinsonde soundings for the zone, and sought to establish the relative importance of the monsoon layer thickness, mid-tropospheric easterly wind maximum, upper tropospheric easterly wind maximum, and upper tropospheric Tropical Easterly Jet for the mesoscale rainfall regimes. Some of this work was reported in a journal article. It also provided the basis for an undergraduate honors thesis and a M.S. thesis.

Another study sought to determine the extent to which the frequency, size, and intensity of the rain-producing Sahelian disturbance lines (DLs) changed during 1951-90. Those changes were inferred from a high-density daily rainfall dataset. The analysis of these data strongly suggests that the striking progressive decline in Sahelian rainfall since the early 1950s has resulted from equally striking progressive decreases in both the size and intensity of DLs. This dual size-intensity finding was also especially characteristic of the interannual extremes, because many of the driest (e.g., 1972,

1982-84) and wettest (e.g., 1952, 1955, 1958) overall monsoon seasons possessed very low or high DL size and intensity index values, respectively. In addition, since about 1965, the total absence of DLs over wide areas of Sahelian West Africa has become more frequent.

The investigation also used two unique sets of observational data to examine the interrelations among the Tropical Easterly Jet, the so-called African Easterly Jet (midtropospheric easterly wind maximum), the monsoon layer thickness, and rainfall over Subsaharan West Africa during several contrasting rainy seasons of the late 1960s and early 1970s. The variability of those tropospheric wind field features was documented from individual rawinsonde soundings for the aerological stations within the zone. The daily temporal resolution of these data yielded insight into the intraseasonal variability of key kinematic and thermodynamic properties of the wind field, including the existence of trends of periodicities that coincide with particular patterns of rainfall variation. The rainfall variability was quantified using an extensive set of daily station rainfall data that extends back several decades. This analysis particularly focused on the frequency, duration, and magnitude of the individual rain events during each of the rainy seasons investigated, from which inferences will be made about the nature of the rain-producing DLs. The overall goal is to identify the wind field features that are most strongly related to the intraseasonal and interannual rainfall variations.

SOCIOECONOMIC EFFECTS OF MESOSCALE WEATHER SYSTEMS AND REGIONAL CLIMATE VARIATIONS

Characteristics of Climate Forecast Quality

Using a conceptual forecasting format that is similar to some in current operational use, trade-offs between climate forecast quality and economic value were examined from the perspective of the forecast user. Various scenarios for climate forecast quality were applied to corn production in east central Illinois. A stochastic dynamic programming model was used to obtain the expected value of the various scenarios. The results demonstrated that the entire structure of the forecast format interacts to determine the economic value of that system. Additional results indicated two possible preferred directions for research concerning climate forecasting and economic applications such as corn production in Illinois. First, increasing forecast quality through decreasing the error between the observed condition and the forecast condition may be preferred to increasing quality through increasing the number of predictions in the correct category. Second, corn producers may prefer research to increase the quality of forecasts for "poorer" climatic conditions over research directed towards increasing the quality of forecasts for "good" conditions. This study was published in a major journal.

A NSF-funded study was completed that investigated the role of decision-maker expectations in climate forecast value, which appears to be considerable.

A project dealing with "Government Institutional Effects on the Value of Seasonal Climate Forecasts" was funded from the Economics Element of the NOAA Climate and Global Change Program. It will assess how the federal farm program, federal crop insurance program, and federal income and employment taxes affect the value of climate forecasts.

Influence of Southern Oscillation (SO) on Global Crop Yields

Research established the effects (existence, direction, magnitudes) of SO-related weather variations on crop yields for regions of the world that have been determined to have consistent and strong SO-related weather anomalies. The work, which formed the basis of a Ph.D. dissertation in Agricultural Economics, used a time series methodological approach. Three crops (corn, wheat, and sorghum) were considered for the following nations/states -- Zimbabwe-South Africa, India, Venezuela, Uruguay-Argentina, Texas, and Australia.

Modeling Value of Climate Forecast Information Using Hierarchical Systems Evaluation

The process of interdisciplinary research in aggregating sub-system models to model larger systems was reviewed and applied to valuing Midwestern (USA) crop climate forecasts. Elements of climate forecast information schemes and characteristics of users and their environment that give rise to or restrict climate forecast information value in corn and soybean production were identified. Methods of varying these elements were applied to determine their effect on the value of climate forecast schemes. This study was published in a major journal.

Impact of Decadal-Scale Climate Change on Midwestern Agriculture

Two manuscripts were publication on this subject. They were drawn from a recent NSF-funded Ph.D. dissertation that dealt with "The Effects of Data Aggregation on Econometric Estimates of Climate Change Impact on Corn and Soybean Production in the Midwest".