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INVESTIGATIONS OF PURPOSEFUL AND INADVERTENT WEATHER AND CLIMATE MODIFICATION IN ILLINOIS

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Nancy E. Westcott, Robert W. Scott, and Mark Belding

Illinois State Water Survey
Champaign, Illinois

Contract Report No. 577

A Report of the Board of Trustees of the
University of Illinois pursuant to
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OVERVIEW

The investigations during this project addressed a wide range of interrelated topics involving studies of how the atmosphere is modified to change clouds, precipitation, and storms, and how these changes affect the physical environment and social systems of Illinois and the Midwest. The one-year effort described is part of a multi-year program which includes four broad goals:

1. To understand how to purposefully modify precipitation in Illinois for environmental and economic benefit.

2. To understand how the atmosphere and in particular clouds, precipitation, and storm activity, are accidentally modified by human activity.

3. To understand how the atmosphere and in turn the clouds, precipitation, and storm activity are affected by surface conditions including soils, topography and large water bodies.

4. To understand how the modification of clouds, precipitation, and storm activity, due to any cause (cloud seeding, natural factors, or accidental modification), affect physical environmental systems and weather-sensitive social and economic activities in Illinois.

The work of this year builds upon 13 prior years of research accomplished under these goals. The latest series of studies were designed to further our understanding and informational base.

The major accomplishments of this one-year period, June 1993-May 1994, are presented according to the research activities done under the four major goals of the program identified above. In addition, the planning and administration of this long-term program is a fifth major on-going activity that is highlighted.

Purposeful Weather Modification

The primary activity focused on the analysis and interpretation of the 1989 summer cloud-rain modification experiment. This highly successful experiment yielded extensive data that has been carefully analyzed since the end of the program. Much of the data was brought to the final stage of analysis during this year. This led to the completion of a major 154-page report published by the State of Illinois entitled, *Results from the 1989 Exploratory Cloud Seeding Experiment in Illinois.* In addition, several scientific papers summarizing various aspects of the experimental findings were prepared and submitted to various scientific journals. Some have been published and some are under review.

Another aspect of this research has involved laboratory studies investigating ice formation and microphysical interactions between droplets. This research, which is also relevant to our inadvertent weather modification studies, continued. The results show that a collision-freezing mechanism is important in the origin of ice in the warm-based convective rain clouds of the Midwest. We also maintained close communication between our research program in purposeful weather modification and those elsewhere. In particular, we exchanged information and had extensive discussions with scientists involved in the North Dakota and Texas programs which are also investigating purposeful modification of summer cumulus clouds.

Inadvertent Weather Modification Studies

Research in this area included continuing investigations of the effects of jet contrails on cirrus cloud formations, initiation of studies of potential urban influences on thunderstorm activity; and the initiation of studies of radar-based urban effects on nocturnal summer rainfall at St. Louis. A three-year project conducted by scientists at Indiana University and our staff investigated the development of widespread cirrus formation due to jet contrail activity in the Midwest, and the radiative properties of these "false cirrus" as compared to those of natural cirrus. Contrails induce a net reduction of energy (cooling) in the daytime and a model was developed for predicting outbreaks of contrails. A major report summarizing the past two years of data was completed.

Prior project research has dealt with answering questions about urban influences on clouds, rainfall, and storminess. The influence of large conurbations in Illinois, Chicago and St. Louis, on local and regional weather are of considerable concern. Prior studies using historical records had indicated that both cities exerted an influence on summer storm activity. To further investigate this possibility but utilizing a better database, the lightning data from the new national lightning detection network established in 1986 throughout the region was employed. Studies were made of Chicago, St. Louis, and 14 other Midwestern cities. Results indicated that there is an enhancement of lightning activity over and east (downwind) of 13 of 16 cities investigated.

A third area of research was launched; that being investigations of how Chicago and St. Louis effect nocturnal precipitation. The METROMEX raingage data suggested that the city exerted influence on nocturnal storm activity, a very unexpected finding. We proceeded, using data from the new radar at St. Louis, to begin a probing study of these events and the mechanisms by which an urban influence occurs.

Influence of Natural Surface Conditions on the Atmosphere

Our third area of investigation represents a continuation of a series of studies aimed at obtaining a better definition of how, when, and where natural surface conditions including soils, soil moisture, topographic features, and large lakes affect clouds, precipitation, and storms. We include in this area of investigation studies of extreme events, including prolonged dry periods, excessive wet periods, and heavy rainfall. These events greatly effect the precipitation regime in the state and understanding their causes and impacts is relevant to understanding weather and climate modification.

During this year, our research into influences of natural conditions on the atmosphere included completion of a multi-year study by our staff and Woodley Weather Consultants on the use of satellite data to measure precipitation over Lake Michigan. This was done to better measure the influence of the lake on precipitation and to learn if we could use this technique to define the influences of Chicago on precipitation over the southern end of Lake Michigan. The studies of over-lake summer season precipitation revealed amounts 1 to 17% less than shoreline values. We also participated in a study to define the areal extent of influences of Lake Michigan and the other Great Lakes on seasonal precipitation.

The investigations revealed major differences between the amount of change and areal extent of change during dry years versus average and wet years, with much less influence downwind of the lakes during dry seasons. The year brought the once-in-300-year flood to the Upper Mississippi River valley and the extensive heavy rains in Illinois afforded a unique opportunity for heavy rainstorm investigations. The investigations of the flood-producing storms rainfall revealed an extremely large number of massive mesoscale rain systems with 72 of these events. Interactions of Principal Investigator Changnon with the NOAA flood survey team also led to the collection of extensive data. We also conducted a fourth study, further investigations of heavy rainfall frequencies over urban areas.

Effects of Changed Weather and Climate on Physical and Social Systems

The primary activities done as part of this long-term area of project investigation included: a) continuation of the agricultural plot experimentation during the summer of 1993; b) summarization of findings from the first five years of plot research into a major report; c) studies of the impacts of weather and climate extremes including those due to the floods of 1993 and those from urban drought; d) continuing studies of the influence of altered weather/climate on urban agencies; and e) involvement of Principal Investigator Changnon as scientific advisor to the Illinois' Task Force on Global Climate Change.

The 1993 agricultural field experimentation focused on further studies of influence of altered soil temperatures and the influence of rainfall changes during different periods of corn growth stages; these data are still under analysis. The first five years of agricultural plot experimentation, involving the covered shelters and uncovered plots, was brought to a successful conclusion, and a major state report summarizing these results was published. This research provided extremely useful insights into the timing and value of altered summer rainfall, revealing that enhanced summer rainfall achieved most of its potential benefit in the drier 35% of all growing seasons. Capability to enhance rainfall in the more normal and wet summers had little positive value. These results, coupled with economic simulations of seeding programs, reveal that purposeful modification of summer rainfall in Illinois, given various climatic, legal, and technological constraints would have limited value, capable of producing 2 to 4 percent regional income increases, if utilized over a period of years.

The heavy rains associated with the 1993 summer flooding were analyzed as to their physical and societal impacts. An excessive amount of soil erosion was noted along with a major impact on the state's transportation system and agricultural production. Studies of urban drought were initiated to gain understanding of impacts and responses available to cities. This research has relevance to dealing with future drought in major Midwestern cities. Efforts to assess how the weather effects agencies in the Chicago area were continued to gain understanding of how weather changes and climatic shifts might influence the city. Changed weather was found to have a wide influence on many urban agencies.

Principal Investigator Changnon was assigned by the Governor of Illinois to be the science advisor to the Illinois Task Force on Global Climate Change. In this role, time was spent assessing information on the scientific knowns and unknowns related to climate change in Illinois and preparing reports for the task force.

Administration

This project staff conducted a large number of interactions involving project leaders and project staff with scientists at numerous other institutions, with NOAA leaders, with other members of the NOAA Atmospheric Modification Program, and with numerous external interests in Illinois. The Illinois constituency for this research includes the agriculture and water resources communities and we worked with them to provide information they need. Other endeavors included working with NOAA leaders and University of Illinois leaders in seeking to establish a NOAA Cooperative Institute at Illinois. Planning of future research remained another major project activity.

PURPOSEFUL WEATHER MODIFICATION

Laboratory Experiments on the Effect of Air Temperature on the Coalescence of Small Precipitation-Size Drops in Free Falling

Laboratory experiments were conducted on isolated collisions between small precipitation-size drops falling freely at terminal velocity in a refrigerated collision chamber. Results were published in the *Journal of the Atmospheric Science* (Vol. 51, No. 20,1994). The experiments were conducted to improve basic understanding about the natural origin and evolution of precipitation to provide a better framework from which to understand potential seeding effects. The experiments involved the design and construction of a refrigerated drop collision chamber, a set of computer controls and photographic system for recording the collisions. The experimental setup is shown in Figure 1. The average radii of the drops studied was 353 and 306 μm for the large and small drop respectively. Drop collisions occurred in air temperatures that ranged from 20° C to -15° C. Corresponding drop temperatures ranged from 20° C to approximately 2°C.

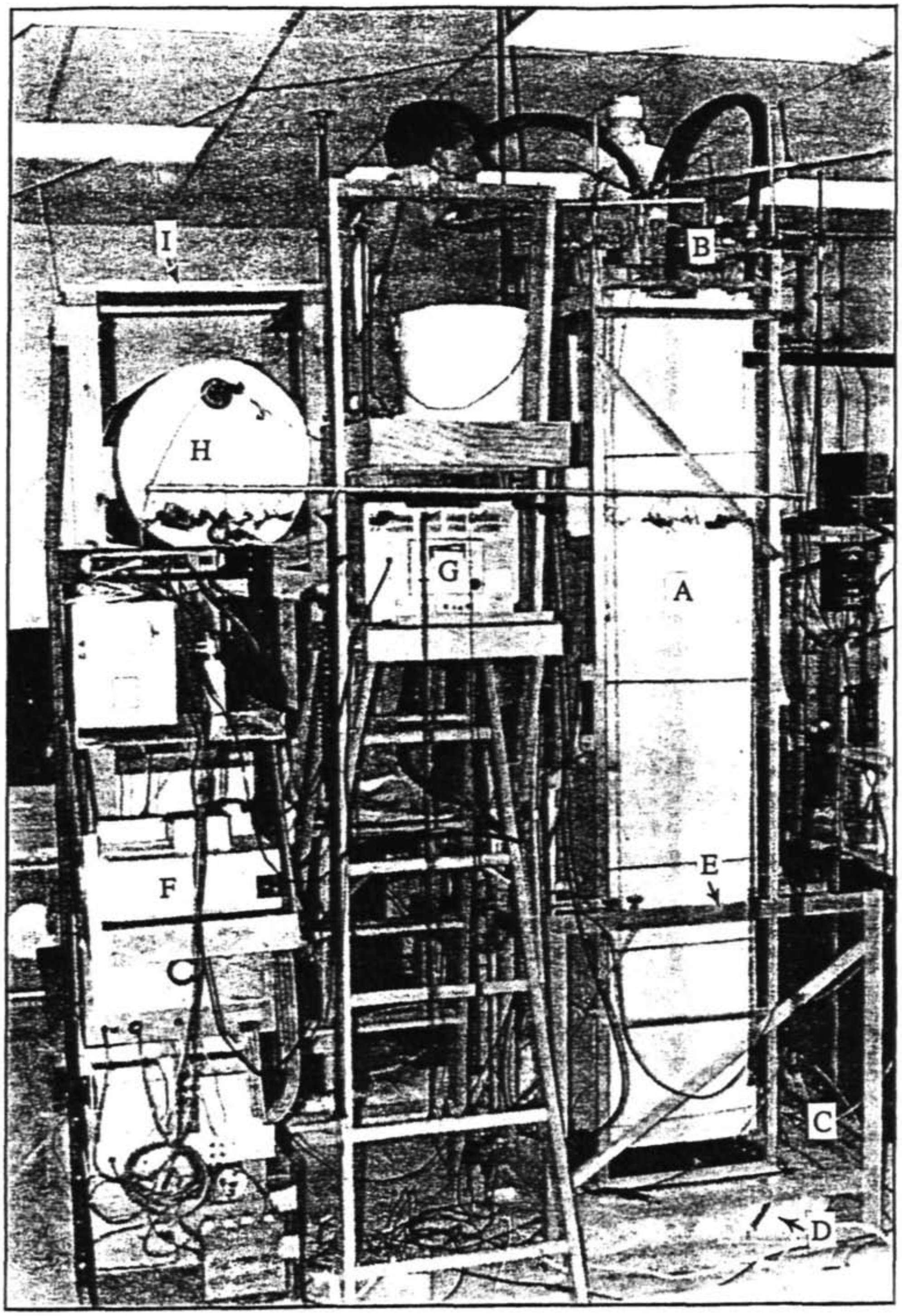


Figure 1. Photograph of the experimental apparatus: (A) 2.1 m tall refrigerated collision chamber, refrigeration unit adapted from an NCAR ice nucleus counter is located to the right and is not shown; (B) drop generators and mounting hardware; (C) "floating" drop generator support structure; (D) vibration isolation platform; (E) chamber support stand; (F) back of computer control system; (G) back of computer monitor; (H) water reservoir for drop generator "B"; and (I) water reservoir stand.

Experimentation revealed that the coalescence efficiency increased from approximately 42% for mean drop temperatures between 20° C and ~10°C to about 81% for mean drop temperatures between ~10°C and 2°C. The change in coalescence efficiency with mean drop temperature is shown in Figure 2. A particularly interesting finding that can be noted in the figure was an abrupt, rather than gradual, increase in coalescence efficiency once mean drop temperature reach a value of 10° C. Increase in coalescence efficiency with decreasing air (drop) temperature probably resulted in the experiments from a reduction in drop deformation related to a substantial increase in the viscosity of the water. Each experimental trial involved a detailed measurement of drop charge. Analysis of the drop charge measurements proved that the behavior of the coalescence efficiency data could not be attributed to some secondary effect related to drop charge. The apparent abrupt increase in coalescence efficiency is still under investigation. The important implication of the experimental results is that rain production by the coalescence process may be more efficient than previously credited because coalescence efficiency may increase as cloudy air parcels rise and cool.

Review of Hygroscopic Seeding Experiments to Enhance Rainfall

Field experiments and computer modeling studies of the possibility to promote the coalescence process by hygroscopic seeding for rainfall enhancement were extensively reviewed. The review was conducted in the preparation of a field program to probe for precipitation enhancement by the introduction of artificial CCN in strong updraft regions at cloud base and the findings were published in the *Journal of Weather Modification* (Vol. 26, No. 1, 1994). The review showed that most previous field experiments focused on the use of water sprays or common salt particles, but the practical delivery of the massive bulk sources of these products has been a limiting factor. The use of "new" hygroscopic seeding flares at cloud base in deep warmer-based convective rain clouds in South Africa has produced very encouraging results, although the number of treatments is too small to draw firm statistical conclusions. The new seeding flares have apparently overcome earlier problems associated with transporting bulk amounts of seeding materials. Results from previous field experiments leave the distinct impression that perceived effects were generally consistent with that expected from the hygroscopic seeding hypothesis under investigation. Expected effects from seeding include broadening of the cloud droplet distribution, and triggering of coalescence sooner than would have occurred naturally which are discernible in echo morphology. Changes in echo behavior are consistent with rainfall enhancement.

Microphysical effects from seeding beyond those expected on the coalescence process were also uncovered in the review. Some experiments have suggested effects on the initiation and evolution of ice. The effects are possible because concentrations of supercooled drizzle and raindrops may be enhanced, or because rime-splintering may have been enhanced by the presence of broader distributions of supercooled cloud droplet in ice multiplication zones, or for perhaps both reasons. Indications of "dynamic" effects in some of the experiments were noted that may have occurred either in conjunction with the latent heat of condensation, or from a more active conversion of supercooled water to ice, or for both reasons.

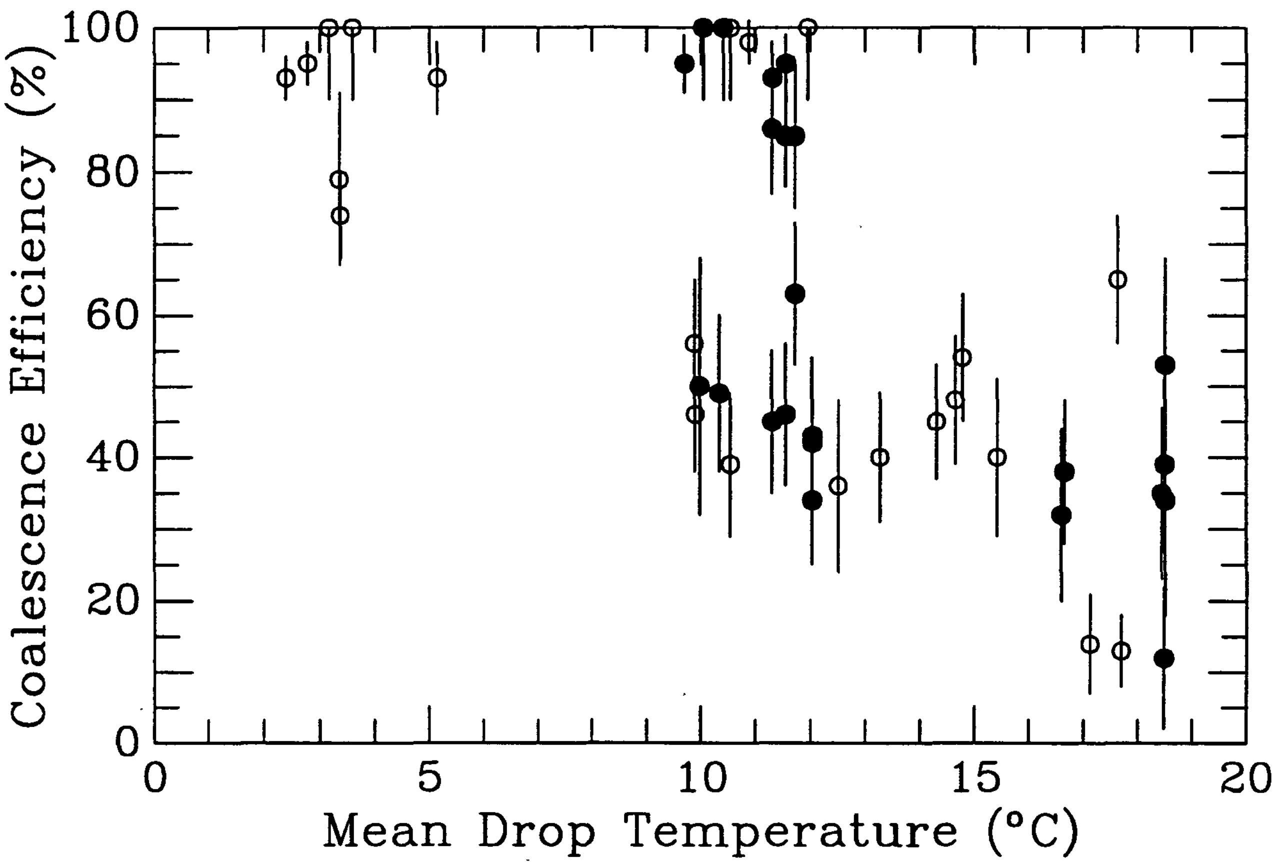


Figure 2. Experimentally determined coalescence efficiency versus mean drop temperature.

Review of computer modeling studies has indicated that seeding at cloud base with appropriately sized artificial cloud condensation nuclei to foster Langmuir-type precipitation growth trajectories may be the seeding technique to investigate. Model results indicate that the largest effects occur when the precipitation growth trajectory is long enough to allow the initial population of natural and artificial raindrops to undergo breakup, thereby multiplying seeding effects. Model results also suggest that seeding opportunities do not necessarily have to be limited to cold based clouds characterized by a marginal coalescence process.

Findings from the review provide guidance for field experimentation design. Experimentation should be conducted on cloud systems that will grow deep enough for raindrop multiplication to be active and for ice to initiate. Randomization should be based on a threshold of cloud base temperatures to obtain a balance between seed and no seed cases for both cold and warm cloud base conditions. Evaluation of seeding effects should look for warm cloud region effects expected from an enhanced coalescence process as well as effects on cloud growth that may occur from a second stage of effects on ice processes.

INADVERTENT WEATHER MODIFICATION

Urban Effects on Thunderstorms

During this past year, the study of urban effect on thunderstorms continued and culminated with the submission of a manuscript to the *Journal of Applied Meteorology.* This research was undertaken because past studies have indicated that summertime rainfall and storms are enhanced over and downwind of very large urban areas. The frequency and spatial coverage of cloud-to-ground lightning activity were analyzed in and around 16 central United States cities to discern possible effects. Cities were selected to span a range of sizes, populations, pollution characteristics, and topographic features.

This study, based on summertime 1989-1992 data, found that lightning frequencies were greater within and downwind of many of the urban areas. The increases were largest and statistically significant for the larger cities and for cities not adjacent to a large water body, such as one of the Great Lakes. The increase in lightning flash density were found to range from 10 % to 140 %. No single factor, however, was found to explain the observed increase in lightning flash frequency.

In general, the larger cities had higher annual values of SO_2 and PM10 and larger increases in lightning activity. There were exceptions, however. Dallas-Fort Worth was relatively clean, but exhibited some of the largest changes in lightning flash frequency; and Detroit and Cincinnati, relatively dirty cities by this measure, had some of the smaller (and even downwind decreases) changes in flash frequency.

If the four cities located adjacent to one of the Great Lakes were disregarded, there was weak evidence that the urban effect on lightning frequency increased with urban size. For cities adjacent to a large lake, it appears that the local influence of the lake on convection may have overwhelmed (Detroit and Toledo) or at least diminished (Chicago and Milwaukee) possible urban effects.

The enhancement of lightning activity was largest during the afternoon hours when the urban-rural temperature differences may be smallest, but when the atmosphere is generally the most unstable and most apt to produce convective storms. The results suggested that existing convective activity was effected.

Urban Effects on Nocturnal Rainfall

The purpose of this research is to investigate the presence and magnitude of urban areas on summertime storms using cloud-to-ground lightning and precipitation data, so that local and regional shifts in clouds and precipitation due to urban influences can be better understood and predicted. Research based on a 4-year climatology of summertime lightning flash data indicated that the urban area has a considerable effect on the frequency of lightning on many large Midwestern cities, with an overall increase in the urban and downwind areas on the order of 10 to 140%. The increase was largest and statistically significant for the larger cities and for cities not adjacent to a large water body, such as one of the Great Lakes.

In the Missouri-Illinois area, approximately 50% of the summertime rainfall occurs during the nighttime hours. A climatological study of the St Louis area indicated that for St. Louis, there was both a bimodal peak in total rainfall and a difference in rainfall between an upwind control location and a downwind location (Huff and Changnon, 1972). The peak values fell at about 1700 CDT and at about 0400 CDT. During the 1971-1975 METROMEX study centered on St. Louis, similar results were found. In particular, an increase in nocturnal rainfall was found in the Granite City-Edwardsville area to the east and northeast of St. Louis. A number of theories have been suggested to explain the urban influence on rainfall, and it was suggested that the causes may be different for the daytime and nighttime storms. If there are indeed differences in daytime and nighttime storm characteristics, or in the physical mechanisms resulting in the presence of an urban influence on rainfall and lightning, this could have important bearing on planned weather modification efforts, and on understanding the possible impacts of the ever growing urban areas on future climate change.

This research has examined storm characteristics between daytime and nighttime storms. Efforts have been made in two directions, first to develop the ability to employ the WSR-88D radar data to examine precipitation events moving over an urban area, and second to study associated lightning activity.

A study was initiated to examine several case studies of nocturnal summertime storms over the St. Louis Area employing the newly available WSR-88D reflectivity data. This was to better understand the factors which lead to this nighttime urban maximum.

Possible case studies days were first identified from hourly raingage data recorded at the Illinois Climate Network site at Belleville, Illinois. Time periods when more than 0.5 inches of rain occurred at the site have been noted. The synoptic conditions present during these periods were examined.

During the summer of 1993, WSR-88D data was collected in the St. Louis region. In early November, with the assistance of the St. Louis WSFO, radar data from the predetermined cases were examined, in order that WSR-88D data could be acquired from the National Climate Data Center. Two case studies for which radar data appeared to be available were selected. The two periods of study involved convective lines which passed directly over the St. Louis urban area. However, only data from one of the two cases (September 22,1993) was obtainable from NCDC.

During the September 22,1993 case, an east/west oriented lined passed from north to south over the St. Louis region during the early evening hours, from about 18:45 to 22:15 CDT. Convection formed in association with an outflow boundary ahead of a cold front. Rainfall totals generally exceeded 2.5 cm. No severe weather was reported, although the system resulted in flash flooding.

During the winter, a series of software packages were obtained from NSSL and various divisions of NCAR and these software packages were ported to ISWS computers to process the WSR-88D data:

1) A2COPY from NSSL, to convert WSR-88D data to universal format;

2) REORDER from NCAR-ATD, to interpolate reflectivity and velocity data to cartesian grids using universal format data as input,

3) CEDRIC from Dr. Jay Miller of NCAR-MMM, to compute rainfall from the interpolated data files, and

4) RDSS from NCAR-ATD, to display the raw universal format data and the interpolated data on a color graphics display monitor.

A fifth program (THAN, NCAR-RAP) was obtained to produce a climatology of summertime radar echo statistics from our existing ISWS radar field tapes from 1986,1988 and 1989. This program is expected to be adapted to the WSR-88D format in the upcoming year.

The first four programs were ported to ISWS computers and a test set of WSR-88D data were taken through these steps to compute and display radar-rainfall estimates. As this was one of the early requests for WSR-88D data, the time required for acquisition of the case data was long, being received in early May. The four programs were employed to compute reflectivity and rainfall fields for the initial case study, September 22,1994:18:30 - 22:30. The line of convection moving through the area, moved from north to south. St. Louis was located on the eastern end of the time, with new cells propagating to the ESE. From a cursory examination of this case, any influence the urban area might have had on cloud-to-ground lightning frequency was not discernable.

Jet Condensation Trails

A 2-year study of jet condensation trails addressed their characteristic morphology, their relationships with atmospheric conditions, and their influence on radiative forcing. Empirical results were used to develop and validate a predictive model of the likelihood for contrails, given values of temperature and moisture in the mid-upper troposphere. The study was significant in that it was the first to use multispectral satellite remote sensing to enhance the contrail signature, to determine contrail characteristics, and to identify the environments in which they form. Moreover, this study was the first comprehensive study of contrails to include simultaneous observations from the Earth's surface and from satellite altitudes. Conventional meteorological soundings were additional sources of data used to determine the atmospheric environments suitable for the formation and persistence of contrails.

The major results of this investigation are as follows:

1. *Contrail areal coverage varies significantly according to time of day. Contrails are significantly greater in areal coverage at night and in the early morning hours than those occurring during the mid-afternoon or early evening hours. This demonstrates the importance of meteorological conditions on contrails rather than the absolute density of aircraft flights.*

2. *Contrails persisting within "natural" cirrus clouds are significantly greater in length (167.0 km) and areal coverage (451.2 km^2) than those present in "partly cloudy" (123 km; 388.9 km^2) or "clear" (119.1 km; 361.2 km^2) areas. This means that the radiative impact of contrails is also likely to differ according to the sky condition in which they occur.*

3. *Simultaneous observations of contrail outbreaks from the surface and from satellite indicate agreement when outbreaks exist and do not exist 87% of the time. The greatest difference occurs with overcast conditions where contrail outbreaks are recognized by the satellite but not from the surface.*

4. *Contrails persist in a relatively narrow range of temperature and moisture conditions that can be identified using "real time" rawinsonde and GOES water vapor absorption band data, respectively. The specific range of "favorable" conditions for contrail persistence are; 1) a 300-100 mb layer mean temperature of between approximately -50 and -60 C, and 2) a 700-100 mb layer integrated water vapor value of between approximately 170 and 190 "counts."*

5. *Contrail width is significantly associated with the 300-100 mb layer mean temperature (negative relationship); 300-100 mg layer mean temperature (negative relationship; 300-100 mb layer wind shear (positive relationship); and 300-100 mb layer mean wind speed (positive relationship). No significant association is found between contrail width and the stability of the 300-100 mb layer.*

6. *Contrail radiative "forcing," determined as the sum of the change in the OLR and shortwave reflectance induced by the contrail presence, is most positive ("warming") during the summer and fall seasons and most negative ("cooling") during the winter and spring seasons. The net "annual" contrail forcing is close to 0.*

7. *Contrail radiative "forcing" is most positive when contrails are located in otherwise clear sky situations, and most negative when contrails are located in cloudy (mostly cirrus) sky.*

8. *Contrail "forcing" on OLR is significantly associated with latitude (negative relationship), the 300-100 mb layer stability (negative relationship), and contrail width (positive relationship). The latter result implies that contrail "forcing" changes as the contrail persists and spreads. Contrary to the suggestions of previous work, contrails do not tend to thin vertically as they spread, implying that vertical growth of the contrail occurs concurrently with lateral spreading.*

9. *When considering the contrail morphological and radiative characteristics together, and their variation according to cloud situations, it is concluded that, overall, contrails most likely induce a net reduction of energy ("cooling"), during the daytime period, on the Earth-atmosphere radiation budget, especially when compared to natural cirrus.*

10. *A predictive model for the likelihood of persisting contrails was developed using the 300-100 mb layer mean temperature and the 700-100 mb layer integrated water vapor. The model correctly predicts (at greater than a 90% probability) the occurrence or non-occurrence of persisting contrails for 44 of the 66 observations used to develop the model. For 20 of the remaining 22 observations, the model correctly predicts, at a probability of greater than 50%, the occurrence or nonoccurrence of contrails.*

The model performance was evaluated through application to a separate set of 33 temperature and water vapor observations. The model correctly predicts (at greater than a 90% probability) the occurrence or nonoccurrence of persisting contrails 20 of the 33 observations. Each of the remaining 13 observations are correctly predicted at a probability of greater than 50%. The model is also evaluated through application to conditions on April 17,1987 for the eastern United States. The model performs well in identifying the location of a major contrail outbreak in the Midwestern United States.

These results are a significant advancement in obtaining better understanding of the role of contrails in the earth-atmosphere radiation balance, and of their detection using satellite remote sensing. The radiative differences demonstrated to exist between contrails and natural cirrus suggest that contrails could potentially play a significant role in future climate change scenarios to offset a portion of the warming induced by increases in trace gases, at least on the regional scale.

The unique set of ambient conditions that characterize contrail environments are now better understood. Prediction of contrail persistence can be undertaken, in "real time," from a knowledge of the current temperature and water vapor conditions for the portion of the troposphere in which contrails form. Application of the model developed means that it is now possible to reduce the abundance of contrails, and minimize their radiative influence, by directing aircraft away from "favorable" areas for contrail development and persistence, should this be deemed appropriate from a policy perspective. This is critical in the continued efforts to reduce human impacts on climate, and especially those on clouds.

INFLUENCE OF NATURAL SURFACE CONDITIONS IN THE ATMOSPHERE

Effects of Soil Moisture Deficiencies Induced by Drought on Evaporation and Precipitation

Analysis of the effects of soil moisture deficiencies on evaporation and precipitation in the Midwest was continued. A manuscript describing initial findings was completed. This manuscript entitled "Effects of Drought on the Surface Energy Budget in the Central United States," by Kenneth E. Kunkel and Robert W. Scott, was been submitted to the *Journal of Climate.*

Urban Droughts

An assessment of several recent urban droughts, and responses to these, at major cities across the United States was done. This assessment provides guidance as to the potential need and likelihood of use of rain enhancement as a tool to help Midwestern cities during prolonged drought. A report was generated which includes a comprehensive bibliography.

Satellite-Data Studies of Lake Michigan Precipitation

A third area of research has involved the satellite-based studies of summer rainfall over the Great Lakes. This research has been conducted by Woodley Weather Scientists, NOAA/NSSL staff, and our staff. The interesting findings were summarized into a paper submitted to the *Journal of Great Lakes Research* and accepted for publication.

Several studies have demonstrated that precipitation is the most variable and most critical parameter in the water budget of the Great Lakes region. Because the lakes cover one-third of their drainage basin, rain that falls on the lakes themselves is a significant component of the hydrologic balance. Currently, however, there is no way to estimate lake rainfall within an accepted level of tolerance. In this work, a method is proposed by which GOES imagery and rain gauges are used to provide accurate estimates of lake rainfall.

A streamlined version of the Griffith-Woodley satellite-based rain estimation technique was used to infer rainfall over the Great Lakes region for the June, July, and August of 1988, 1989, and 1990. Estimates were made for each hour over a 2000-km square domain of the central United States and southern Canada that included Lakes Superior, Michigan, and Huron. Because the empirical relationships of the Griffith-Woodley technique apply to south Florida convective storms, adjustments had to be made based on local raingauge measurements. The final product was a hybrid; rain gauge measurements provided baseline mean rain depths, and the product derived from the satellite imagery provided the spatial continuity, or gradients. Results suggest that it is possible to use this method for useful long-term estimates of rainfall for the Great Lakes. Errors in mean summer estimates of lake rainfall are likely to be acceptable provided that care is exercised in adjusting the satellite estimates using local raingauge clusters or nearby statewide climatological networks from states that share long common borders with the lakes.

In agreement with previous applications, this study showed that the accuracy of the rain estimates becomes greater as the period of rain estimation becomes longer. More confidence can be placed on summer totals, and especially on mean summer estimates for a number of years. The error in the mean summer rain products was estimated at 2%, whereas errors in individual monthly estimates of lake rainfall were greater. For example, about 80% of the monthly lake rainfall estimates were in error by 30% or less. Satellite-based, gauge-adjusted summer estimates of lake rainfall were somewhat less than those computed from the current operational method, which infers lake rainfall from shoreline gauge measurements. Differences in the mean summer estimates from these two methods for the three largest lakes ranged from 1 to 5%; whereas differences in lake rainfall for individual summers ranged between 1 and 16%. The greatest discrepancies were for Lake Superior, and the least were for Lake Michigan.

Because the water storage in the Great Lakes hydrologic system is so great, there is a considerable lag (3 months to 2 years) between the time that the precipitation occurs and the time that lake levels are affected. In that the accuracy of the satellite estimates improves with accumulation time, the large lag time characteristic of the basin's water cycle provides ample justification for the use of long-term satellite-estimated rainfall as input to water balance models used to forecast lake levels.

In addition to demonstrating how satellite-based rain estimation may be used to estimate accurate long-term lake rainfall, much has been learned about the characteristics of warm-season rainfall in the region. It is believed that these estimates represent the first attempt to directly assess summer lake rainfall amounts and patterns for the three largest lakes. On the basis of our 3-year sample, Lake Superior receives the most summer rain (23.83 cm), followed by Lake Michigan (22.66 cm) and Lake Huron (18.80 cm). The state of Michigan, which is apparently affected meteorologically by the presence of these large cold bodies of water to the east, west, and north, averaged less summer rainfall than Lake Superior (22.76 cm vs. 23.83 cm). However, the states to the west and southwest (upwind) of the Great Lakes received substantially more rain than the lakes, as expected. A rain shadow effect was documented in narrow strips, about 1-2 degrees longitude wide, to the east of the three lakes studied. Mean summer rainfall for the downwind shores of Lakes Michigan and Superior were 15% and 23% less than that of their upwind shores, respectively. The interannual and monthly variability of these deficits were rather stable for Lake Michigan, but unstable for Lake Superior. Lake Huron's rain shadow in southern Ontario was quite distinct, but it was not quantified because the upwind weather in Michigan is already affected by the lakes. Finally, a peculiar east-west-oriented rainfall minimum was documented across the southern half of Lake Michigan that extended well into both Lower Michigan and Wisconsin. Although no meteorological explanation is offered, this feature is believed to be real because it recurred in all three summers of this analysis, and it also appeared in an independent assessment of the summer rainfall for the region by Changnon (1968).

The properties of the Griffith-Woodley rain estimation technique render it well suited to this application. However, independent testing with new data is necessary to confirm the results reported here. Perhaps the quantitative products presented could be used in retrospect to test the sensitivity of the Great Lakes hydrologic models to these new lake rainfall estimates. It is hoped that this work will evolve beyond this exploratory phase to the point where satellite-based rain estimates are computed in real time to provide alternative lake rainfall input to water balance models of the region. With the rapid improvements in communications and the improved availability of GOES data, the real-time implementation of such a method is feasible.

Lake Effect Assessment

The Great Lakes exert a considerable influence on the climate of their region. Interests in the impacts extend far beyond initial meteorological effects. Those involved in lake hydrology and laKe management have deep concerns on the long-term weather features of the region and feedback mechanisms in place within the basin. Although substantial climate research has been performed on portions of the Great Lakes, specifically Lakes Michigan and Ontario, the effects of the remaining lakes, and the entire basin as a whole, on the local climate have received much less attention. What is not available for hydrologic research is detailed information on the average spatial patterns of lake effects by all lakes to seasonal precipitation, temperatures, winds, clouds and vapor pressure.

Research has been ongoing with the primary objective to estimate, in detail, the magnitude and extent of the lake effect that occurs over the entire Great Lakes region relative to various weather conditions. Seven parameters were selected for analysis including: precipitation, mean temperature, mean maximum temperature, mean minimum temperature, cloud cover, wind speed, and water vapor pressure. Past Water Survey research based on the Lake Michigan basin provided climatological techniques for defining the analytical processes employed. These results and other studies found significant lake effects within a variety of distances from the lake shores. From all considerations, an 8-km wide band around the lakes was selected as area which would encompass all lake effects on climate.

Data were digitized, sorted by season (winter, spring, summer, and autumn), plotted, and analyzed to derive seasonal measures of lake effects around each lake, and to establish the spatial distribution pattern of each element within the Great Lakes basin and the surrounding areas. A second map was constructed similarly, except all stations in the 80-km lake effect band were eliminated, resulting in a pattern across the basin derived from the buffer region only, and thus, defining a "no-lake-effect" chart. The two maps were compared, and differences attributed to the "lake-effect" within the basin, were determined by graphical subtraction.

Results show strong seasonal influences across the Great Lakes Basin, especially in precipitation and minimum and maximum temperature. Lake-induced precipitation during winter is found over the eastern sides of all lakes and adjacent land areas, totaling from 60% to 100% more than expected no-lake effect amounts. Similarly, increases in mean minimum temperature of 6° C to 8° C exist in the same vicinity. Conversely, lake-effect patterns indicate 10% to 20% less rainfall across all lakes during summer while at the same time, mean maximum temperatures range from 3° C to 6° C lower. Thus, the heat capacity differences between water and land are quite sufficient to generate lake effects on seasonal temperatures and precipitation.

Although precipitation and temperatures reveal the clearest lake effects, changes in the other parameters are apparent also. Wintertime cloud cover is one to two tenths higher, an approximate 30% increase. A large change in vapor pressure is found in summertime, a decrease of more than 1 mb (about 8%) covering much of the upper peninsula of Lake Michigan and adjacent Lake Superior. This result is tied closely to decreases in mean maximum temperatures in the same area. Finally, analyses of wind speed present the least amount of evidence for a pattern of lake-effects on the climate of the Great Lakes basin. Due to various factors in the analysis, especially unknowns of the history of site exposure, data extremes throughout all seasons appear not to be tied to the lake, and thus, a lake-effect analysis of wind speed is not considered credible.

Analysis of Dry Periods

Research concerning precipitation modification potential in Midwestern dry periods was initiated. Past data from the Metropolitan Meteorological Experiment were assessed for urban effects on summer precipitation during dry seasons in the St. Louis regions. This represented the initiation of research which will be emphasized in the next year.

Attention has been concentrated on determining definitions for dry periods that are applicable to needs of the agricultural and hydrological (water supply) communities. These are the major users and beneficiaries of weather modification operations. Results will be used as the analytical basis in the planned climatological research on the time and space distributions of dry periods of various intensity and duration in the Midwest.

Initial analyses have been confined to agricultural definitions which involve warm season conditions primarily. Hydrological needs may involve the entire year. Monthly and seasonal data for each of the nine climatological divisions in Illinois (as defined by the National Weather Service) are being used to develop the relations, based on 1949-1993 data. This data set contains the observational data on rainfall, mean temperature, and soil moisture deficiency which are needed for the investigation.

Results are not adequate to specify conclusions and recommendations at this time. However, preliminary analyses do indicate a relatively strong relation between soil moisture deficiency and total rainfall for the more severe occurrences of July-August dry periods. For example, in Division 4 (central Illinois), it was determined that all of the nine most severe periods of moisture deficiency in July-August were included among the lowest 33% of total rainfalls. Previous research has shown that these are the months in which weather conditions are most critical to crop production in Illinois.

Severe Rainstorm Studies

Efforts were concentrated on investigating the hydrometeorological characteristics (temporal and spatial) of severe rainstorms in the Midwest and the causes of such events. Information on the characteristics of these storms is pertinent to our studies in weather modification and agricultural impacts.

Twostorms were studied in detail during this period. One was centered in the Champaign-Urbana area of east-central Illinois on August 11, 1993. Rain amounts for storm periods of 3 to 24 hours exceeded 100-year expectancies for Champaign-Urbana and east-central Illinois. Meteorologically, this was a micro-storm system embedded in a larger mesoscale storm system (squall line) associated with a low centered in western Illinois. This detailed study was made possible by an urban raingage network operated in the Champaign-Urbana area for many years by Water Survey employees, along with a 104-year record at the local climatic station. A paper published in the *Bulletin of Meteorology* summarized the findings from this study.

A second study involved hydrometeorological analyses of the most severe rainstorms that have occurred in the Chicago urban area in the past 45 years, during which a recording raingage network has been operated through the efforts of several government agencies. These data provide a unique opportunity to contribute much needed information concerning the characteristics and causes of such storms which have resulted in an unexpected frequency of major floods in the metropolitan area in recent years. Specific causes being studied include urban enhancement of on-going storms (inadvertent weather modification), climate trend, and natural variability. Results should be applicable to other large urban areas and small basins that are subjected to flash floods produced by heavy rain systems. A paper summarizing the findings has been completed and will be submitted to an appropriate journal.

Weather Analyses Related to the 1993 Flood

Some time was spent field surveying the 1993 flood, in collecting data on the impacts of the flood, and in analysis of the meteorological conditions which caused the flood. Bob Scott prepared a paper on the weather conditions related to the flood, and the article was published in *Storm.* Analysis and understanding of such events are relevant to the wise pursuance of weather modification research in Illinois.

The meteorological and climatological aspects of the 1993 flood in the Midwest were under investigation. In particular, certain of the impacts of the flooding were being assessed. Excessive heavy rainfall remains a problem that precipitation modification must deal with and answer to. Hence the need to investigate certain aspects of the flood situation as it pertains to questions relating to precipitation modification. This research led to the presentation of three scientific talks by Stanley Changnon; one about the flood and its effects was presented at the Annual Meeting of the American Association for the Advancement of Science, another talk about the flood and its effects in Illinois was presented at the Annual Conference of the Transportation Highway Engineers for Illinois, a third talk about the weather causing the flood and its impacts was given at the Annual Conference of the National Crop Insurance Services.

EFFECTS OF CHANGED WEATHER AND CLIMATE ON PHYSICAL AND SOCIAL SYSTEMS

Weather Effects on Corn Yield

Early Season Soil Temperature Effects on Corn Yield. The experiment to study the effects of early season soil temperature on corn yield was an outgrowth of the weather modification impacts work from 1987 to 1991. This earlier work showed that final corn yields were smaller with warmer temperatures during the first 30 days of corn growth. The objective of the experiment was to determine if this effect was due to soil temperature, and to determine the effects of early season soil temperature on corn development.

The second year of the early season soil temperature effects on corn yield experiments were conducted with the first date of planting occurring on May 8 and the second planting date on June 7, 1993. Leaf and stem measurements were conducted throughout the growing season, and the crop was harvested in October. All data were entered into the database with the 1992 data and analysis of the data begun. Weather data collected during the two growing seasons were developed and combined with the crop data to evaluate the effect of the different soil temperature treatments on corn growth and final yield.

Analysis of the data showed that soil temperature affected the leaf area development of the corn crop. Cool early season soil temperature resulted in larger leaves from leaf 1 to leaf 14, than were observed in the warmer soil treatments (Figure 3). Conversely, the warmer soil temperatures resulted in larger leaves in the upper part of the canopy (leaves 15 to 21). The leaf area data were fit using the Richard's Function and the coefficients obtained from fitting the Richard's Function to each treatment for the two years related to soil temperature from planting to tassel initiation, air temperature from planting to tasseling, and air temperature from the fifth leaf stage to tasseling. Coefficients of determination obtained from these relationships were in the 0.85 to 0.99 range. The relationships between the air and soil temperature and the Richard's Function coefficients will be used to develop a model to simulate the final corn yield to further explore the relationship between leaf area and final yield.

The results of this experiment are currently being analyzed further, and will be published during the next year as a Ph.D. thesis and in refereed journal articles.

Effects of Rain During Different Corn Growth Stages on Final Yield. The plots in the rain shelter to evaluate the effects of rainfall during different corn growth stages were established in late May of 1993. In spite of various problems with the rain shelter experiment during the 1992 growing season significant differences in the plots were observed in response to the different water treatments at different growth stages. The corn experiment in the rain shelters was harvested in November and the yield component data determined in December.

Results of the rain shelter experiments have not been completed, because we are repeating the experiment during the summer of 1994. Preliminary analysis shows that rainfall during the period from planting to tassel initiation results in the greatest yield increase (Figure 4). In this figure the bars represent the yield increase resulting from applying water equal to 100 percent of potential evapo-transpiration compared to no water applied during that growth period. In 1993, the surface soil was very dry and additional rain during the period from planting to end of row set resulted in increased yields. However, in 1992 when surface soil moisture was adequate for seed germination and stand establishment, water applied during the period from ear initiation to silking did not increase yield. These differences may be due to response of root development to soil moisture during the period from ear initiation to silking.

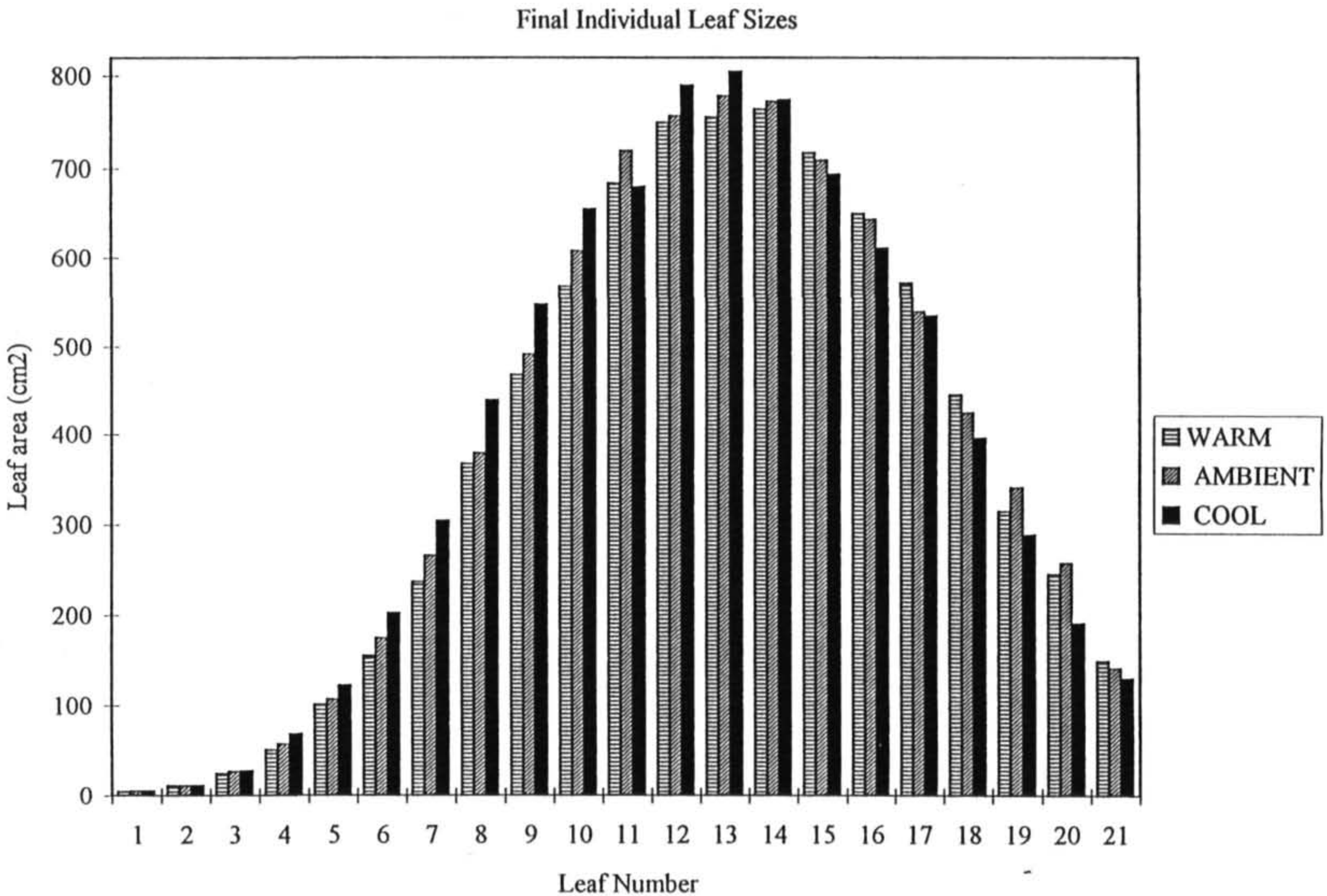


Figure 3. Leaf areas for leaf number 1 through 21 for the warm, ambient and cool treatments..

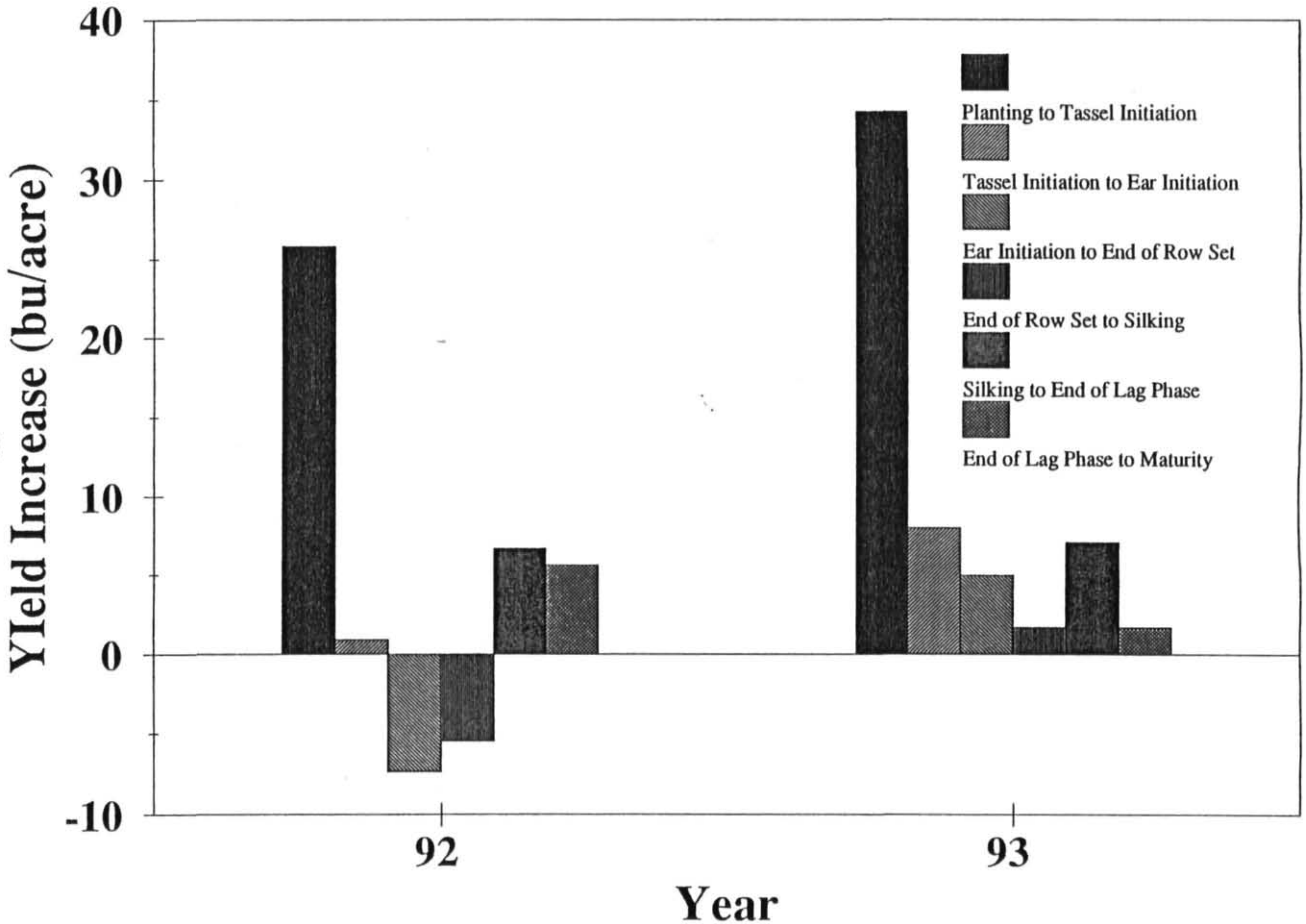


Figure 4. Yield increase/decrease according to rainfall for six phases of plant development.

This experiment was continued during the summer of 1994, with the corn planted in the rain shelters on May 18. Following the harvest of the 1994 experiment, a complete analysis of the three years of the experiment will be conducted.

Flood Impacts

The project's interest in the massive 1993 flood and the heavy rain events which caused it, also embraced studies of the impacts. These help provide a measure of the potential extremes of the impacts of weather events, a fundamental need in our long-term investigations of this issue.

Our flood impact studies focused broadly. They included the entire spectrum of impacts embracing the physical-environmental effects (soil erosion, water quality, aquatic biological effects, and hydrologic characteristics), the economic impacts, the social effects, and impacts to government (Changnon and Laver, 1994). We also focused in on the considerable damage to railroads and transportation systems (Changnon 1994a), and on the effects and responses to the flood in the Illinois River basin (Changnon 1993).

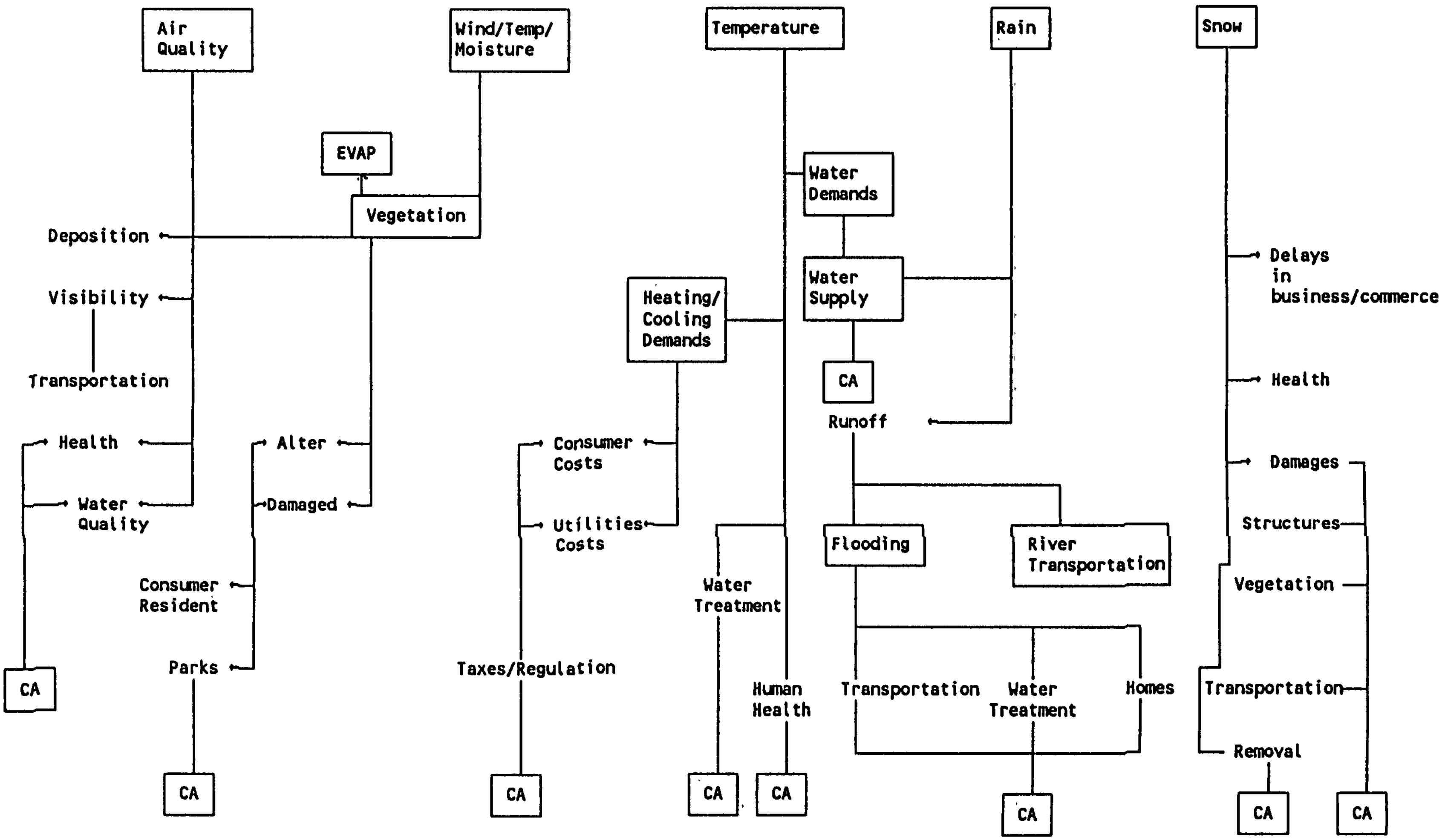
Urban Impacts

The earlier studies of urban responses to the potential of global climate change at Chicago and Toronto ended early on this one-year period. However, we continued to assess how weather events affected the various types of city agencies in Chicago. Data were collected through discussions with agency staffs. Figure 5 presents a schematic showing him temperatures, precipitation, snow, and other conditions produce effects on urban activities, facilities, or the environment. These effects then relate to impacts on a variety of city agencies.

Task Force on Global Climate Change

In the fall of 1992, Governor James Edgar established a 20-member Illinois Task Force on Global Climate Change with eight members from the General Assembly and 12 members representing various business sectors and environmental groups. The Task Force's mandate was to assess existing information about climate change and its effects in Illinois, and to prepare a report by June 1994 with policy-based recommendations for the Governor and the General Assembly. P.I. Changnon was appointed by the Governor as the Science Advisor to the Task Force.

The Illinois Task Force conducted 14 meetings at which they assessed, for example, the impacts of the Clinton administration's energy tax proposals, both for their effects on the global climate change issue and on the state's economy. We were asked to prepare in-depth assessments of the scientific issues, including the status of knowledge on climate change, how the change was and could be monitored, and its impacts on Illinois (Changnon and Wendland, 1994).



*CA = -City Agencies impacted.

Figure 5. An analysis of how different weather conditions affect various agencies in Chicago.

The Task Force (1994) ultimately identified five major issues relating to state policies: 1) What are the economic, social, physical, and environmental implications of climate change in Illinois? 2) How does the national global climate change policy concern Illinois? 3) What are the appropriate global climate change mitigation strategies of Illinois" 4) What adaptive responses to global climate change can Illinois take" and 5) How can climate change research, monitoring, and education be enhanced in Illinois?

One major conclusion of the Task Force's assessment is that federal program interest in and support of state and regional research relating to impacts of climate change, and to adaptation to climate change, were inadequate. Hence, the Task Force's recommendations urge enhancing state research addressing these two areas. In the science arena, the Task Force also identified a need for monitoring conditions in Illinois to help detect the onset and development of climate change.

The Task Force's other major recommendations concerned establishing a tree planting program, launching an enhanced energy-efficiency and conservation program, establishing a statewide research committee to help plan and develop multi-disciplinary research projects, and enhancing a public education effort.

PROJECT MANAGEMENT

The final report describing the 1992-93 project efforts was completed in October 1993. Copies were mailed to NOAA and interested scientists.

A confirming activity concerned long-term planning for the Illinois project. Staff discussions, coupled with assessment of prior findings, led to a plan for atmospheric modification research during the next 3 to 4 years. This information became the basis for preparing our future research proposals.

A "user friendly" custom plotting package using NCAR Graphics was updated and enhanced for use with color plotting. Various routines were improved, and new routines were added. This new version will be released in the next quarter w.

We had two visitors from NCAR; Al Cooper and Roelof Bruintjes. During this two day visit we shared general information about the PreCCIP project and specific information about our exploratory cloud seeding results from 1989. Drs. Cooper and Bruintjes discussed their interest in studies of the coalescence process and recent encouraging results about intentional coalescence enhancement for rainfall augmentation. As a result of this meeting, we decided to consider investigating an alternative seeking hypothesis for Illinois along with the possibility that we would help form the nucleus for a summer cloud seeding experiment to explore for rainfall increases from hygroscopic seeding.

We responded to a solicitation for proposals from the University of Illinois at Urbana-Champaign, and were selected by IBM to participate in its Shared University Research (SUR) program. Our proposal requested a RISC System 6000 workstation and related equipment (keyboard and monitor, disk and tape drives, etc.) that would be applied to our current research tasks. Its use will initially focus on: 1) numerical simulation of rain drop temperatures with applications to destructive ice accumulations in freezing rain storms as well as other atmospheric phenomena as it relates to modified cloud processes, and 2) four-dimensional extraction of radar indicated cloud characteristics with implications for discerning seeding effects.

Considerable effort was put forth towards seeking a NOAA Cooperative Institute at the University of Illinois. A major document describing the "Atmospheric Sciences" activities and staffing and facilities at the University and Illinois State Water Survey was prepared in concert with UI staff. This document was sent to NOAA leaders in OAR and NWS in June, and an ensuing meeting involving Dean Gamer, Dr. Robert Wilhelmson and Professor Stanley Changnon was held with NOAA officials, including the Program Manager, on August 31 and September 1 in Silver Springs, MD. This meeting was followed by a visit of Program Manager Golden, Dr. Hooke, and Dr. Friday (Head of NWS) to Champaign-Urbana on October 26. Discussions concerned the Institute and a briefing about PreCCIP was presented along with a visit to project facilities. Discussions continued with Dr. Golden on the project and future proposals.

Various negotiations were carried on with subcontractors. This included discussions with Dr. Lambright about this final report and about a potential future research project, one which we are unable to fund this year. Discussions with Indiana University scientist David Travis concerned their annual report and the plans for the year's research. Travis visited the Water Survey in June 1993 and in May 1994.

PI Changnon was asked by NOAA to serve on the NOAA Disaster Survey Team for the 1993 floods. This endeavor involved seven days in the field during August with the team and additional time to prepare a text describing the hydrometeorological conditions which caused the record Midwestern floods of 1993.

During this 12-month period, there were extensive interactions of our project leaders with leaders of the other five state projects in the Atmospheric Modification Program. This involved discussions about program management, funding, and interactions with NOAA. Also involved in these discussions and communications were several interactions with the AMP Program Manager in Silver Springs.

We had monthly meetings to update everyone on the progress on our research. The proposal for the next two years of research on our program was revised during this period in relation to reviewer comments. Revised sections of the proposal were submitted to NOAA

The senior principal investigator met with the leaders of the Illinois Farm Bureau to discuss the project progress and future funding. Briefings of certain members of the Illinois Congressional delegation were held locally (and in Washington) during the project.

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