Miscellaneous Publication 171

A SCIENTIFIC HISTORICAL REVIEW:

THE ATMOSPHERIC SCIENCES PROGRAM AT THE ILLINOIS STATE WATER SURVEY

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Champaign, Illinois
A Division of the Illinois Department of Natural Resources

PREFACE

Events occurring in 1995 led to the idea of writing this historical treatise about the Atmospheric Sciences program at the Illinois State Water Survey. The Water Survey's long-running project dealing with weather modification, inadvertent weather modification and climate change, and the impacts of weather-climate changes was at a point of accomplishment that required long-range planning. We decided that an extensive review of all facets of past Survey research was necessary to provide a perspective on what was needed in the future.

As long-term members of the Atmospheric Sciences program, we also envisioned some value to the future science of the entire organization to review the past in an effort to glean potential applications for future programs. Another factor that influenced the performance of an in-depth review was that several persons who had been key staff members died over a short period of time in 1995: Douglas M.A. Jones in May, Edna Anderson in June, Bernice Ackerman in July, and Loreena Ivens (January) who as Editor for the Survey for 20 years had been instrumental in the issuance of many atmospheric publications, including three addressing weather modification for which she served as coauthor. In considering these events, we realized we possessed unique information about most of the events in the Survey's atmospheric sciences endeavors since 1947. Floyd Huff has been at the Survey since 1947 and was the first staff member employed for the new Meteorology Group. Stanley Changnon joined the Survey as a graduate student in June 1951 and has been a staff member ever since.

Thus, we concluded it was time to review and record, as best we could recall and document past findings and events, the history of the Atmospheric Sciences program at the Water Survey. In assembling this document, we have tried to be unbiased in our reporting of undocumented events. The reader should understand that our assessment obviously rests on our perspectives about the value of certain scientific activities, findings, and accomplishments. We have presented information on certain undocumented events based solely on our memories and the memories of others who have reviewed the text.

DEDICATION

We dedicate this document to the memories of past Water Survey Chiefs Arthur M. Buswell and William C. Ackermann. They had the foresight to allow and encourage the development of the Atmospheric Sciences program.

We further dedicate this document to the hundreds of staff who served the Water Survey and the State of Illinois well as part of their work in the atmospheric sciences program.

Finally, we dedicate this document to departed senior scientists including Paul T. Schickedanz, Bernice Ackerman, and Douglas M.A. Jones.

ACKNOWLEDGEMENTS

The costs of this document were partly borne by the National Oceanic and Atmospheric Administration (NOAA) as part of NOAA Cooperative Agreement NA47RA0225. This long-running program has supported research in several of the primary areas of the Water Survey's atmospheric program, including radar meteorology, planned weather modification, inadvertent weather modification, climate change, cloud physics and rainfall forecasting, and impacts of weather and climate on agriculture, water resources, and policy.

Several associates have reviewed the document and offered helpful comments that improved it. Don Staggs reviewed Chapter 3 and provided much historical information. Don Gatz reviewed Chapter 9 and provided many useful suggestions. Bob Czys carefully reviewed Chapters 6, 7, and 8, a major effort. Ken Kunkel did a thorough review of Chapter 5, and Dick Semonin carefully reviewed Chapters 6, 8, and 9, providing numerous improvements in the text. We are extremely grateful for the reviews of these past and present staff members. We also deeply thank Eva Kingston for her excellent editing of the document. Linda Hascall helped collect several of the photographs and illustrations appearing in the document. Jean Dennison did an excellent job of typing of the manuscript and organizing the enormous amount of reference material.

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The antenna of the CHILL radar inside its radome.
The design, construction, testing, and operation of this unique weather radar was one of the major technological achievements of the Atmospheric Sciences Group at the Illinois State Water Survey

Chapter 1

AN OVERVIEW

Stanley A. Changnon and Floyd A. Huff

This document describes the atmospheric sciences endeavors at the Illinois State Water Survey from the beginning of the Meteorology Group in 1947 up to 1996. We have attempted to describe scientific findings, major projects, staff and facilities involved, and the overall programmatic evolution of the data collection, research, and services. The only existing document about the history of the Water Survey was published in 1980 (Hayes, 1980). It treats the history of all three scientific Surveys and as a result contains very limited information about the atmospheric sciences endeavors at the Water Survey.

Why a review and historical analysis of the atmospheric sciences program? As part of a long-running research project entitled "Precipitation, Cloud Changes, and Impacts" (PreCCIP), we sought, for long-range planning purposes, a past and future perspective on our project research, which currently embraces cloud physics and dynamics; rainfall forecasting; planned weather modification through cloud seeding; inadvertent weather modification and climate change; and the effects of weather and climate on physical systems, socioeconomic conditions, and government activities and policies. This research has been going on at the Water Survey for nearly 40 years. Moreover, the Survey's Atmospheric Sciences program is 50 years old, a useful milestone for assessing an institution and for reviewing its accomplishments. More importantly, this review has shown us the uniqueness of the atmospheric sciences research group established and sustained at the Illinois State water Survey, a state-supported institution. No other comparable research institution exists anywhere in the United States. Furthermore, by any measure, the Atmospheric Sciences program at the Water Survey has been extremely productive and has made major contributions that enhanced the nation's understanding of the atmosphere and its importance to the state and nation. As a result of this program, Illinois possesses more data and information about its weather and climate than any other comparable entity in the world. Finally, we believe that a serious review has been useful for analyzing where our research can and should take us. To ignore the past creates the potential for repeating past mistakes and fails to gain me benefits taught by the lessons of the past (Santayana, 1905).

To understand how the program and group developed, grew, and succeeded requires knowledge of this institutional environment and thus the Illinois State Water Survey and me Survey's place in two institutional domains: state government and the University of Illinois. The Water Survey was formed in 1896 with the mission "to study and report on the state's water resources." The organization existed within its early home, the University of Illinois at Urbana-

Champaign, but was funded by state appropriations separate from those of the university (Hayes, 1980). In 1917, the Water Survey (and its two sister scientific Surveys) were formally established as self-standing state agencies and were made divisions of the Illinois Department of Registration and Education. Importantly, the Surveys were mandated to be located on the University of Illinois campus, a scientific blessing, and their staffs were *not* to be employed in the same fashion as other state employees. Instead Survey employees were hired (and fired) by a Board of Natural Resources and Conservation appointed by the Governor of Illinois. This approach provided the institutional protection necessary to ensure a non-politicized staff of qualified scientists and engineers operating in an academic-like environment.

In its early decades (1896-1930), the Water Survey was essentially a water quality-chemistry institution, but by the late 1920s, a program in hydrology was developing (Hayes, 1980). Extensive water resource studies occurred in the 1930s and by 1940, the Water Survey had two groups, a Chemistry Section and an Engineering (hydrology) Section, both oriented to data collection, analyses, and services. When the new Meteorology Group was formed in 1947 (see Chapter 2), the Water Survey had 18 staff members and an annual budget of $51,000 with all funds coming from the state but with offices and labs in Noyes Laboratory, a university building. In many respects, the Water Survey served for many years as a training ground for numerous newly graduated chemists and engineers from the University of Illinois, who worked at the Survey for a few years and then moved on to more lucrative positions. There were few long-term staff members.

The five decades beginning in the mid-1940s have seen a revolution in American science that greatly changed the Water Survey. World War II advanced science and technology light years ahead, and as the sciences grew, so too did the Water Survey. Under the far-sighted leadership of Water Survey Chief Arthur M. Buswell from 1920 until 1957, the Meteorology Group was formed in 1947 and became the Survey's third scientific section in 1953. Under the growth-oriented leadership of Chief William C. Ackermann from 1958 until 1979, the Meteorology Section grew, and by 1970 the new Atmospheric Sciences Section had 70 staff members and an annual budget of $2.3 million, making it the largest section in the Water Survey. During the 1980s, Chief Stanley Changnon (1980-1985) and Chief Richard Semonin (1986-1990) sustained the strong program in atmospheric sciences. Most of the financial resources for the Section came from grants and contracts from external sources (largely federal agencies), not state funds. Consequently, the group had to perform high-quality, competitive scientific research and services that addressed national issues. For example, the new Meteorology Group became involved early in the nation's fledgling efforts in radar-rainfall research, a major issue for national defense agencies in the 1950s. Later the group embraced weather modification, a new focus of the federal atmospheric research during the 1960s and 1970s. Then the expanding program embraced inadvertent weather and climate change during the 1970s as they became key issues. Unlike the Chemistry and Hydrology Sections of the Survey the Meteorology (later named the Atmospheric Sciences) Section was much more oriented to research, both basic and applied, than services.

Analysis of the evolution of the Atmospheric Sciences program since 1947 shows the endeavors ultimately encompassed nine major areas of atmospheric research, or *major programs*.

These program areas and year that each began follow:

- Measurement of precipitation (1947)
- Hydrometeorological studies (1948)
- Climate research and services (1952)
- Cloud physics and mesoscale meteorological research (1953)
- Weather modification (1957)
- Inadvertent weather and climate modification (1960)
- Atmospheric chemistry (1962)
- Impacts of weather and climate (1965)
- Assessment of research and government policy (1970)

Some program areas developed through conscious planning, whereas others developed in response to external stimuli. The internally formulated and planned programs included hydrometeorology, climate research and services, weather modification, inadvertent weather and climate modification, impacts, and assessment of research and policy. Programs launched in response to external stimuli included precipitation measurements (which included the start of the Meteorology Group), atmospheric chemistry, and cloud physics and mesoscale research. Each of these nine program areas is treated as a separate chapter (Chapter 3 through Chapter 11). Each chapter is a chronological treatment of the subject and events beginning with an introduction that describes the early development of the program, the reasons for its development, and major events during its history.

Each program area was found to have three or more "themes," or sub-program areas. For example, the 1957-1996 program in planned weather modification has consisted of major efforts in 1) rain modification experimentation, 2) design and evaluation of weather modification projects, 3) study of hail suppression and other forms of weather modification, and 4) assessment of programs and governmental policies affecting weather modification. Additionally, research dealing with the physical and socioeconomic impacts of weather modification occurred and these efforts were in the program on weather impacts research (Chapter 10).

It was necessary to arbitrarily assign research that overlapped two program areas to one area. For example, several precipitation studies dealt specifically with weather modification, but they were also an integral part of the precipitation measurement program. For the benefit of the reader, strongly overlapping studies are cross-referenced in both relevant chapters.

Chapter 2 offers an historical treatment of the group's formative years, from its start in 1947 to 1953 when it became a Section. The final section of this historical review, Chapter 12, is a summary that focuses on the staff and facilities of the group, the institutional structure, the trends in research, and key accomplishments. It also offers our thoughts about what the future may hold for atmospheric sciences at the Water Survey.

The 50-year history of the Survey's weather group reveals amazingly diverse scientific endeavors, constantly shifting to meet new challenges. Hundreds of projects covered all major functions that an atmospheric sciences group can address, including basic and applied research; data collection, evaluation, and storage; field projects; instrument design, development, and testing; and a services program featuring publications and responsiveness to the needs of the public and specialized users of weather and climate information. The leaders of the Atmospheric Sciences program have actively promoted our programs and needs through scientific circles and through interactions with state and federal government bodies.

To handle the many varied projects, the Water Survey's Atmospheric Sciences Group has included highly diverse staff with expertise in civil and electrical engineering, meteorology (and its many specialty areas), climatology, geography, chemistry, physics, computer sciences, and statistics. The precise number of staff since 1947 is not known, but it is in excess of 1,250 people. Many scientists have come and gone, but interestingly, a small core group has spent most of their careers at the Water Survey, a tribute to the fact that the Survey has been an excellent environment for scientists to work and attain their personal goals and those of the organization.

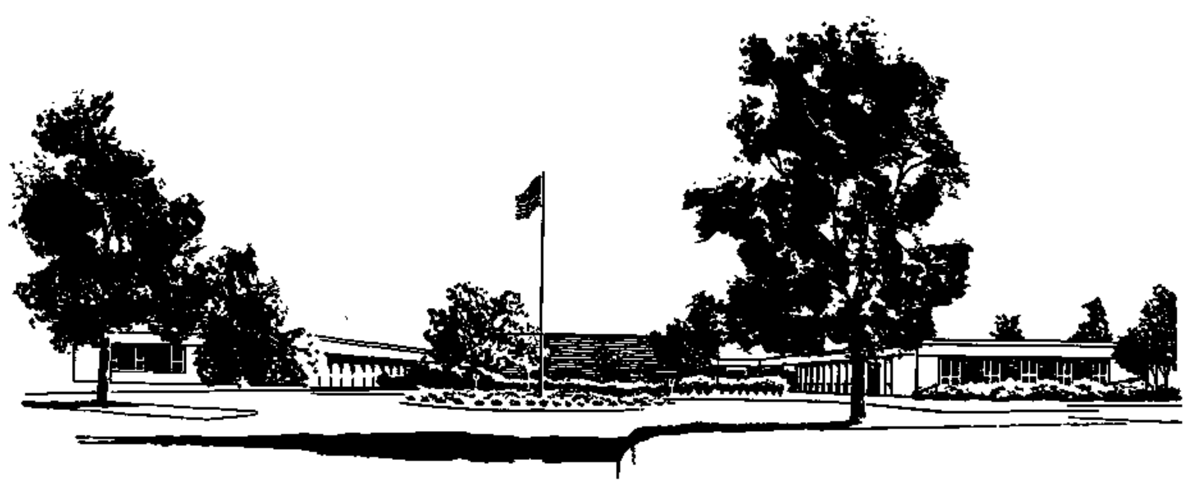


Figure 1-1. The Water Survey's buildings on South Campus, headquarters for the staff since 1984.

Chapter 2

THE FORMATIVE YEARS: 1947-1953

Floyd A. Huff

1947-1948: THE BEGINNING

Meteorology became a part of the Water Survey in 1947 as a result of unusual circumstances. In post-war America, "rainmaking" (weather modification) had aroused considerable interest among agricultural groups, including certain individuals in Illinois. This wide interest was spawned largely by the media's reporting of rainmaking's potential as an interesting news topic, plus early unverified claims by several commercial cloud seeders of their successful attempts at making rain. A new, potentially lucrative business was developing.

Inquiries about the new technology during 1946-1947 were being directed to the Water Survey, as the state's scientific water agency. Water Survey Chief Arthur M. Buswell recognized the need for state attention and channeled the inquiries to staff. At that time the Survey had only two employees possessing any meteorological background or experience:

- Glenn E. Stout, an assistant engineer in the Engineering Section, had been an aerology officer in the Navy during World War II, and

- W.J. Roberts (later to become a local TV celebrity), an engineer-hydrologist who had studied tornadoes while a master's candidate at Brown University and who taught weather courses at Chanute Air Force Base during the war.

During the summer of 1947, Lester Pfister, President of the Pfister Hybrid Corn Company, El Paso, Illinois, contacted the Water Survey. He was planning to initiate a cloud-seeding operation in the 1948 growing season and he asked the Survey to cooperate in this endeavor on a consultant basis in the planning and operation of the project, and also to analyze the results of the project. After discussions with key staff members, Dr. Buswell decided that the Water Survey would actively cooperate in the project for at least one year and so informed Mr. Pfister. Glenn Stout was placed in charge of the Survey's activities on the project.

The Survey's Report to the Board of Natural Resources and Conservation for the period of May 1, 1947-October 15, 1947 presented a recommended budget of $22,000 for procurement of equipment, monitoring of operations, and evaluation of results for the scheduled 1948 program. It was recommended that the rainmaking (cloud-seeding) investigation include such related factors as meteorology, hydrology, economic impacts, and legal ramifications. An initial need was to procure meteorological equipment, such as raingages and a radar, both considered necessary for monitoring and evaluating the cloud seeding operations. Another need identified was to increase the staff to provide adequate support for this and other anticipated meteorological activities of the Water Survey. In essence, the leadership of the Survey was committing itself to a meteorological program. The Board approved the requests and the new program was launched as part of the Engineering (Hydrology) Section of the Water Survey, a group headed by Herbert E. Hudson, Jr.

Under Stout's leadership, the initial staffing and facilities were obtained during late 1947 and early 1948. Floyd Huff, a meteorologist with experience as an Air Force weather officer and forecaster for Pan American World Airways, was hired as Stout's assistant to supervise the "local meteorological activities of the Survey, Survey-operated weather stations over the state, and the induced precipitation project being planned for central Illinois in the coming summer." Huff started in March 1948, and was given the assignment of completing the design and installation of a dense raingage network for the 1948 project. He was also to supervise operations of the University weather station (Figure 2-1). With a new focus on the weather program, the Water Survey had agreed to take over the operations and maintenance of this station from the University's Department of Agronomy on May 15, 1948. This weather station (fig.2-1) had been in operation since 1888 and offered a wealth of data for local climatological studies.

Stout procured sufficient raingages to meet the anticipated needs and acquired an Army surplus APS-15 aircraft radar (Figure 2-2) and other equipment considered essential for the cloud-seeding program by spring 1948. The Pfister Company provided some financial support to procure the equipment. *Meteorology had become a new activity of the Water Survey.*

Installation of the raingage network was completed by mid-spring of 1948 and consisted of 17 recording and 31 nonrecording (stick) raingages distributed over 280 square miles in Woodford County where Pfister had seed farms. Installation was facilitated through efforts of the Pfister Company, which furnished transportation and a foreman to accompany Huff in securing use of scattered sites within the farming community. Installation of the APS-15 radar in a Pfister building at El Paso was also completed during the spring, and personnel were hired to perform the radar-raingage operations.

1948-1949: FIELD ACTIVITIES AND RESEARCH BEGIN

Radar-raingage operations were carried out during the 1948 growing season, but no cloud-seeding operations were undertaken due largely to problems with Pfister's aircraft. The meteorological operations received considerable media attention, and arrangements were made to furnish the Peoria and Bloomington radio stations with weather radar reports each day. Data gathered in these operations were also provided occasionally to the U.S. Weather Bureau station at Peoria.

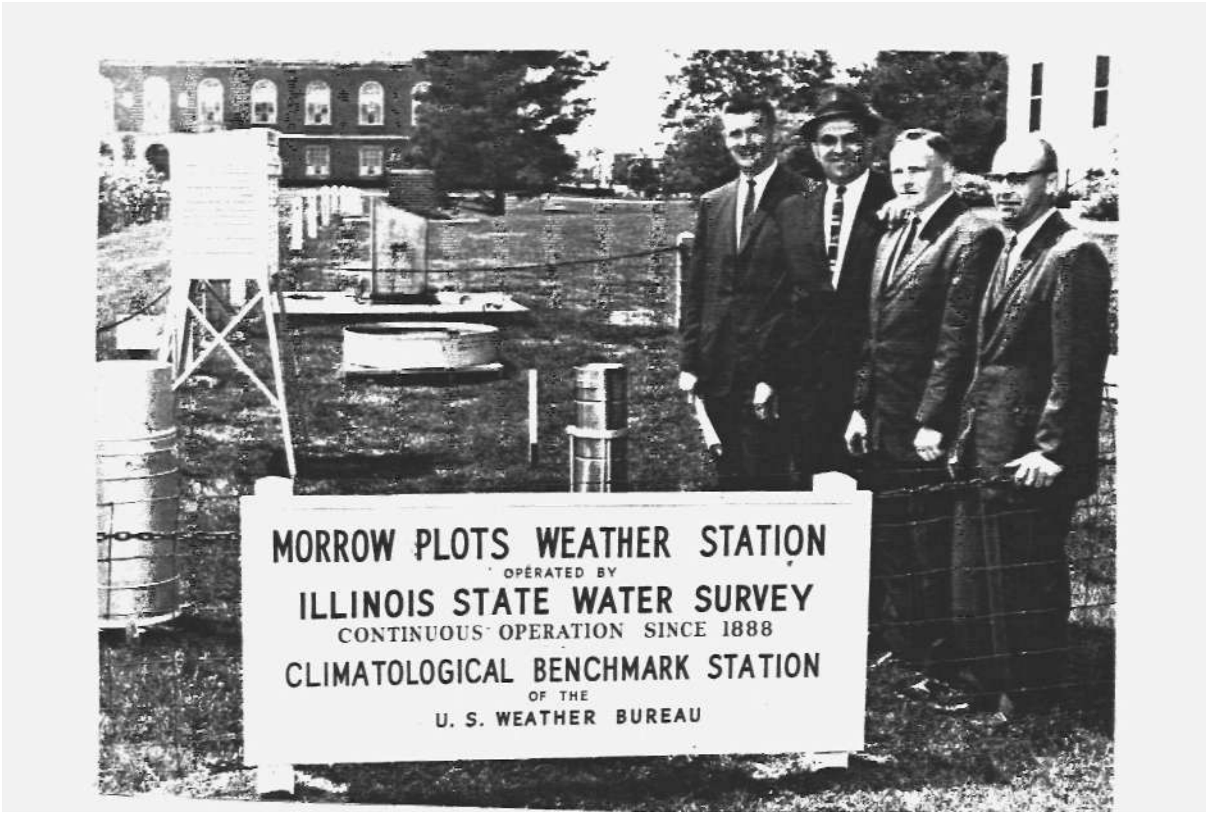


Figure 2-1. Fifteen years after assuming the responsibility of the Urbana Morrow Plots weather station, the station had its 75th anniversary in 1963. Here, left to right, are Glenn Stout (Head of Meteorology Section), Stanley Changnon (in charge of station operations), George Boyd (weather observer), and BUI Denmark (State Climatologist for the U.S. Weather Bureau). The Weather Bureau had selected this station as one of 22 in the nation to be a "Benchmark Station "for monitoring climate change. Selection was based on longevity and quality of records dating back to 1888.

These 1948 meteorological operations resulted in the first report of the Survey's Meteorological Group entitled *Radar and Rainfall* (Stout and Huff, 1949). The report provided a description of the 1948 project and emphasized (1) the potential of radar for quantitative rainfall measurements, and (2) the benefits of data from dense raingage networks for better definition of the space-time distribution characteristics of convective rainfall.

The group's second report provided rainfall frequency relations for Champaign-Urbana (Huff, 1949) using the long-term rainfall records of the University of Illinois weather station to meet an existing hydrological need in the design of a municipal storm sewer system. *This report marked the Survey's initial contribution in applied hydroclimatology.*

Rainfall was plentiful in 1949, and Pfister did not want to undertake seeding under those conditions; consequently, no seeding flights occurred that year. However, radar and raingage network operations were conducted and analysis of the data continued throughout the year. The cloud-seeding project was terminated at the end of 1949 when Pfister decided to use irrigation to supplement water supplies in dry growing seasons.

1950-1951: A CHANGE IN DIRECTION

At the close of the 1949 field operations, Water Survey leaders Buswell and Hudson decided to continue the ongoing radar-rainfall studies in the El Paso region as part of an evolving program in hydrometeorology with potential applications for hydrology. A network of 25 recording gages was installed in 1950 across the 100-square-mile Panther Creek watershed. Additionally, surface water and ground-water recorders were installed at selected locations. Radar operations continued from the Pfister installation at El Paso during the summer of 1950.

At this stage, the Survey's Meteorology Group temporarily departed from the weather modification field to become a pioneer in the application of radar in meteorology during the 1950s. Efforts were also concentrated on the use of dense raingage networks to advance existing knowledge on the distribution characteristics of precipitation in Illinois. Special emphasis was placed on developing applications for hydrology where major needs existed in the design and operation of water control structures. These early decisions to exploit radar and raingage networks were to prove exceptionally important foundations for future growth and diversification of research by the Survey's Meteorology Group. Radar meteorology became a key field of national research in the 1950s, and hydrometeorological research also expanded rapidly in the 1950s and 1960s.

Two additional professional staff members were hired in early 1950. Gerald Farnsworth, a recent electrical engineering graduate from the University of Illinois, was employed to supervise radar operations and instrument development. Douglas M.A. Jones, a meteorologist with a master's degree, was employed to supervise field operations for the radar and raingage networks. Both would make major contributions to the developing meteorology program. Members of the small meteorology staff in 1950 are shown in figure 2-2. An important step in the advancement and recognition of the program occurred in 1950 when Dr. Horace Byers, Head of the Meteorology Department at the University of Chicago, agreed to serve as a consultant for the Survey's meteorology program. Dr. Byers was one of the nation's outstanding scientists in the field, and his department was considered the best in the nation.

A TPL-1, 10-centimeter (cm) wavelength radar obtained on loan from the University of Illinois in late 1949 was moved to El Paso in early 1950, as shown in figure 2-3. The plan was to compare rainfall data as measured by the 3-cm (APS-15) radar with that from the 10-cm (TPL-1) radar. Another dense raingage network (Farm Creek) was installed in 1950 west of El Paso away from the radar "ground clutter" to provide ground-truth for the radar studies. Operations progressed routinely and data collection and analysis continued throughout the summer of 1950. To advertise their capabilities, the group took the TPL-1 radar to the Illinois State Fair in 1950. The public found the radar rainfall information to be exciting and for several years thereafter the radar was set up at the fair.

More major events occurred in 1951. It was decided to concentrate future field operations at the University of Illinois (UI) Airport located five miles south of Champaign-Urbana so as to have operations and staff closer to the Survey headquarters. The APS-15 radar

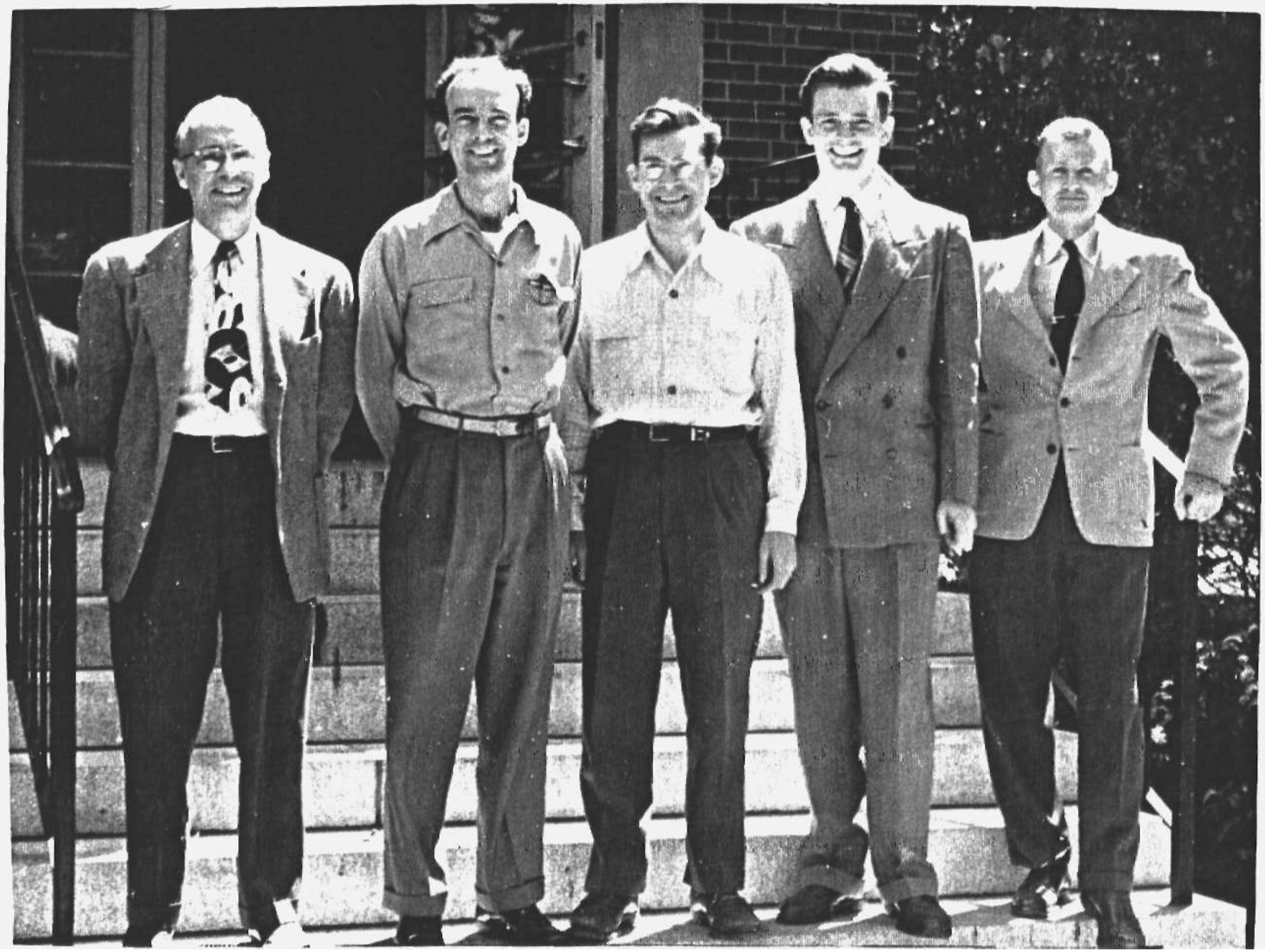


Figure 2-2. The meteorological staff of the Water Survey on the steps of the Survey's new building, in June 1951. The staff (l. to r.) are Floyd Huff, Douglas Jones, Gerald Farnsworth, Glenn Stout, and Homer Hiser.

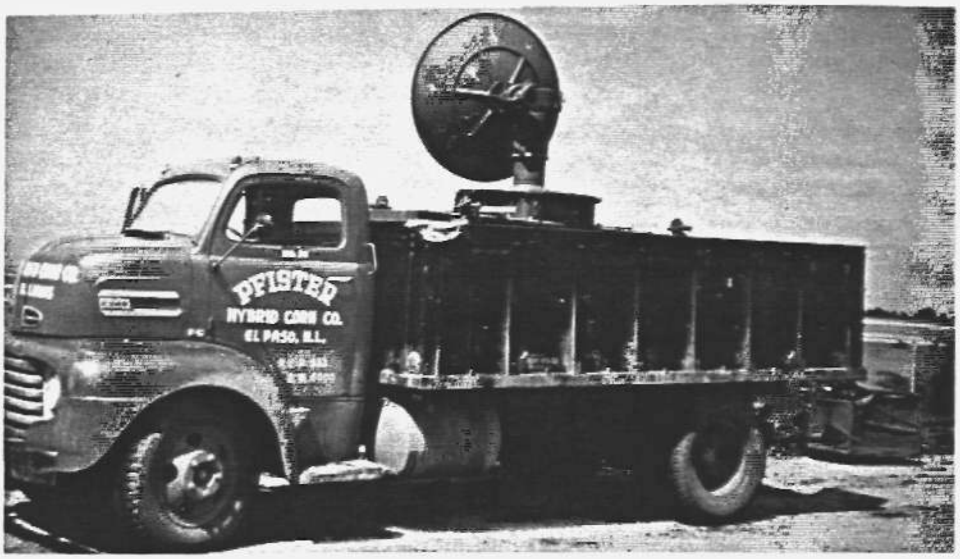


Figure 2-3. The TPL-1 radar antenna being moved to El Paso, Illinois, in 1950 on a Pfister truck for installation. This 10-cm wavelength as to provide rainfall data for the cloud seeding project in the area.

was installed in a small building at the airport, and the TPL-1 radar was also moved to the UI Airport. Figure 2-4 shows the installations (APS-15 left, TPL-1 right) at the "well house" in the north part of the airport. Recording raingages at Farm Creek were moved to the Goose Creek watershed located 20 miles west of the radar site. This 1951 network of 25 gages originally encompassed a 50-square-mile area, but it was later expanded to 50 gages over 96 square miles in 1952. Although me network was designed for the radar-raingage comparative studies, it also provided data useful for hydrometeorological studies.

In June 1950, Dr. James Neill was employed as meteorological analyst and statistician to replace Floyd Huff who had been recalled to active duty as an Air Force weather officer during the Korean conflict. Neill later became the Survey's statistician.

A major meteorological event forever to affect the Survey's meteorological program occurred on the night of July 8-9, 1951. A huge convective rainstorm with 6-hour rainfall amounts exceeding 13 inches occurred in north-central Illinois. These amounts far exceeded the 100-year storm rainfall frequency values at the storm location. As part of the Survey's new hydrometeorological program, it was decided to conduct an extensive field survey using Survey personnel to obtain detailed rainfall measurements not reported by official Weather Bureau raingage stations. The field survey and ensuing analyses provided unique new information on this type of severe storm event. This was the first of 12 severe rainstorms over a 20-year period to be extensively field surveyed. *These surveys provided a wealth of new data and unique information for hydrologic applications and also resulted in five Water Survey reports and several research papers about these unique rainstorms.*

Three papers were written and published in scientific journals during 1951, including (1) "Radar Tracks of Rainstorms for Radio" (Stout and Huff, 1951) published in *Weatherwise,* (2) "Radar—Tomorrow's Raingage" (Hudson et al., 1951) published in *Civil Engineering,* and (3) "A Preliminary Study of Atmospheric Precipitation-Moisture Relationships over Illinois" (Huff and Stout, 1951) published in the *Bulletin of the American Meteorological Society*. Importantly, the Survey's relatively small meteorology program was starting to receive national attention.

Attempts to improve radar measurements of rainfall were also underway in 1951. Farnsworth developed a gain-step device useful for the measurement of varying intensity levels in rainstorms, and this device was integrated into the radar operations. Jones took initial steps in the development of a raindrop camera that would be used to learn more about the size distribution of raindrops in rainstorms. Drop size data was considered essential to improve the accuracy of radar-indicated rainfall amounts since only very limited information was available in 1951 on raindrop-size distributions.

1952-1953: RAPID GROWTH

Major growth occurred in the meteorological research program during 1952. In 1951, the University of Chicago's Meteorology Department expressed interest in using the Survey's meteorological staff and facilities in support of a major cloud physics research project they were launching under a contract with the U.S. Air Force. As a result, a subcontract was negotiated between the Water Survey and the University of Chicago in 1952, which involved operation of the Survey's TPS-10 radar and the Survey's installation and operation of other extensive meteorological instrumentation developed by the University of Chicago's Cloud Physics Laboratory. Sizable funding for this project also provided for the construction of a 40 x 80 foot Quonset building at the UI Airport. After its completion in June 1952, this building housed the entire meteorological staff who moved from a frame house at the corner of Sixth Street and Springfield Avenue in Champaign.

The contract took effect in February 1952, and Stanley A. Changnon, a graduate of the University of Illinois Department of Geography, was transferred from the Survey's Engineering Section to the Meteorology Group to supervise this activity. It is very likely that the Survey's relationship with Dr. Byers was instrumental in awarding this contract to the Survey. Aircraft for atmospheric sampling and experimental cloud seeding were provided by the U.S. Air Force, and these aircraft were housed at nearby Chanute Field. Other staff were added, including Donald Staggs (radar engineer), Jack Fatz (engineer), and several students.

A contract negotiated in early 1952 between the Survey and the U.S. Army Signal Corps called for an extensive literature search on all known methods of measuring precipitation and the preparation of a report summarizing the findings (Kurtyka, 1953). This was considered confidential information at the time, but when cleared by the Army for distribution, the report became widely cited as a monumental review of precipitation measurement techniques.

Another proposal had been made in 1951 to the U.S. Army Signal Corps Engineering Laboratories relating to studies to determine the use of radar for rainfall measurements.

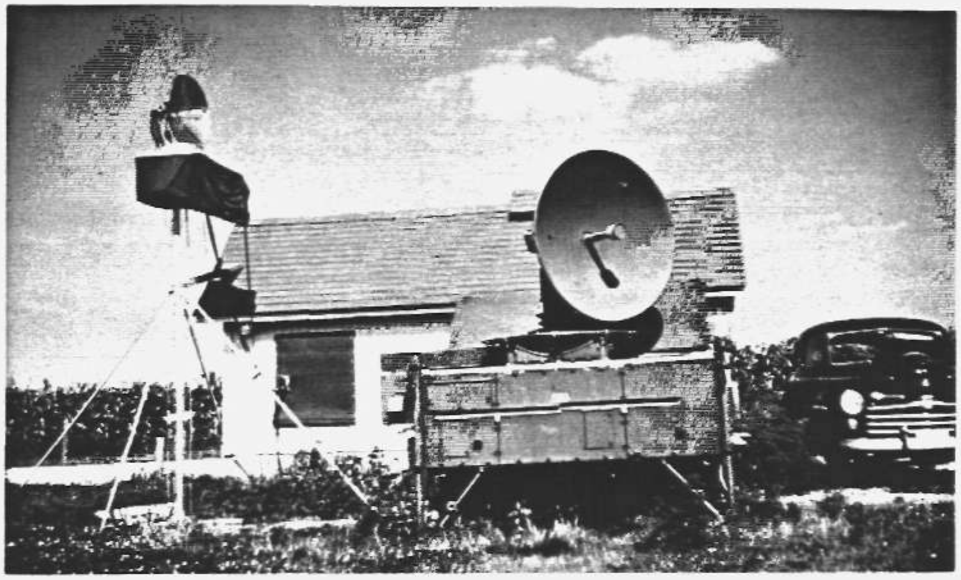


Figure 2-4. The Survey group re-located its field operations from El Paso to Champaign-Urbana in 1951. The two radars, APS-15 (left) and TPL-1 (right) were installed at the well house (where operations were conducted) located at the University of Illinois Airport.

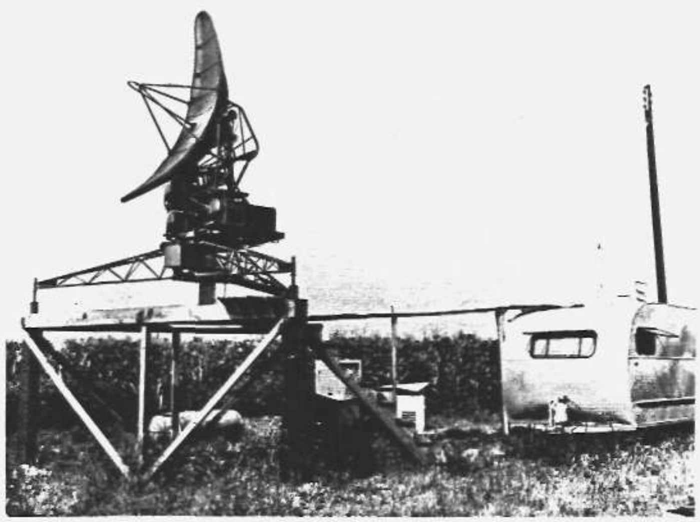


Figure 2-5. The cloud physics project performed by the Survey for the University of Chicago required installation of the TPS-10 radar 18 miles east of the UI Airport in a leased corn field south of Homer, IL. Operations were in 1953-1954. Don Staggs and students built this installation and brought in a rental trailer for operations. This became typical of many more field projects that were to follow in the future.

Although the Signal Corps indicated that funds were not currently available to support this proposal, the Survey was invited to submit a bid for such a research program in January 1952. The bid was accepted, and a contract went into effect on July 1, 1952. This was a relatively large contract ($120,000 per year), and additional meteorologists were employed to help carry out the research. The contract also provided $15,000 for the purchase of additional equipment to facilitate the radar operations and calibration. *This contract and ensuing renewals would prove to be a major source of support for the radar-rainfall research at the Water Survey for more than 15 years.*

A fourth contract was awarded in mid-1952 by the Bureau of Aeronautics, U.S. Navy, and involved use of radar data and rainfall data from the dense raingage network on the Panther Creek watershed to determine the effectiveness of radar as a forecasting aid (Hiser and Bigler, 1953). This series of contracts obtained in 1952 revealed the Survey team had made a good decision when it decided to concentrate its research efforts on radar meteorology and hydrometeorology, following the rainmaking experience in 1948-1949. Another long-term trend also began in 1952—*the development and dependence on "soft" money from federal grants and contracts to sustain the meteorology program.*

Instrument development progressed steadily in 1952 as work continued on the raindrop camera and on the area integrator, a device Farnsworth was developing for calculating radar-indicated areal mean rainfall over any selected area at intervals of one minute or longer. This device was essential not only in evaluating experimental results, but also necessary in any practical application of radar for rainfall measurements over areas (basins, cities, etc.). A TPS-10, RHI radar was obtained on loan from the Signal Corps to assist in the radar-rainfall measurement program, and a K-band (1.35 cm) radar was operated for the Chicago Cloud Physics project during this period. At the end of 1952, four radars were available for operations at the Survey's Meteorology Lab (APS-15, TPL-1, TPS-10, and K-Band). Special equipment was installed, including an impactor for sampling aerosols and two panoramic cameras from the University of Chicago for cloud photography, and the TPS-10 radar was installed at a remote site 18 miles east of the airport (and away from the two camera sites) to collect data on clouds being routinely photographed near Champaign (fig. 2-6).

In addition to several contract reports, two papers were published in professional journals during 1952-1953. "Area-depth Studies for Thunderstorm Rainfall in Illinois" presented a method for calculating the spatial distribution of rainfall in convective storms (Huff and Stout, 1952). The second paper described the genesis of an Illinois tornado identified by radar in April 1953 (Stout and Huff, 1953). Most of the staff effort during this period was devoted to the operation of the radars and dense raingage networks as well as processing data from these operations. All radar scope film was developed in a dark room built within the Survey's Quonset building.

Research launched under the various projects awarded in 1952 continued in 1953. Construction of the raindrop camera was completed, and observations began from its location at the UI Airport. Work was also completed on the area integrator, which was placed in operation on the radar-rainfall project. Major field operations were pursued during March-October 1993 in support of the Cloud Physics and the Signal Corps projects.

On April 9, 1953, a major tornado traversed a southwest-northeast course about 15 miles north of Champaign. Fortunately, the APS-15 radar was in operation at the UI Airport, putting the storm 20 miles away. The storm was seen clearly on radar and photographed throughout its course (fig. 2-6). After a field survey a detailed meteorological study was performed. This special study led to the discovery that radar could detect tornadoes of significant size and intensity, and that they could be identified by a hook-shaped echo (figure 6 shape) located on the southwest edge of the parent thunderstorm echo, a finding that garnered considerable national prestige for the Survey's meteorological team and its programs.

A major administrative change occurred in 1953: the growth of the Meteorology Group was of sufficient magnitude to consider its separation from the Engineering Section. A new Meteorology Section was established and headed by Glenn Stout, who had served as the group's

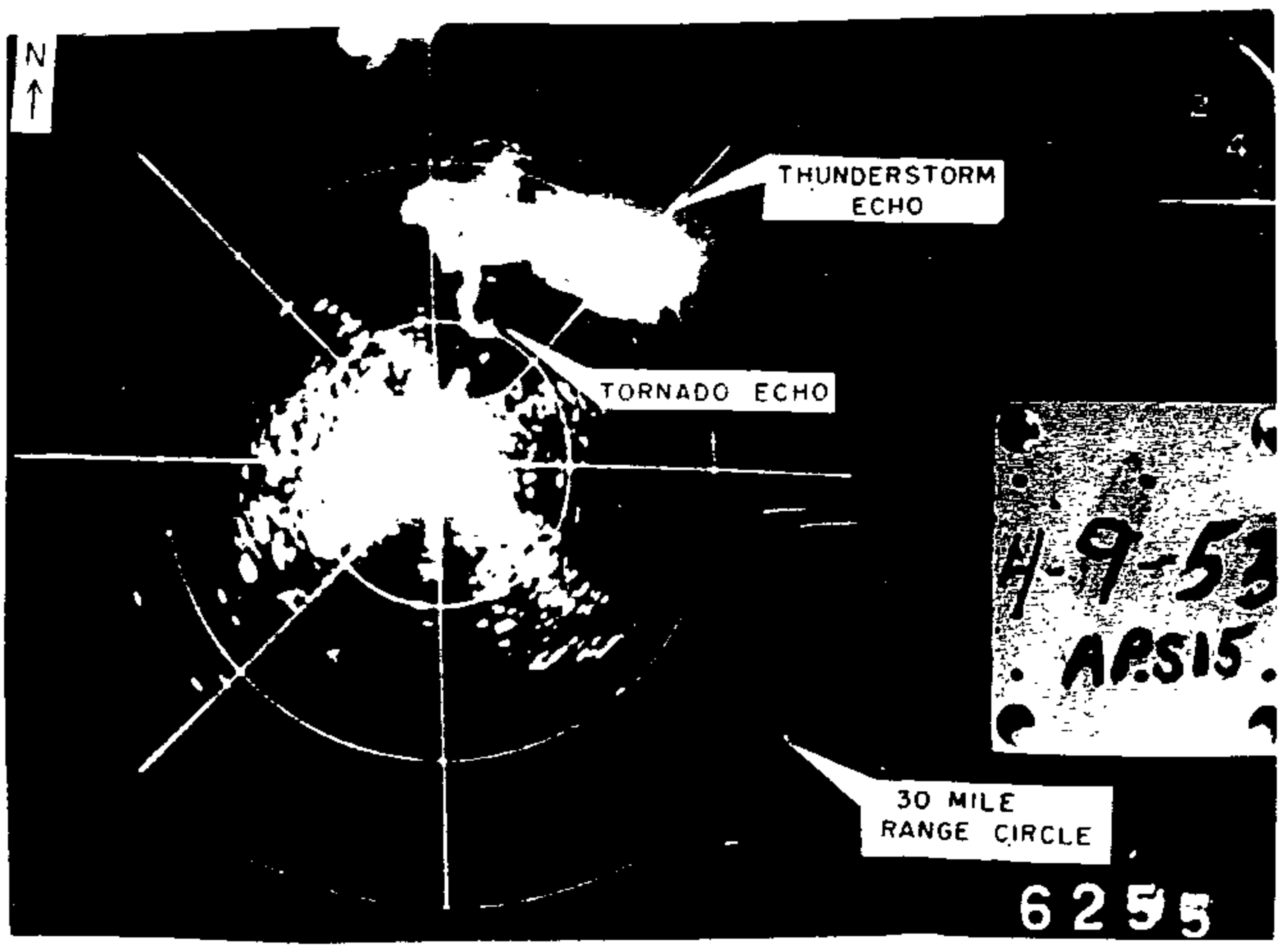


Figure 2-6. The Survey collected the first radar photographs of a tornado, illustrating the capability of weather radars for storm detection. This scope photograph of the APS-15 shows the hook-shaped echo extending south from a storm echo north of the radar and Us ground clutter. The hook was the tornado funnel. This event made national news and helped get the Survey's weather program more visibility in the scientific community.

administrative supervisor in the Engineering Section. Floyd Huff returned from his Air Force tour in late 1952, and was assigned technical supervision of the meteorological research. Staffing at the end of 1953 included: Stuart Bigler, Stanley Changnon, Gerald Farnsworth, Jack Fatz, Floyd Huff, Homer Hiser, Douglas Jones, Eugene Mueller, James Neill, Donald Staggs, and Glenn Stout.

MAJOR EVENTS

The most important decision made during the formative years occurred in late 1949 after the abortive cloud-seeding effort; it was decided to continue the weather research program but to concentrate the meteorological activities in radar meteorology and hydrometeorology. Historical interest and needs for information in these fields expanded rapidly in the 1950s. Growth of the Survey's meteorology program became highly dependent on attracting research funds from federal sources. This 1949 decision led to the development of weather radar facilities and installation of dense raingage networks. Such facilities and related research activities brought national attention to the Survey's weather group and provided the incentives for obtaining the early contracts from the University of Chicago, the U.S. Army Signal Corps, and the U.S. Navy Bureau of Aeronautics.

Another important development that helped the Survey's research programs in future years occurred in 1951. This was the decision to conduct comprehensive field surveys and detailed meteorological analyses of severe rainstorms occurring in Illinois, which ultimately provided basic input to our expanding hydrometeorological research on the time and space distribution of flood-producing rainstorms. This decision resulted form the rainfall information and new knowledge obtained from the initial field survey of the north-central Illinois storm in July 1951.

Another severe weather event, the April 1953 tornado, enabled the Survey to be the nation's first group to observe and track a tornado using radar. This capability won national acclaim for the Survey's meteorological program.

Development of instruments to improve the use of radar for the measurement of rainfall was another key contribution. These developments included the gain-step device, the raindrop camera, and the area integrator, all of which facilitated and improved the use of radar for rainfall measurement. Analytical sampling and analysis procedures were also developed for evaluating radar rainfall measurements.

The events of 1947-1953 served as the foundation for the future meteorological program of the Water Survey: (1) the rainfall measurement emphasis (radars, raingages, and supporting devices); (2) the hydrometeorological research program, and (3) the focus on studies of severe storms. These all became research themes that have continued to this day. Nine major program areas developed, including the measurement of precipitation, hydrometeorology, climate research and services, planned weather modification, inadvertent weather modification and climate change, atmospheric chemistry, cloud and precipitation formation, impacts of weather and climate, and planning and assessment of research and policy. Each program area is discussed separately (Chapters 3-11).

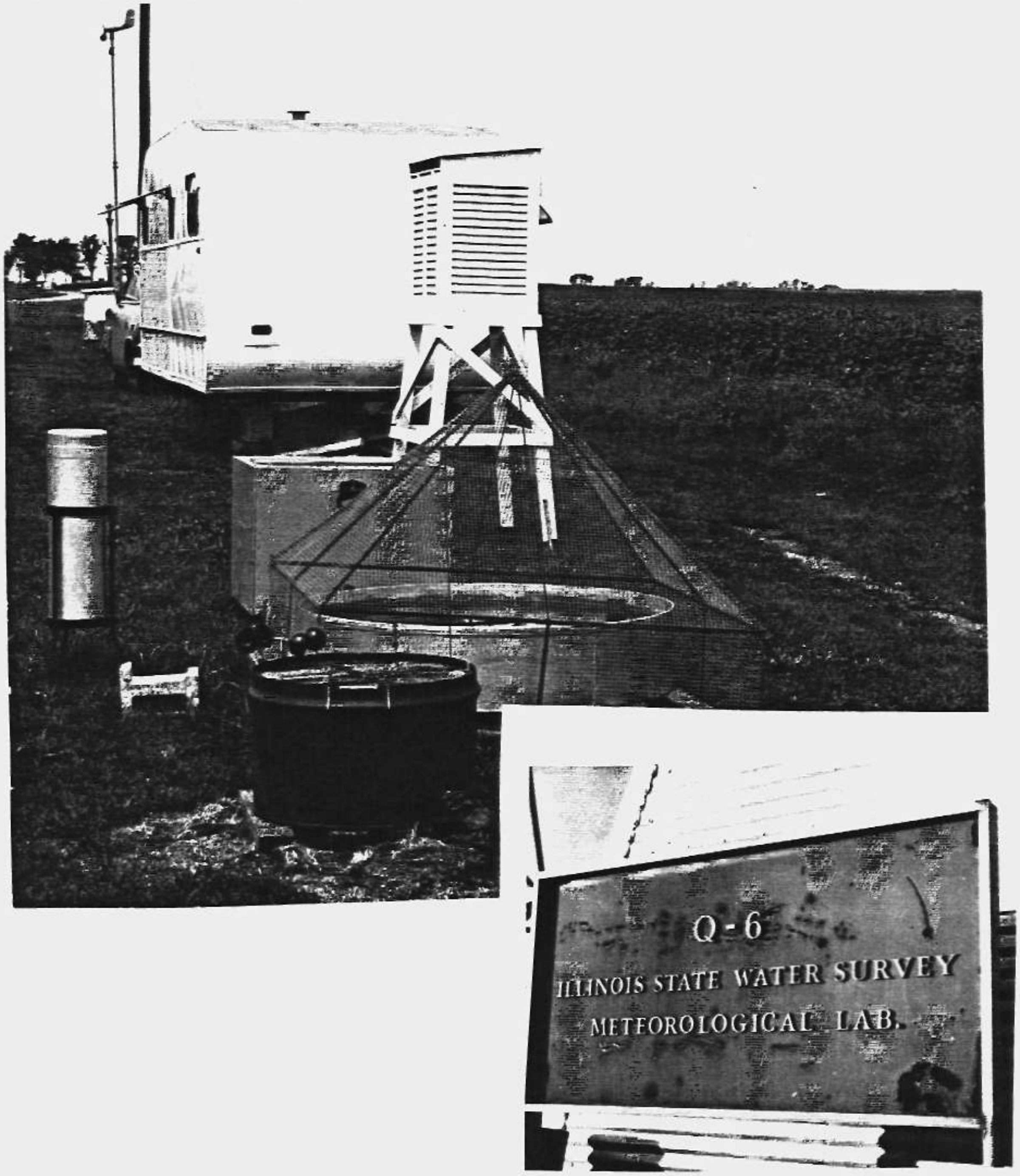


Figure 2-7. The end of the formative years saw the start of field research west of Champaign. The upper photograph is of the 1966 field station near De Land, IL, with a rented house trailer for equipment recorders and a host of instruments including a home-made evaporation pan made from a oil barrel (foreground). The home of the group was in a quonset building numbered Q-6, the Meteorology Lab at the University of Illinois Airport.

Chapter 3

MEASUREMENT OF PRECIPITATION

Stanley A. Changnon and Floyd A. Huff

INTRODUCTION

The longest running major program of the Atmospheric Sciences Group at the Water Survey has involved the measurement of precipitation. As was described in Chapter 2, the measurement of rainfall, with a surplus military radar and a network of raingages, was the first activity of the fledgling Meteorology Group in 1948. In 1995, the Water Survey is still measuring precipitation in two dense raingage networks operating in Illinois, as well as from raingages at the Urbana weather station, the Bondville field site, and at the 20 sites of the Illinois Climate Network.

Delineating activities under the banner of "precipitation measurements" was not easy because several of the other major program areas involved measurements and analyses of precipitation. The authors chose to separate the measurement activities and studies by their purpose; hence, the precipitation research directed to topics such as climate change, weather modification, and hydrometeorology is addressed by those topics in separate chapters. For example, the many studies of rainfall at St. Louis pertaining to measuring and understanding the urban influence on rainfall were classified as "inadvertent weather modification" (see Chapter 7). However, a review of the Survey raingage networks, including the one at St. Louis, was classified under "precipitation measurements." Figure 3-1 shows many of the weather networks around Illinois and their names. This chapter covers topics such as *how rain was measured, what radars were used for measurements, the shape of raindrops, methods to measure hail and its variability across short distances, and rainfall characteristics as measured by radar and by raingages*. There is a strong emphasis on instrumentation, methodology, and comparison of precipitation measurements from different sources or types of instruments. Also included are some basic measurements of precipitation characteristics (typically of rain and hail) and conditions, particularly as they pertain to measurement methods and their accuracy.

The early and long-lasting impetus of the precipitation measurement program is related to *the use of radar to measure various forms of precipitation,* particularly rainfall. By the late 1960s, the impetus had shifted more towards rainfall measurements from raingage networks and the applications of radar to measurements of hail, in-storm motions, and other phenomena, including insect pests. The radar-rainfall emphasis from 1948 to 1967 led to a three-tiered sequence of activities involving surface "ground-truth" measurements. Several raingage networks

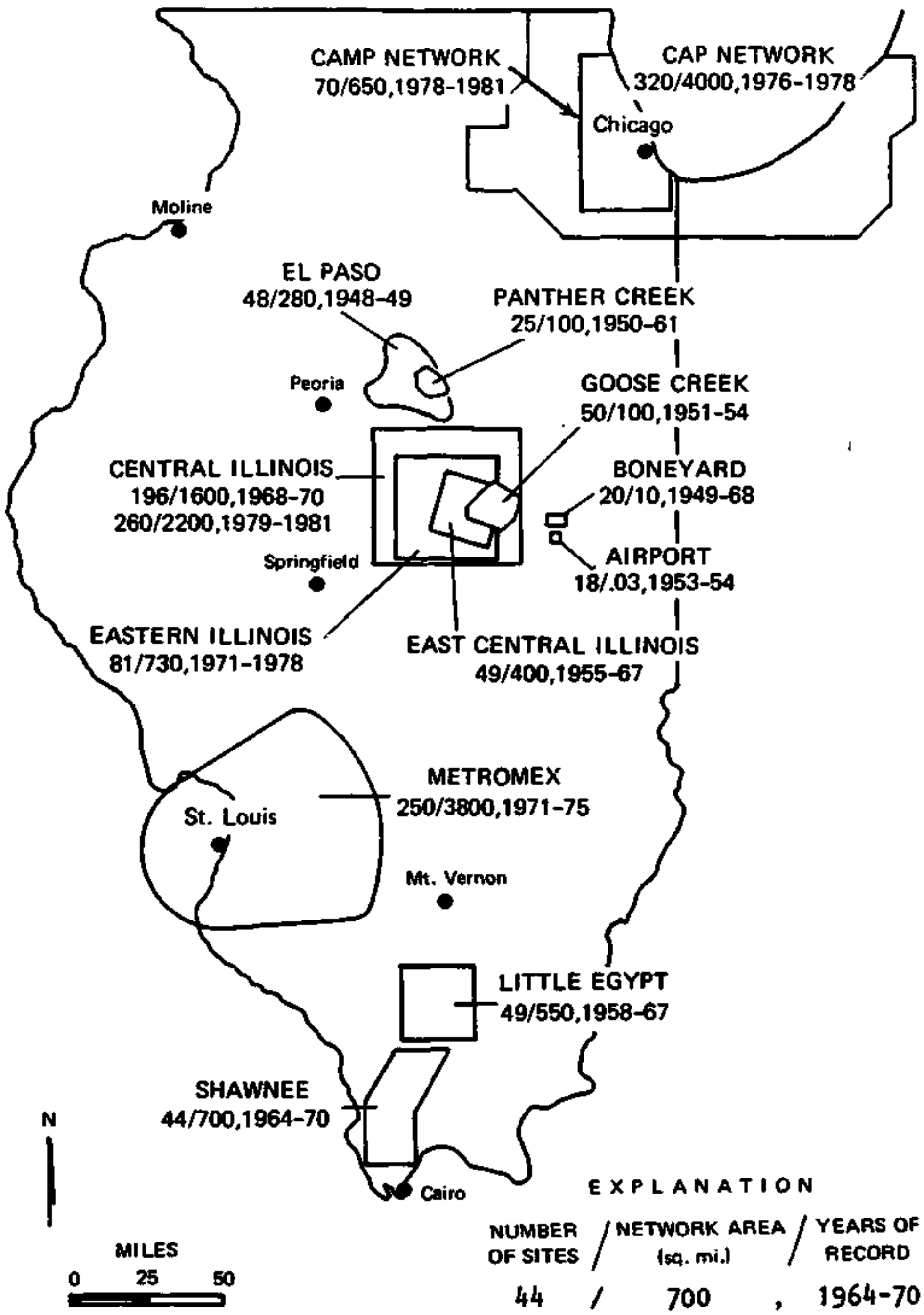


Figure 3-1. The dense raingage networks operated in Illinois by the Water Survey between 1947 and 1981. They are named and years of operation are indicated.

were established in central Illinois to measure rainfall for comparison with radar measurements, each entailing network installation and operation, data extraction, and analysis. This same sequence was followed for several hail networks that involved observers, hail pads and other hail sensors, and crop-loss data from insurance assessors. A third major ground-truth effort involved the measurement and study of raindrops since their sizes and frequency per unit volume determine what a radar measures as rain. The 12-year series of raindrop projects involved surface instrumentation, data collection at 12 sites throughout the world, very laborious data extraction, and finally research. Figure 3-2 shows the Survey's raindrop camera installation in central Illinois. Many other instruments were designed and tested as part of the evaluation and use of the weather radars at the Survey.

Reflection on the myriad of activities and projects within the realm of precipitation measurements reveals two recurring themes: 1) the work was heavily dependent on external funding from federal agencies, and 2) the projects were supported by several long-lasting federal grants/contracts. For example, funding from the U.S. Army Signal Corps to collect data and study radar-rainfall relationships began in 1951 (see Chapter 2) and lasted through 1967. Similarly, the Crop-Hail Insurance Actuarial Association (CHIAA) supported a 14-year effort (1959-1972) that involved various studies of surface hail, ranging from point measurements of hailstone sizes up to field investigations of the hail patterns in major storms. The National Science Foundation (NSF) supported a series of proposals that involved studies of surface hail with networks and radars from 1967 to 1976, as well as the development, testing, operations (at many sites around the nation), and maintenance of the CHILL (University of CHicago-*ILL*inois State Water Survey) radar system from 1969 through 1989.

These complicated, often expensive projects required longevity to complete 1) the project design, 2) acquisition and installation of the instrumentation, 3) simultaneous operation of several pieces of equipment involving extremely accurate timing and definitive measurements, 4) careful interpretation of the values measured by each instrument, and 5) data interpretation and derivation of results. Such complex operations and analyses were very labor intensive because they required a variety of skills and expertise from electrical engineers, scientists, field and radar technicians, shop workers, and data analysts. *The "crew of experts" assembled at the Water Survey to perform these complex field operations was unique and unmatched by staff at any other weather institution in the nation from 1950 to the late 1980s.*

Project activities repeated each year from April until October 1948 to 1967 by the Water Survey involved: 1) operating one or more radars during each rain event, 2) photographing the radar scope (with gain-step reductions to measure the heavier rain), 3) developing the resulting film, and 4) frame-by-frame scrutiny by analysts using projectors in darkened projection rooms. Simultaneously, a network of 40 to 200 recording raingages (the number varied from year to year to satisfy changing objectives) was operated somewhere west of the radar site at the University of Illinois (UI) Willard Airport. The Goose Creek and East Central Networks (figure 3-1) were the primary networks used for radar-rainfall comparative studies during 1951-1967. Each weighing bucket raingage (see fig. 3-3) was calibrated frequently and set for careful timing to obtain 1- or 5-minute amounts, and each gage was visited after each rain event to change the

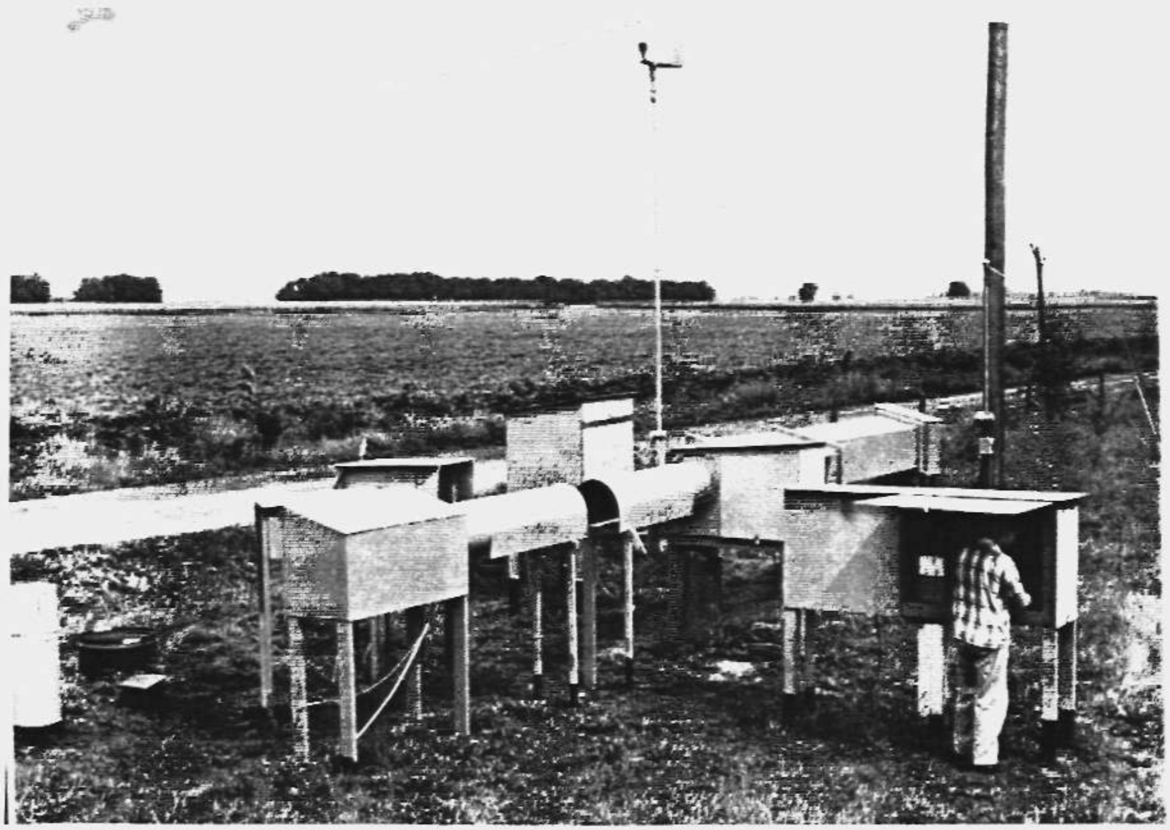


Figure 3-2. The Survey's unique raindrop camera shown at its installation in rural central Illinois in 1955.

Figure 3-3. Field station #136 in the Central Illinois Network during 1970 showing (l.to r.) a weighing-bucket recording raingage, a Survey designed and built recording hailgage, an anemometer (behind the hailgage), a hail pad, and a plastic rainwater collector. The hail pad was a one square foot foam block (1-inch thick) covered with aluminum foil and it recorded as dents any hailstones that fell.

recording charts. The charts were then carefully analyzed with respect to time and gage calibrations, rain amounts were measured at each interval, and then isohyetal maps were prepared for each 1-minute or 5-minute interval and for the total storm. The device used after 1962 for strip chart analysis and direct digitization of data is shown in figure 3-4. The amounts from the gages were then used in direct comparisons with the radar-indicated rain amounts plotted on maps.

Typical operations of several hail networks during 1959-1961 and again during 1968-1975, involved obtaining reports of hail (time of occurrence, hail sizes, and number of stones) from hundreds of volunteer observers recruited in central Illinois, and the measurement of hailstone dents in hail pads, hail stools, and hail cubes, instruments all invented by Survey scientists (fig. 3-3). Times at which hail occurred were determined from recording raingages modified to also record hail. Reports of crop-hail damages were obtained from in-field measurements by hail adjustors along with data from special hail-recording devices (fig. 3-3) designed and built by Survey engineers and technicians (Mueller and Changnon, 1970). Figure 3-5 shows the detailed pattern of a crop-damaging hailstorm studied in great detail by Survey scientists and hired hail adjustors.

After 1967, design and operation of the dense raingage networks were shifted to serve other purposes, including studies of rainfall variability, heavy rainstorms, evidence of rainfall modification by large urban areas or due to cloud-seeding experiments, amount of precipitation over discrete areas, and rain patterns to test and verify mesoscale rainfall forecasting. In 1980, the Survey launched the Illinois Climate Network (ICN), with raingages located at 20 stations scattered across the state. Since 1989, the Survey has operated a raingage network in the Chicago area to provide data as part of the Lake Michigan diversion monitoring effort of the U. S. Army Corps of Engineers. The hail networks operated after 1968 were used for several purposes, including comparison with radar echoes for hail detection, studies of hail variability on various spatial scales, and the relation of hail characteristics including wind to crop damages.

Operations and testing of weather radars after 1967 were focused largely on hail studies in Illinois (1968-1975); on use of the CHILL radar as a "national" facility for measuring hail, rain, atmospheric motions (Doppler measured); and on measurements of insect pests. Operations were performed at various locations, including Colorado (1971-1976), northern and central Illinois, Michigan, North Dakota, and Oklahoma. Some of these operations served the needs of non-Water Survey scientific projects. The Hydrologic Operational Tool (HOT) radar was developed with NSF funding for use in the Metropolitan Meteorological Experiment (METROMEX) during 1974-1975. The HOT radar was later used in the Chicago Area Project (CAP) for urban and lake rainfall studies and for rainfall measurements in the Precipitation Augmentation for Crops Experiment (PACE) weather modification experiments in 1986 and 1989. The Survey stopped using its weather radars in 1990, ending 44 years of highly valuable operations and research. The Water Survey still possess the HOT radar but has no staff to operate or maintain it.

Figure 3-4. Analyst Ileah Trover seen operating the Oscar chart reading system in 1963. This was used to follow the trace on the chart and to simultaneously digitize the values at discrete intervals onto IBM punch cards.

Table 3-1 shows the number of publications issued relating to measurements of precipitation from 1948 to 1995. Several interesting trends become obvious. First, there is a large number of publications in the contract report category (83)—many of these (24) were progress reports issued quarterly to fulfill contract requirements and most of these describe the work in progress. The number of scientific papers published during the early years (1948-1965) that focused on the radar-rainfall research was low, only 5 in 17 years. This suggests a lack of attention to publishing scientific papers in this major area of work, which was consumed by operations and data collection. However, several state reports (13) were issued during the 1951-1958 period describing the radar and raingage results, and four of these were scientific papers

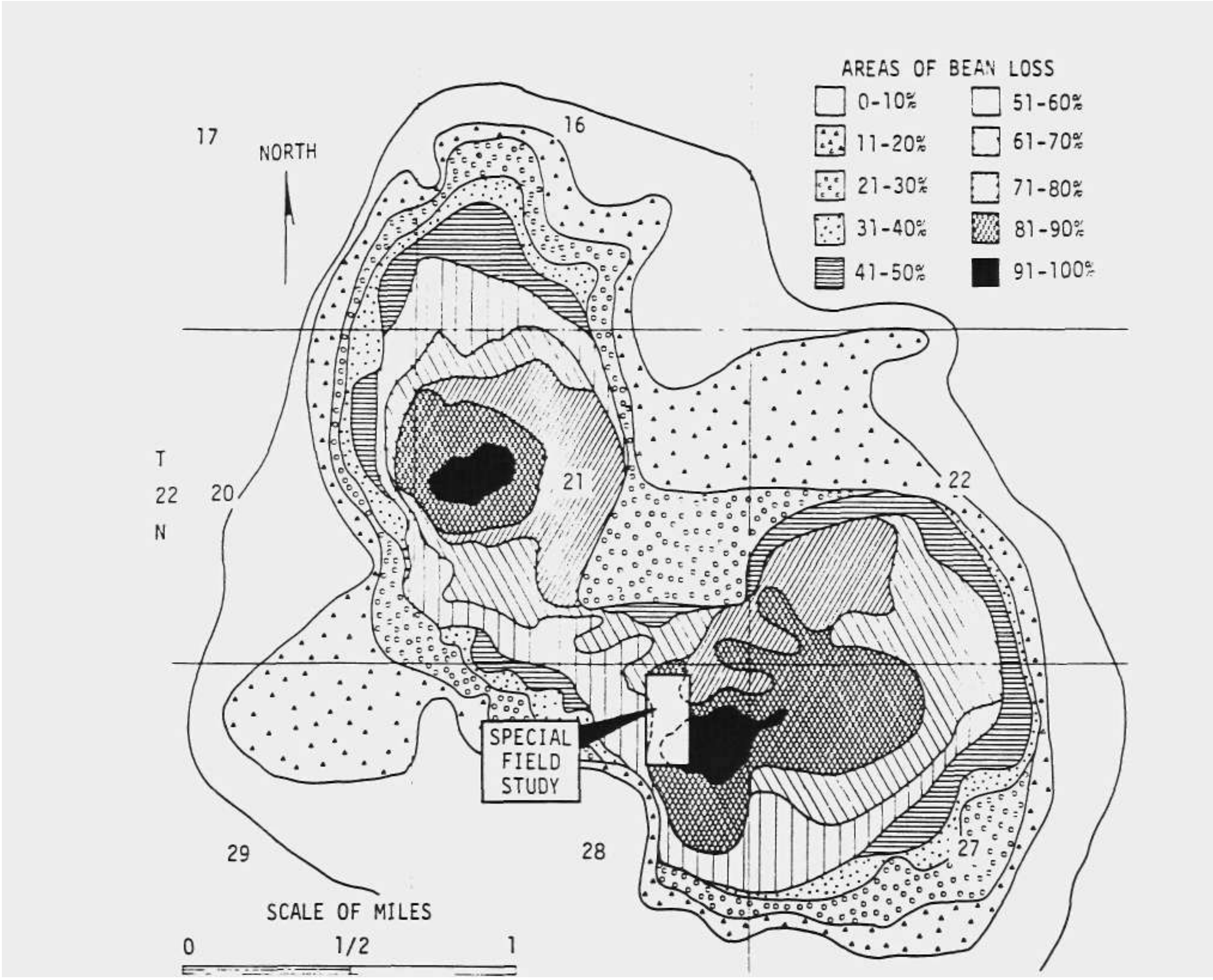


Figure 3-5. The detailed crop-loss pattern for a hailstorm that occurred in central Illinois. The data were collected by two hail adjustors working for the Water Survey.

issued as state publications. The increase in papers beginning in 1966 and lasting through 1980 was largely due to the hail research projects. Assessment of the 173 publications and the direct involvement of the authors in much of the precipitation program were the basis for identifying the major themes of activities under the banner of "precipitation measurements." Assessment led to the identification of three major themes that were interrelated.

First and foremost among these themes was *the measurement of rainfall.* As explained in Chapter 2, this work was initiated in 1948 in support of the Pfister instigated project to evaluate rainmaking near El Paso, IL, and it was driven after 1950 by the new group's interest in assessing the capability of weather radar to quantitatively measure rain. Radar and raingage data collected since 1948 have been used in numerous studies of rainfall characteristics in space and time. With no significant topographic features, the flatlands of central Illinois allowed direct assessment of "natural rainfall variability" as a strict result of atmospheric processes. Considerable attention was devoted to the measurement and analysis of raindrops. As mentioned previously, the rain measurement projects were largely funded by federal agencies. State funds were used to pay salaries of a few senior staff.

Table 3-1. Number of Publications Issued Relating to Precipitation Measurements during the 1948-1995 Period

		Reports		
Years	*Papers*	*State series*	*Contract*	*Total*
1948-1950	0	1	0	1
1951-1953	1	5	6	12
1954-1956	0	5	3	8
1957-1959	1	3	4	8
1960-1962	1	0	9	10
1963-1965	2	0	10	12
1966-1968	10	0	16	26
1969-1971	7	0	13	20
1972-1974	3	1	5	9
1975-1977	11	0	5	16
1978-1980	7	2	2	11
1981-1983	6	1	1	8
1984-1986	8	0	0	8
1987-1989	3	3	3	9
1990-1992	5	1	3	9
1993-1995	3	0	3	6

The second research theme involved *studies of severe storms*. These extensive field projects dealt largely with measuring hailstorms and surface hailfalls for various applications, including storm avoidance by aircraft, hail insurance, and evaluation of hail suppression. The Survey's early detection of a tornado by radar (described in Chapter 2) also set the stage for occasional radar-related studies of other tornadic storms and damaging thunderstorms, and in later years this research benefitted by Doppler wind and airflow measurements from the CHILL radar.

The third theme involved the *development and assessment of instruments* for use in precipitation measurements: instruments to improve radar measurements, surface instruments to measure rain and hail, and use of other forms of remote sensing including aerial photography, to assess hail damage to crops. Much of this work was motivated by the need to improve or test radar measurements and to gather data on precipitation at the surface. Certain Water Survey radars were also used to detect and track the flights of waterfowl or insects.

MEASUREMENT OF RAINFALL

Radar

The first radar-rainfall studies resulted in one the earliest state publications from the new Meteorology Group (Stout and Huff, 1949). The 1951 dedication of the new (and first) building for the Illinois State Water Survey was commemorated by the Survey hosting the nation's first "weather radar conference" at the Allerton Estate in Monticello, IL (Water Survey, 1951). This event and the Survey's early radar work based on the El Paso projects of 1948 and 1949 made the Survey a key player in the nation's developing research endeavors relating to radar measurements of rainfall, a position the Survey's radar-rainfall research would hold into the early 1980s. Table 3-2 lists the 18 various weather radars the Water Survey tested and operated during the 1948-1990 period.

In 1951 the Water Survey group entered into a contract with the U.S. Signal Corps (SC) to define the capability of 3-em wavelength weather radars to measure and quantify the rainfall

Table 3-2. Radars Used for Weather Research at the State Water Survey during 1948-1990

Type	*Wavelength, cm*	*Scan type*	*Research application*[1]
AN/APS-15	3	PPI	P, WM, SS
TPL-1	10	PPI	P
AN/APS-4	3	X-Y	BT
SC-545	10	PPI	P
AN/APS-34	1.25	3-D	C
TPS-10	3	RHI	C, H, SS, P, WM
CPS-9	3	CAPPI	P, SS, H
AN/APS-31	3	PPI	BT
M-33X	3	PPI, XYZ	P, BaT
M-33S	10	PPI	P
GPG	3	CAPPI	C
MPS-6	6.7	RHI	P, SS
APQ-39	0.866	V-P	C
APS-69	3	X-Y	C
MPS-34	3	CAPPI	P
AN/APS-36	23	PPI	P
CHILL	3 and 10	CAPPI	P, H, SS, S, Po, WM
HOT	10	CAPPI	P, WM

[1] The applications are coded as follows: P=precipitation, WM=weather modification, SS=severe storms, BT=bird or fowl tracking, IT=insect tracking, H=hail, C=cloud properties, S=snow, Po=polarization, and BaT=balloon tracking.

over an area; the SC's interests were related to military applications on the battlefield, and the use of small antenna, low-powered radars was seen as essential for this purpose. The SC program was handled by Donald Swingle of the SC who promoted the 3-cm radar for this purpose, and who was to sizably fund the Survey's radar-rain research from 1951-1967.

As radar and raingage data from the early 1950s were analyzed (figure 3-6), Survey scientists and radar engineers realized the 3-cm radar approach to quantifying rainfall had serious drawbacks. First, a method for rapidly integrating the radar signal data over a fixed area, for example, 400 square miles, had to be resolved. Second, the radar-rainfall relationship depended heavily on the shape, size, and number of raindrops (per unit volume of the atmosphere) being sampled by the radar beam, and in the early 1950s there was no adequate information about raindrops and the backscattering from raindrops (Mathur, 1955). Third, 3-cm wavelength radar signals were attenuated by heavy rain, which meant that rains behind a storm core could not be adequately measured. Fourth, in 1951 the Survey lacked a 3-cm radar system designed specifically for rainfall studies; available radars had been designed for use in aircraft or surface vehicles to sense aircraft and other objects including rain. The evolving measurement projects attempted to address and solve these problems.

The first "contract" report focused on results from the 1951 radar-rainfall data based on measurements with a 3-cm radar and raingages located just west of the radar near Champaign (Stout et al., 1951). Many more such progress reports would follow over the next 16 years. Results of the radar-rainfall analyses of the 1952 data were summarized next (Neill, 1953a, 1953b). Changnon (1953) reviewed the principles and procedures involved in radar-rainfall measurements, and Buswell et al. (1954) summarized results from the 1948-1952 Survey radar studies. In 1954, the Survey acquired a model of the new 3-cm radar (a CPS-9) designed specifically for weather purposes and supposedly capable of satisfactorily addressing the problem of earlier radars. The long sought development of the "area integrator" for averaging radar signal over an area and needed for area rain estimates was completed and tested satisfactorily in 1955 (Farnsworth and Mueller, 1956). Interestingly enough, 1956 marked the end of state reports devoted to rainfall measurements until 1979.

Huff et al. (1956) discussed the 1951-1954 results from the continuing radar-rainfall studies, and Mueller (1958a) assessed the use of the new CPS-9 radar, and reviewed efforts to handle the rain measurement problems, including those related to measuring raindrops and needs for other radar instruments to improve rain estimates. Stout (1960a) reviewed the Survey's radar-rain results up to 1958 and suggested use of radar for tracking severe storms. Figure 3-7 depicts the Survey's quonset building (which by this time had been lengthened) in 1958, and on the towers (left to right) are the MPS-6, the CPS-9, and the TPS-10 radars. As part of an Air Force contract, Changnon and Huff (1961) analyzed lines of rainfall echoes, as measured by Survey radars since 1951, to develop a climatic description of line characteristics (figure 3-8).

Mueller (1961) issued the first of 14 quarterly reports on the Signal Corps funded contracts during 1962 (4 reports), 1963 (3), 1964 (2), 1965 (2), and 1966 (3) about the progress of the radar-rain measurements and the results of raindrop measurements at various global

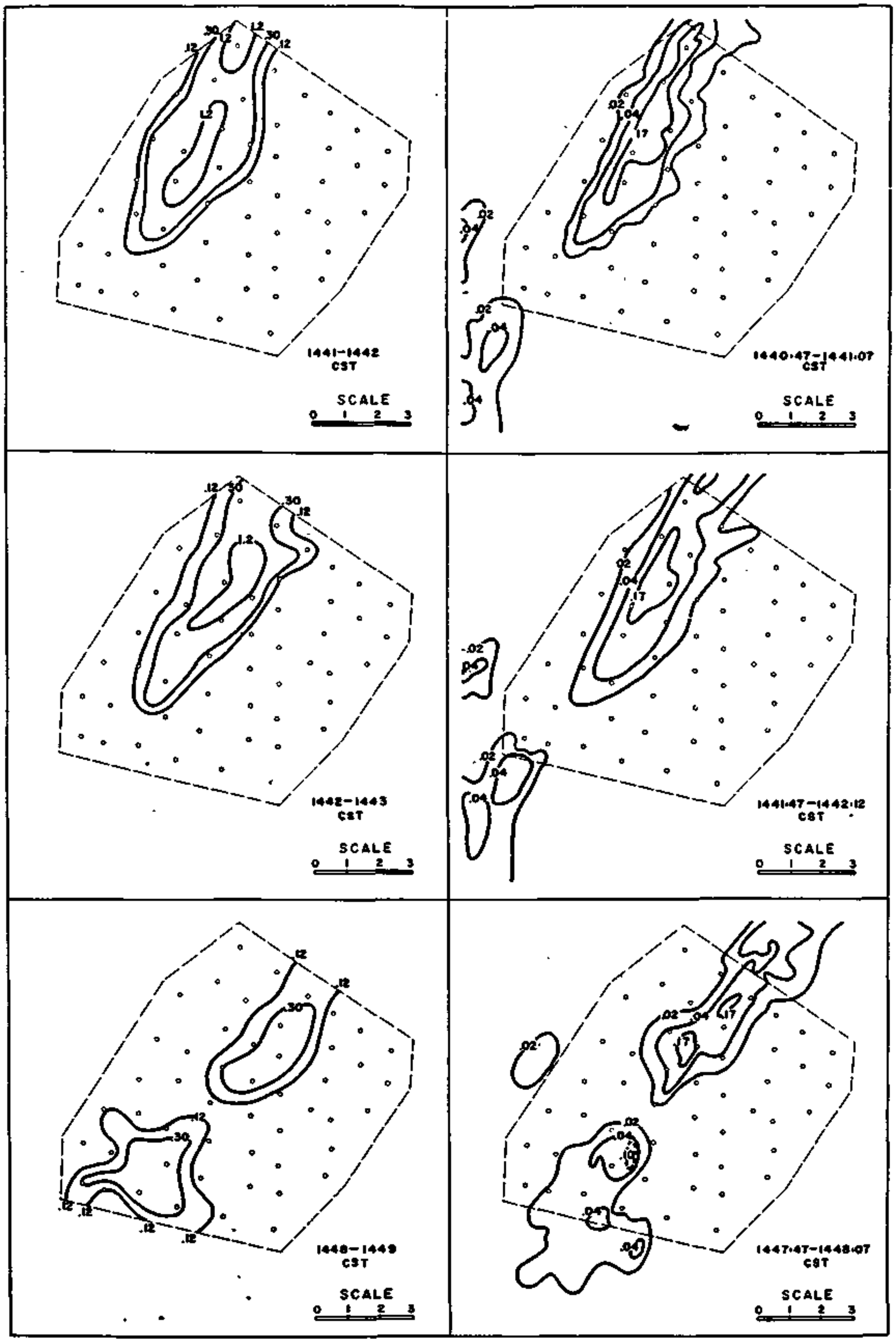


Figure 3-6. A series of isohyetal maps from one of the many comparative studies of rainfall as measured by radar (right) and by raingages (left) for a series of one-minute periods.

Figure 3-7. A view to the northwest of the "Q-6" the Survey's quonset building at the University of Illinois Airport. This photograph, taken in 1958, shows three radars on the towers: Left to right, the MPS-6, the CPS-9, and the TPS-10.

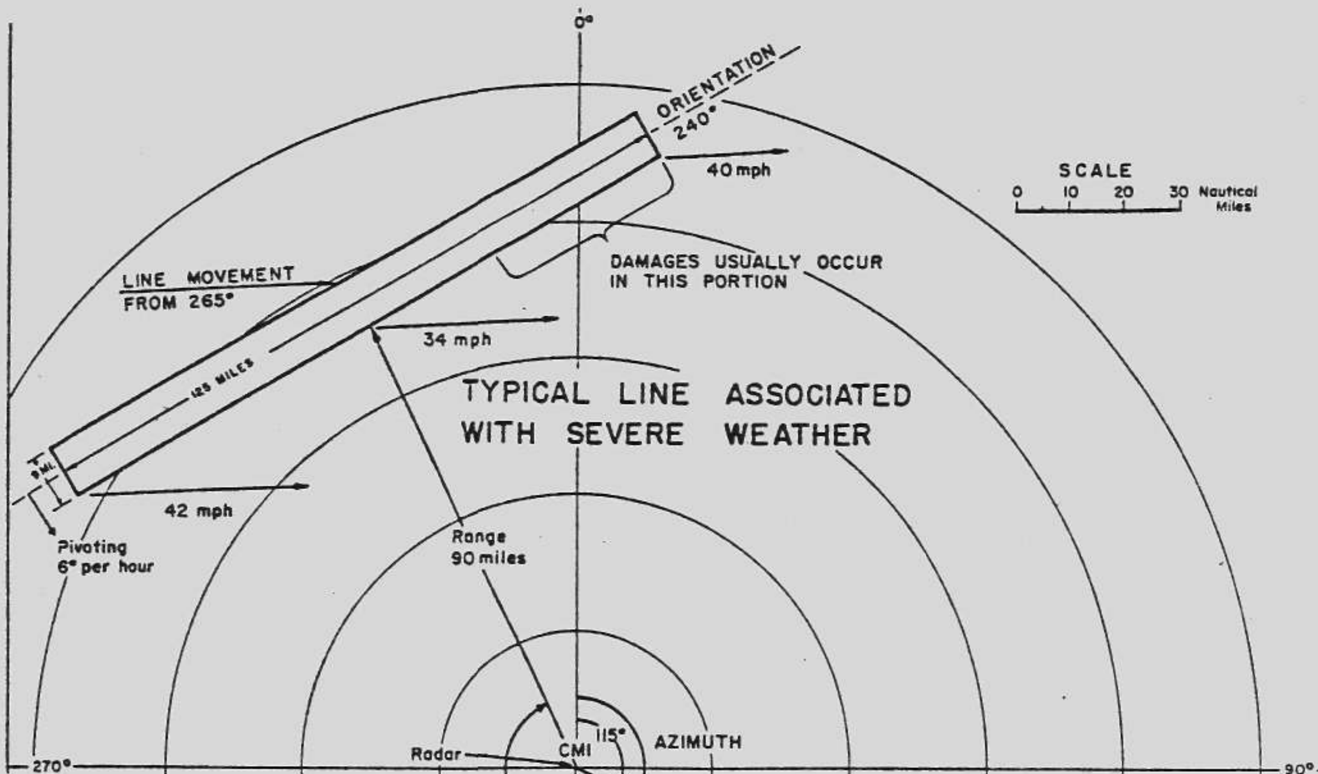


Figure 3-8. The average radar-indicated line associated with severe weather in Illinois, as developed from a study of 123 lines measured by Water Survey radars (Huff and Changnon, 1962).

locations. Sims et al. (1964) summarized the 1961-1964 project work and presented radar-reflectivity relationships (based on raindrop size distributions) to use in different climatic regions. Changnon and Huff (1966) examined the optimum form for radar use to measure rainfall over Lake Michigan. Mueller (1966) assessed the radar cross sections and drop size spectra results and reviewed the accuracy attainable with 3-cm radar-rainfall measurements.

A field project involving Survey scientists and funded by NSF involved radar measurements of warm rain processes in Hawaii during 1965, one of the Survey's first efforts to join in larger scale field projects with other scientists (Semonin et al., 1967). Ways to adjust radar measurements of storm mean rainfall using surface raingage data were offered and showed major improvements in the radar estimates (Huff, 1967a). A major report summarized the research on radar-rainfall relations using 3-cm radars from 1951 to 1967 (Stout et al., 1968).

After Signal Corps support ended in 1967, Survey scientists and radar engineers sought resources to acquire a new 10-cm wavelength radar which was recognized to be best for rainfall measurements, for the group's emerging programs in planned weather modification (Chapter 6) and inadvertent weather modification (Chapter 7). Changnon appealed to NSF based on the Survey's long credible history in radar meteorology and staff expertise, and Fred White (head of meteorology at NSF) suggested we collaborate with University of Chicago scientists David Atlas and Peter Eccles, who had designed a sophisticated dual (3- and 10-cm) wavelength radar system with polarization and Doppler capabilities. An institutional "marriage" was arranged, NSF funding began in 1968, and the Survey engineering staff began building and testing the unique CHILL radar system. This portable system (figure 3-9) was taken to northeastern Colorado in 1971 as one of the nation's bright new meteorological tools for use in the National Hail Research Experiment (NHRE), and used there for the next four summers. Mueller became the person responsible for the care and operation of the CHILL radar and its staff of engineers and technicians.

After 20 years of having to use 3-cm wavelength radars, availability of a weather-designed 10-cm radar facilitated new studies of radar-rainfall relations and the detection of echo structure. An investigation of the gradients in high radar reflectivities revealed a wide range of values (Mueller, 1971). A three-year project supported by the U.S. Air Force investigated the statistics of rainfall distributions along lines using data from radar and raingages (Semonin and Cataneo, 1976). The 10-cm radar data proved valuable in investigating the morphology of a severe rainstorm in northern Illinois (Changnon, 1978a). A feasibility project showed how to use radar and raingage data in combination to help operate Chicago's water management system (Huff and Towery, 1978). The potential use of dual wavelength measurements to detect and track flights of insect pests was also assessed (Mueller, 1984).

Staff of the University of Chicago and three of their graduate students who became Survey staff members (Art Jameson, Peter Hildebrand, and David Johnson) pursued several studies relating to radar-sensed particles and the interpretation of dual wavelength measurements. Srivastava et al. (1979) compared Doppler spectral parameters calculated with those observed by radar to improve the radar's signal-to-noise ratio. An iterative scheme was developed to

Figure 3-9. The CHILL radar was designed as a portable system. Here in 1987 we see the beginning of the disassembly of the huge antenna system at its installation at the University of Illinois Airport, preparing for movement to North Dakota for support of their field operations. The large crane was needed for removal of the radome, always a tedious operation for Gene Mueller and his group of engineers and technicians.

reduce attenuation effects that would improve the radar's rain estimates when coupled with raingage data (Hildebrand, 1978). Other research included studies of ice particles (Johnson and Jameson, 1983), of raindrop oscillations (Beard et al., 1983a) and raindrop canting (Beard et al., 1983b), and the interpretation of the microphysical particles affecting multiparameter radars (Jameson, 1983a, 1983b). Jameson (1984) assessed antenna patterns and dual wavelength measurements, and Jameson and Mueller (1985) estimated the propagation-differential phase shift from linear polarization measurements. Beard (1985) assessed raindrop velocities for use in Doppler radar analysis, and then addressed aircraft observations of large raindrops encountered in convective clouds (Beard, 1986). Differential reflectivity measurements of the CHILL radar were also analyzed (Westcott, 1989a).

Other recent studies have addressed cell development and cell mergers (Westcott and Kennedy, 1989), described the echoes encountered in multi-cell storms (Westcott, 1989b). and speculated about the potential uses of the new NEXRAD radars for applications in a changed climate regime with altered precipitation (Changnon, 1992a).

As part of the large METROMEX study of urban weather effects at St. Louis, the Survey acquired a second 10-cm wavelength radar in 1971 and, under Don Staggs' leadership, developed a second radar system with a large (1.5-degree beam width) antenna funded by NSF. This Hydrometeorological Operational Tool, or HOT radar, was put into use at St. Louis during 1973-1975.

In 1976, the Survey launched a precipitation measuring project in the Chicago area involving the HOT radar and a large dense raingage network (Changnon and Huff, 1976). This three-years data collection effort led to the development of a radar-based rain prediction system with excellent accuracy of storm rainfall estimates using raingage data to help calibrate the radar signal in real time (Changnon et al., 1980a). Survey scientists also participated in a cooperative field project in northeastern Illinois during 1979 designed by Ted Fujita , under NSF grants, and they operated the CHILL radar to collect Doppler data for storms in the study area (Changnon, 1979a; Changnon and Towery, 1979a). Survey radar scientists were involved in the design of the nation's future new weather radar system (NEXRAD) because of their experience and success with the CHILL system (Mueller, 1981). The updated, improved CHILL facility was described (Mueller and Vogel, 1988) and a radar users' manual was developed (Brunkow, 1989). The Water Survey's proposal to continue NSF support for the CHILL system and its staff failed to rate as high as a proposal of Colorado State University in 1989, and the radar and staff moved to Colorado State University.

Raindrop Measurements

The effort to provide information about raindrops led to a 14-year program, done as part of the Signal Corps funded projects, to measure raindrops and define their distributions. In 1952 and 1953, Larry Dean and Doug Jones designed a camera system to photograph raindrops (Jones and Dean, 1953). This large system was built and tested in central Illinois during 1954-1955 (Jones, 1956) at two locations (fig. 3-2). Two cameras set at right angles were used to test the accuracy of measurements from a single camera (Jones, 1959). Methods of measuring raindrops were assessed (Pearson and Martin, 1957), and the drop sizes were measured using an elaborate semi-automated process that was very labor intensive. Fujiwara (1961) showed how various drop-size distributions could be integrated with synoptic weather conditions to develop radar-rainfall relations, and later interpreted the drop data for different types of storms (Fujiwara, 1965). Results were derived for typical drop-size distributions associated with different rain-producing conditions for use in an operational approaches, and the use of these reflectivity factors in the radar-rainfall equation greatly improved the radar-rain estimates for a given storm (Johnson and Mueller, 1961).

The military's need for radars to measure rain in various climatic zones led to several years of operations of the cameras in different climate zones around the globe. Raindrop data were collected for a one-year period at several sites: Miami (Mueller, 1962), Indonesia (Mueller and Sims, 1968a), Marshall Islands (Muller and Sims, 1967), Arizona (Jones, 1969a), North Carolina (Mueller and Sims, 1967a), Alaska (Mueller and Sims, 1967b), Oregon (Mueller and Sims, 1968b), and New Jersey (Mueller and Sims, 1967c). *An important by-product was a unique raindrop climatology for the world (Cataneo, 1969).* Cataneo and Stout (1968) analyzed the North Carolina and New Jersey data, which were considered to be from the same climatic zone, and concluded the drop distributions were similar. Mueller and Sims (1969a) summarized the drop size distributions from the nine sites, and Cataneo (1969) used the drop results to estimate the Z-R reflectivity relationships for each climatic zone, providing a global climatology of Z-R values.

Raindrop and rain rate research led to other military supported projects. One project tested the reality of simulated rainfall created along a vehicle test track in New Mexico. Survey scientists compared the spectrometer data at the track with raindrop distributions (Mueller and Sims, 1971). Raindrop expertise was again found useful in an Army funded project to assess the effects of drop impacts on a military projectile fuze. This involved measurements taken in Panama during 1968 (Mueller and Sims, 1968c), and the findings for drops and rain rates encountered in tropical climates were assessed in the final report (Mueller and Sims, 1969b). In the 1980s Ken Beard (1982) and others revisited the raindrop issue from a cloud physics viewpoint, examining and describing their behavior. Jones revisited his earlier work and summarized available information on raindrop spectra (Jones, 1992).

Raingage Networks

Hudson et al. (1952) evaluated the 1948-1950 rainfall data from three networks. Huff and Hiser (1954) assessed raingages for use in automated weather stations. As part of the same Department of Defense (DOD) contract, John Kurtyka (1953) performed an extensive literature review of all forms of precipitation measurement procedures and produced a notable bibliography. A key paper by Huff (1955) reported on the findings from a comparative study of various types of raingages, showing that small, inexpensive gages reliably sample rainfall. Stout (1960b) summarized findings about rainfall variability using data from several central Illinois raingage networks. Huff and Changnon (1960a) defined the incidence of heavy rain events using the data from ten years of operation of the Boneyard Network centered in Champaign-Urbana.

A dense raingage network was installed in southern Illinois in 1957 to collect data for comparison with the rainfall statistics from central Illinois (figure 3-1). Results from the first five years of the Little Egypt Network operations were presented showing slight differences in storm characteristics (Changnon, 1963a). Huff and Changnon (1966a) reviewed the eight raingage networks operated by the Water Survey between 1948 and 1965 and illustrated the many applications of their data.

Many studies evolved in the mid-1960s based on the ever growing data from the raingage networks. Huff (1967) assessed gradients found in convective rainfall. Huff (1969) detected storm rainfall occurrences by differing densities of raingages, and Huff (1970) defined the sampling errors inherent in measurements of storm, daily, and monthly rainfall, based on varying raingage densities. Jones and Sims (1971) used network data to analyze "instantaneous" rainfall rates at points (gages) and along lines (rows of raingages) to assess the statistical distribution of expected rates in two climatic zones, and they summarized the data for Illinois and Miami (Jones and Sims, 1975). Jones later (1978) challenged the adequacy of other scientists' efforts to measure 1-minute rain rates from recording raingages. Schickedanz (1976) assessed the effects of gage density on sampling of storm mean rainfall. Changnon and Wilson (1971) analyzed a series of severe rainstorms on the networks. Huff and Schickedanz (1972) used past network data bases to perform a major review of the space and time uncertainties in precipitation measurements. Changnon (1975a) analyzed the issues affecting the design, installation, and operations of dense raingage networks and later summarized years of raingage network data on the patterns of individual convective rain cells occurring on the larger dense raingage networks (Changnon, 1981a). .?

Hollinger and Reinke (1990) described the Illinois Climate Network. The Survey installed a new dense network in the Chicago area during 1987 (Peppier et al., 1990) and has since issued a series of annual reports describing the past year's precipitation patterns (Vogel, 1988, 1989; Peppier, 1990, 1991, 1993a, 1993b). The Survey installed a new network in 1992 in Tazewell County to provide precipitation data in that heavily irrigated area, and Hollinger and Peppier (1995) reported on the first two years of precipitation from this 24-gage network.

SEVERE STORMS

Efforts were extended to measure severe storms with a major emphasis on hail. Three projects funded most of the research: a three-year Air Force project (1959-1961), hail insurance association (CHIAA) projects (1959-1972), and the NSF projects (1967-1975). Storm-related measurement research was based on data collected a) during special case studies of individual storm events (using radar, poststorm surveys, and existing rain and hail networks), and b) from observations taken with specially-developed hail sensors, and multiyear operations of radars and dense sampling networks.

Hail

The first of many hail measurement studies occurred in 1955 primarily using radar observations to investigate five hailstorms that occurred during a 12-day period (Stout and Hiser, 1955). The objective of this and other early case studies was to prove that radar could detect and track such storms. Various hailstorm conditions were defined using insurance data and historical U.S. Weather Bureau records in an initial overview report to the insurance industry (Blackmer et al., 1959). Wilk (1961) summarized the findings from a three-year project That showed only limited success with use of a 3-cm radar to detect hailstorms.

Because the insurance industry sought information on the structure of such storms, Changnon made the first of several field investigations of severe hailstorms focusing on a June 22, 1960, storm in northern Illinois (Changnon, 1960a). A second case study was for a hailstorm in May 1962 (Changnon, 1962e). With the advent of an interesting hailstorm in the middle of the Survey's dense raingage network on August 8, 1963, detailed cell observations from two radars led to a very comprehensive study of the storm's internal structure and the surface hail pattern (Changnon and Stout, 1963). Subsequent storm case studies were performed for a series of very damaging hailstorms in northern Illinois on June 19-20, 1964 (Changnon, 1965a, 1966g), and in central Illinois on July 11, 1966 (Changnon, 1966a). A detailed study of a severe hailstorm in July 1970 near Champaign was pursued using crop-hail loss adjusters, radar, and aerial photography (Barron et al., 1970). Figure 3-10 is an aerial photo using of hail-damaged corn fields in central Illinois, and this process (which also involved use of infrared film) was adopted for routine storm studies by the Country Companies.

Figure 3-10. Survey scientists pioneered in testing the use of aerial photographs with infrared film to sense hail-damaged crops and to quantify the amount of loss across fields. This aerial photograph of corn fields in Illinois shows the swirl-shaped damaged areas, the darkened appearing zones. The technique proved highly useful and was adopted by the insurance industry.

The year 1968 saw an increase in the number of hail measurement publications as a result of the findings flowing from the CHIAA- and the NSF-supported projects. Hail network measurements of hailfalls, from both Illinois and South Dakota, were used to define various surface characteristics and then compare them between locations (Changnon, 1968a). These data were used to analyze the effect of sampling density (points per unit area) on the detection and measurement of hailfalls and hailstorms (Changnon, 1968b).

Accumulating data from the detailed single storm studies led to the development of a surface hailfall model (Changnon, 1969a), as well as a description of the Survey's extensive programs to collect surface hail data (Changnon, 1969b). Changnon (1970a) summarized much of what has been learned about the small-scale surface dimensions of hail and identified "hailstreaks," as individual cell paths of hailfall, an important discovery (figure 3-11).

Radar-hail studies continued. The initial results derived from the 1967 radar-network comparative analyses characterized the differences between hail and no-hail echoes (Changnon, et al., 1968). Towery and Changnon (1970) summarized findings about echo characteristics associated with hail-producing storms. The capability of a modified Changnon and Towery (1970) used the TPS-10 (RHI) radar to detect hail-producing storms and found they could detect 76 percent of all hailstorms. Changnon et al. (1972) assessed the capability of 3-cm wavelength radars to measure hail. Mueller and Morgan (1972) evaluated the development and early use of the CHILL radar for hail detection. Eccles and Mueller (1971) assessed the capabilities of the dual wavelengths of the CHILL to measure hail and liquid water contents through differences in attenuation of the two signals. Mueller and Morgan (1974) described the results of the CHILL radar's detection of hailstorms during NHRE operations in summer 1971-1973 in Colorado, and Mueller and Changnon (1974) compared echoes from seeded storms and nonseeded storms in Colorado.

Changnon and Wilson (1971) analyzed a series of heavy spring hailstorms on May 15, 1968, which occurred in the Survey's dense rain and hail networks in central Illinois. Changnon (1971a) used the detailed hail data bank to define the means to estimate areal hailfall extent with different sampling densities, and also compared data on hailstone sizes collected in Illinois and South Dakota projects were compared with stone size data from other locales (Changnon, 1971b). Changnon et al. (1972) summarized the surface hail studies in Illinois of 1970-1972.

Changnon (1973a) described and assessed the sensing of windblown hail using a micro-network of "hail stools" operated in central Illinois for six years. Data from a similar project involving a dense network of hail sensors within one square mile of northeastern Colorado were assessed and showed large in-storm variability (Morgan and Towery, 1974). Morgan and Towery, 1976a, 1976b) described the hail cube findings and a field investigation of wind and hail relations and their combined effects on crops. Morgan (1976) defined a pattern of wind-induced damage found in damaging hail patterns and named them "hailstripes." Changnon (1977a) reviewed and summarized the varied measurements of hail covering areas ranging from a foot to hundreds of square miles, and from all sources, an appropriate summary to the extensive Water Survey hail studies of that era.

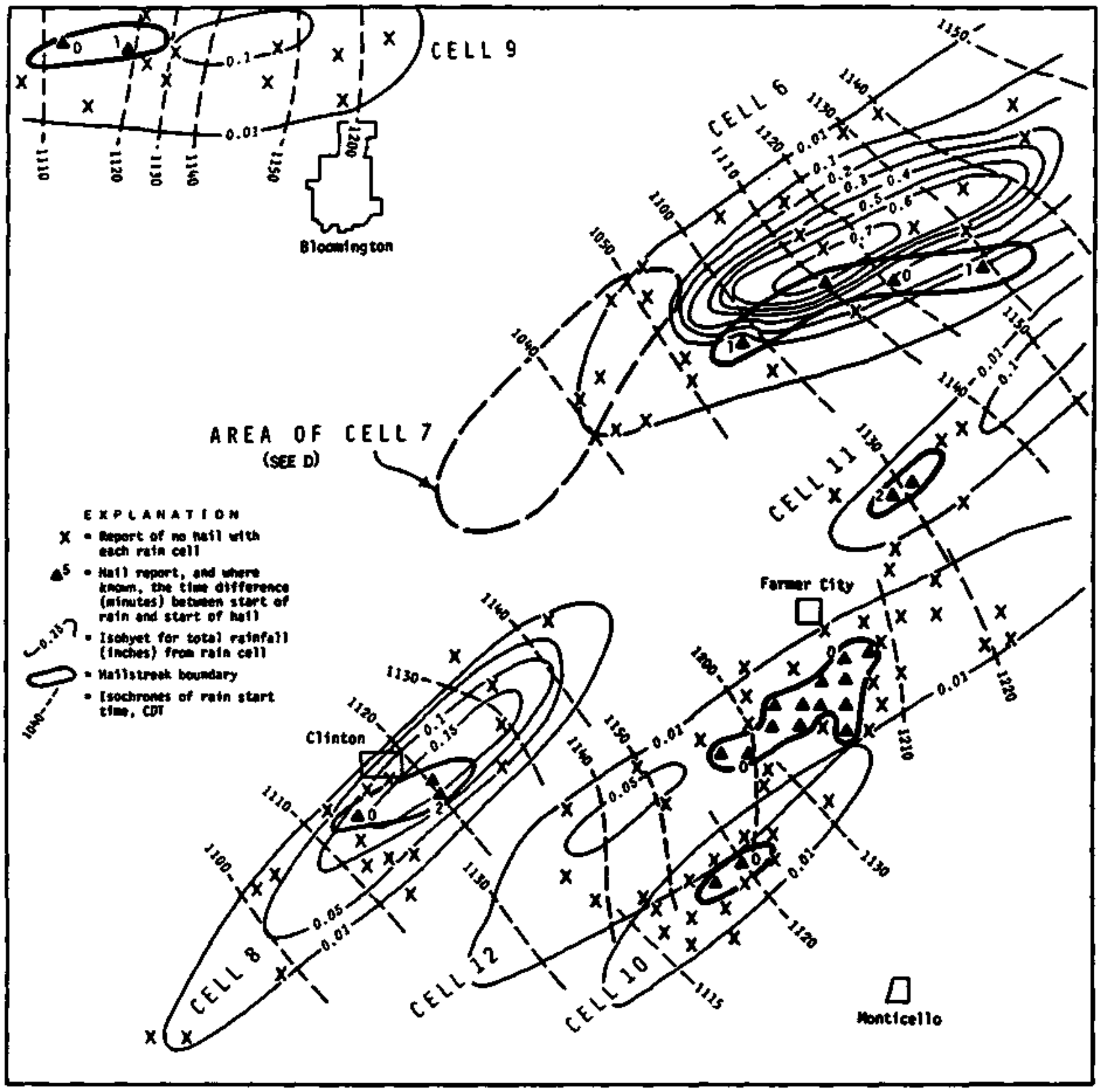


Figure 3-11. The pattern of hailstreaks and raincells as developed from data in the Survey's rain-hail network west of Champaign for a storm in May 1968. The Survey scientists discovered, named, and defined the structure of these two surface precipitation entities.

Tornadoes, Rainstorms, and High Winds

The use of radar echo data to determine upper level winds was an early investigation attempting to use echo behavior to infer wind conditions (Hiser and Bigler, 1953), and it was part of a project assessing the use of radar in short-term forecasting (Hiser and Bigler, 1954). The first radar detection of a tornado, as described in Chapter 2, became the subject of a major storm investigation (Huff et al., 1954). RHI radar observations were used to define the three-dimensional structure of a tornado-producing storm (Schuetz and Stout, 1957). Wilk (1961) summarized three years of research on the radar detection of thunderstorms. A unique large tornado on April 3, 1974, viewed by the CHILL with Doppler data, was the subject of another case study (Morgan et al., 1974). A Survey Technical Letter (1982) summarized the detection of severe local storms with radar. Doppler observations of a small tornado were assessed (Kennedy et al., 1990), and then doppler measurements of larger tornado in a super cell were analyzed (Kennedy, et al., 1993). Figure 3-12 shows both the reflectivity and Doppler patterns for a tornado detected in east-central Illinois. Grosh (1978) and Changnon (1978a) reported on case studies of severe flash-flood-producing rainstorms. Numerous other radar and raingage network studies of rainstorms are described in Chapter 4 on hydrometeorological research.

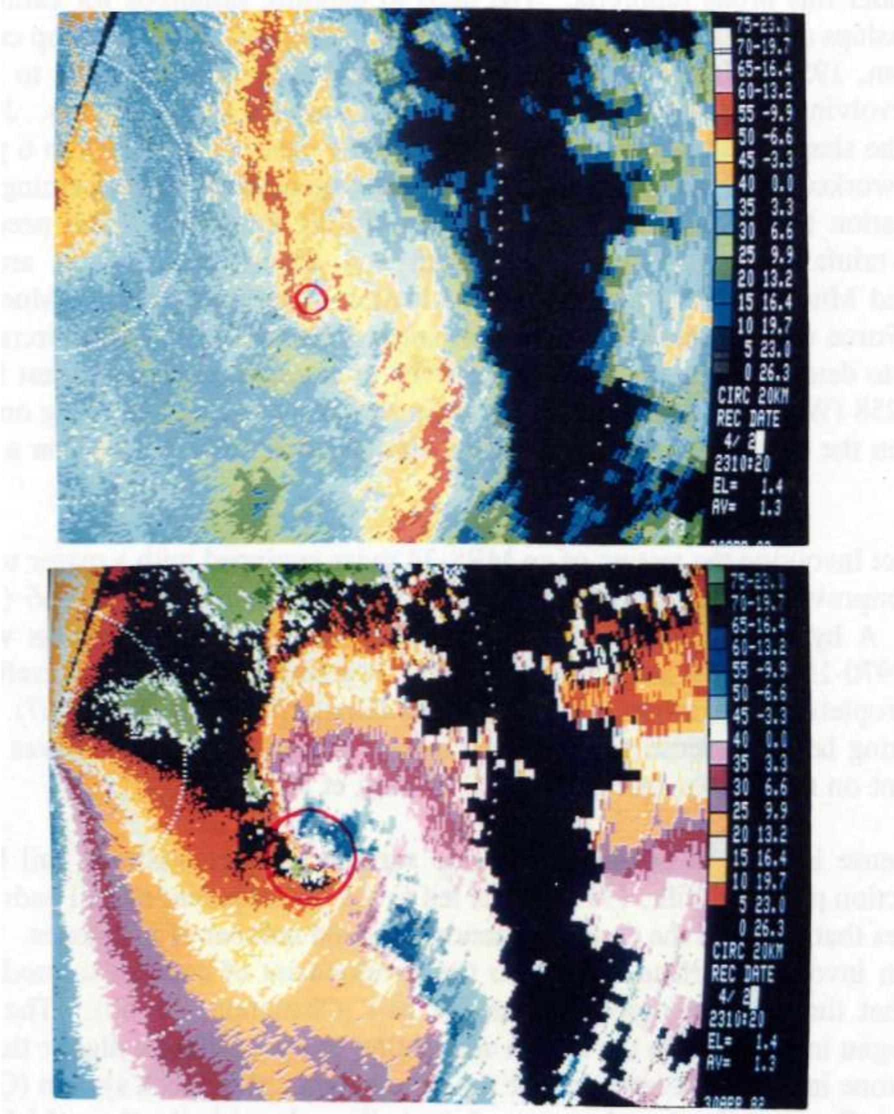


Figure 3-12. The CHILL radar provided both a standard reflectivity pattern (above) and Doppler winds pattern (below) as shown for a late evening tornado on April 2, 1982. The tornado area is circled along the line of higher reflectivity about 40 km to the southeast of the radar. The Doppler depiction of air motions around the tornado-producing system (lower photo) reveal the widely differing air directions as revealed by adjacent different colors in the encircled area where the tornado funnel existed.

DEVELOPMENT AND ASSESSMENT OF MEASUREMENT INSTRUMENTS

Precipitation measurement studies at the Water Survey were faced with never-ending needs for instruments to improve or help with measurements plus needs to assess and test measurements from various measurement devices. A good example of such endeavors is the assessment of a simulated rain field for the New Mexico test track facility done in 1970 and described above (Mueller and Sims, 1971).

Kurtyka's (1953) broad assessment of all known devices to measure rainfall was the start of the work under this broad umbrella. The need to measure raindrops for calibrating radar-rainfall relationships drove the 1952-1953 design and construction of the raindrop camera system (Jones and Dean, 1953). Interests in raingage types and their accuracies led to a small scale field project involving the comparison of a variety of raingages (Huff, 1955a). Jones (1969b) assessed how the shape of standard raingages reduced the catch of rain by 2 to 6 percent. The Water Survey worked with the World Meteorological Organization in performing a three-year raingage evaluation including a new reference gage during the 1960s. The need to spatially average radar-rainfall signals led to the design and development of an area integrator (Farnsworth and Mueller, 1956) and then an evaluation of its performance (Mueller, 1958b). The U.S. Air Force was interested in the performance of an APQ-39, a new aircraft radar, and its capabilities to detect clouds, and hired the Survey to assess its design and test its operations during 1955-1958 (Wilk, 1958). Mike Spock, a Survey meteorologist working on this project, was killed when the Air Force aircraft carrying him and this radar crashed on a test flight in 1953.

A project involving the testing of an MPS-34 radar equipped with a maser to enhance the sensitivity to improve rainfall measurements was conducted during 1965-1966 (Rinehart and Jones, 1965). A hybrid video processor to improve radar-rain measurements was built and tested during 1970-1971 (Silha and Mueller, 1971). A collector for use in aircraft sampling of precipitation droplets aloft was designed and tested (Bradley and Martin, 1967). The use of vertically-pointing lasers to sense temperature changes and particulates aloft was assessed and found dependent on the laser's aperture size (Sievering et al., 1969).

The intense interest in obtaining accurate surface measurements of hail began with a radar-hail detection project (Wilk, 1959). This led to the development of hail pads, simple foil-wrapped devices that revealed the dents and hence sizes and number of hailstones. The CHIAA-funded research involving surface hail led to the development of concept to modify recording raingages so that they also recorded the time of hail (Changnon, 1966b). The NSF-funded projects that began in 1968 led to the design and testing of a recording hailgage that sensed and measured hailstone impacts and recorded the times on a high-speed clock system (Changnon and Mueller, 1968). Survey scientists also created the hail stool and hail cube, which used foil on vertical surfaces to sense wind-driven hail. The data from these devices could indicate the wind with the hail.

A new concept based on using infrared aerial photographs to measure crop-damages due to hail was offered (Barron et al., 1970), and a test of this approach with two storms was found to be surprisingly accurate (Changnon and Barron, 1971). These probing studies led to an insurance-sponsored project to test and develop the aerial photography technique for operational applications (Towery et al., 1975). This project revealed the usefulness of the technique (Towery et al., 1976, 1977), which became an operational system adopted by the Country Companies (fig. 3-10).

Towery and Changnon (1973, 1976) assessed the capabilities of all existing hail sensors, many developed by Survey scientists and engineers. The five-sided "hail cube" sensor developed and tested in 1974 was found useful in assessing hail and wind conditions that produce crop damage (Morgan and Towery, 1975). Relationships between hailfall measures from hail sensors and damages to corn and soybean crops were defined in the NSF-funded project (Morgan and Towery, 1976b). Figure 3-3 shows nearby corn and soybean crops and when hail damages occurred in these fields, the loss values were compared with values measured by the recording hailgage and hail pad.

The METROMEX project at St. Louis needed a system capable of remote sensing of thunderstorm occurrences in and around the urban area. A remotely operating multichannel audio system that allowed geographical positioning of a peal of thunder and its time of occurrence was designed, built, and successfully operated during 1972-1975 (Gardner, 1976).

SUMMARY

Major Achievements

One of the greatest achievements in the precipitation measurement program was the successful operation of complex field programs that were labor intensive and demanded diverse staff talents. These endeavors included the design of networks and field operations, the installation of numerous field equipment including weather radars, and the ensuing reduction of massive amounts of data. The staff developed to handle these efforts was flexible, hard-working, and unique. Field projects took Survey scientists and engineers to Colorado, North and South Dakota, Missouri, Indiana and nine different parts of Illinois. The Water Survey has operated over the past fifty years 29 raingage networks in various parts of Illinois and adjacent states.

The engineering and scientific staff designed unique instruments that they and me technical staff built, tested, and operated successfully to fulfill project objectives. Notable among these were the area integrator, the raindrop camera, thunder detectors, and several hail-sensing devices, including hail pads, hail stools, hail cubes, and recording hail sensors. The Survey pioneered the use of infrared aerial photography to define hail-damaged crops and developed a technology still in use by insurance firms. Development of the CHILL radar system, and its wide use across the country as a "national facility" over the 1970-1988 period is a huge success story. Survey endeavors have contributed mightily to the evolution and creation of weather sensors and sensing studies.

Notable scientific findings emanated from the precipitation measurement research. The operations of raindrop cameras at various sites around the world allowed development of a global climatology of raindrops. The surface hail studies were notably successful. Survey studies have defined most of what is known about hailfall characteristics, and Survey work in hail measurements is widely recognized nationally.

Pivotal Papers

Stout and Huff's (1953) paper on the nation's first radar detection of a tornado was monumental in bringing national scientific and media attention to the new group at the Water Survey. Another major early contribution was the Kurtyka (1953) bibliography on rain-measuring devices, which became famous as the most thorough review ever made of raingages. Huffs (1955a) paper based on comparison of rainfall catch by varying gages forever put this issue of gage differences to rest.

The accuracy attainable for radar-rainfall measurements with 3-cm wavelength radars (Mueller, 1966) summarized 18 years of findings. Cataneo's (1969) paper converted the raindrop results into climate information on Z-R relationships on a global scale. The paper about surface "hailstreaks" (Changnon, 1970a) offered the first fundamental description of hailstorms at the surface, and later "hailstripes" (Morgan, 1976) were detected and defined for the first time. A review paper about the varying spatial scales of hail (Changnon, 1977a) brought together for the first time all known measurements of surface hail. The Barron et al. (1970) paper provided the first convincing evidence that the amount of hail damage to crops could be satisfactorily quantified through use of infrared aerial photography, a new technique with wide applications.

Major Projects

Four series of grants/contracts each lasting many years, were pivotal for supporting the continuing and expensive studies of precipitation including instrument development and extensive field studies. The series of Signal Corps-sponsored projects supported radar-rainfall and raindrop research for 18 years. Annual grants from the Crop-Hail Insurance Actuarial Association supported hail studies from 1959 to 1972. A series of NSF grants sustained hail measurement studies from 1967 to 1976, and the development and operation of the CHILL radar from 1969 to 1989.

Key Staff

Principal radar engineers were Gerald Farnsworth, Eugene Mueller, and Donald Staggs. The major contributing scientists included Robert Cataneo (radar and rainfall), Stanley Changnon (hail and radar), Floyd Huff (radar and raingage networks), Arthur Jameson (radar signals), Douglas Jones (raindrops), Griffith Morgan (hail), Randy Peppier (networks), Art Sims (radar-rainfall), Glenn Stout (radar-rain), Neil Towery (hail), and Ken Wilk (radar meteorology).

Other scientists and engineers played an important role in the research and development activities. Among these were Homer Hiser, Stuart Bigler, Ed Silha, Jack Fatz, Ron Rinehart, Mark Gardner, John Kurtyka, David Brunkow, Marvin Clevenger, Steve Hollinger, Pat Kennedy, and Nancy Westcott. Key data analysts: Edna Anderson, Phyllis Stone, Lois Staggs, and Ileah Trover. Key technicians included Joe Coons, Roy Reitz, Jim Harry, Eb Brieschke, and Lyle Smith.

Figure 3-13. Great contrasts in how radar data were collected and analyzed occurred during the 50 years of operations and research. On the left, a student analyst is tracing radar echoes from scope photographs projected on a film viewer, the analytical practice used from 1948 until about 1970. On the right, is a view of the inside of the CHILL radar user van during PACE operations in 1989 with (l.to r.) Bob Czys, Nancy Westcott, Pat Kennedy, and Dave Brunkow involved in radar operations and data collection, all done by a computer system integral to the CHILL. Later analyses was done by computer.

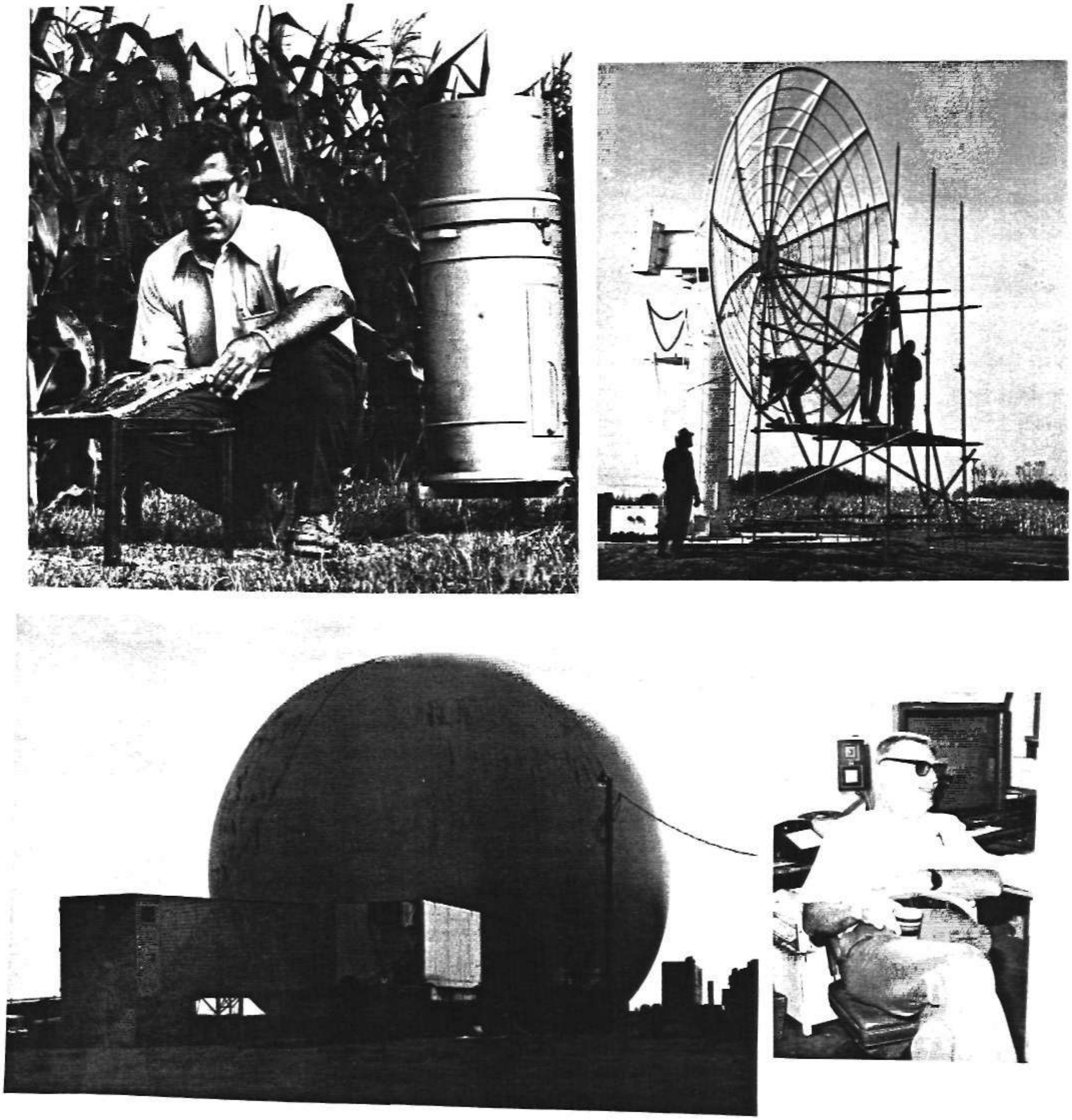


*Figure 3-14. The precipitation measurement program of the Water Survey embraced many persons and facilities. **Upper left** shows Oscar Anderson in 1970 changing a hailpad alongside a weighing bucket recording raingage with a 12-inch top and modified to record hail as well as rain. **Upper right** shows Survey engineers and technicians installing the HOT radar antenna at afield site near Joliet in 1976. **Lower left** is the field installation of the CHILL radar at Anadarko, OK, showing the two trailers in front of the large radome. The CHILL was participating in a three-doppler radar experiment in concert with the National Severe Storms Laboratory. Lower **right** is Gene Mueller, senior engineer and director of the CHILL radar, seen at a 1986 PACE project debriefing.*

Chapter 4

RESEARCH IN HYDROMETEOROLOGY

Floyd A. Huff

INTRODUCTION

Hydrometeorology research began with the initiation of the Meteorology Group within the Engineering (hydrology) Section in late 1947 and has been a central, ongoing research program of atmospheric sciences at the Water Survey for a half century. Consequently, there have been many publications, awards, and recognition of the group as a national, if not international, leader in this arena. Hydrometeorology is a natural field of endeavor for the Water Survey, which is committed to both research and services in the development and use of water resources in Illinois.

Initial research in hydrometeorology was given impetus by the interest and support of H.E. Hudson, Jr., Head of the Engineering Section. He was aware of the needs and problems that were related to inadequate information and knowledge about certain aspects of hydrometeorology during the late 1940s. Although hydrometeorology has applications in several fields, its primary user group consists of the hydrologists involved in the design and/or operation of water supply and water control facilities. Hudson was instrumental in the establishment of the Survey's first hydrometeorological raingage network (Panther Creek watershed), and in the imitation of field surveys of severe rainstorms in Illinois.

Several major themes developed in the research program over time. The first theme was a *study of severe rainstorms in Illinois* using data from field surveys, operations of several dense raingage networks between 1948 and 1980, analyses of major flood-producing storms in a six-basin hydroclimatic study, and analyses of all exceptional storm occurrences in Illinois revealed by data from the climatic network of the National Weather Service (NWS) which began in the 1890s. This study accumulated much needed new information on the frequency, intensity, duration, and areal extent of the "blockbuster" storms that often yield 10-inch or greater amounts at their core in 24 hours or less. These storm occurrences must be considered in the design and operation of water control facilities where the probability of system failure must be kept at a minimum.

A second theme involved *rainfall variability studies* derived from dense raingage data obtained from the Survey's network operations. These studies, which were carried out primarily during the early years of the hydrometeorological program, provided a wealth of data not previously available on the small-scale variations in convective rainstorms. These variations are important in establishing sampling requirements for measurement of convective rainfall, which is the most prolific producer of precipitation in the Midwest and the primary cause of flash floods during the warm season. Furthermore, information on rainfall variability is important in developing a better understanding of atmospheric precipitation processes. It is also relevant to various hydrologic problems, such as storm drainage designs to handle rainfall runoff and excess water storage on small basins and in urban areas.

The third theme involved extensive *studies of the time-space distribution characteristics of heavy rainstorms*. Knowledge of these storm properties is essential for the design hydrologist, and the need increased rapidly during the 1960s and 1970s when the use of hydrological models became widespread. Needs were especially important in attacking small watershed and urban design problems. Data accumulated in the dense raingage networks and in the earlier heavy rainstorm studies provided the means to contribute significantly to alleviating the time-space distribution problems.

The fourth theme involved the *development of rainfall frequency relations in heavy rainstorms*. Studies began in the late 1950s and eventually revealed deficiencies in existing rainfall frequency relations that were being used by hydrologists in the design of storm sewer systems and other water control structures in Illinois. This led to development of more realistic relations for Illinois and eventually for a nine-state region of the Midwest. Initially, it was intended only to establish frequency relations for precipitation periods of 1 to 10 days in Illinois to supplement relations for periods of 30 minutes to 24 hours provided in NWS Technical Paper 40. Later the study was expanded to cover shorter time periods, because numerous Illinois users were dissatisfied with the existing relations appearing in Technical Paper 40.

The fifth theme was *urban hydrometeorology*, with particular emphasis on the impact of urban-induced changes in the normal precipitation regime affecting the frequency of flash-flood events in large metropolitan areas. Accumulation of information on this subject eventually helped to launch the Water Survey's comprehensive research program dealing with inadvertent weather modification (Chapter 7). Extensive field research followed by comprehensive data analyses was carried out in the St. Louis area during 1971-1975 under this program known as METROMEX (Changnon et al., 1977). In the late 1970s, the Survey's expertise in radar and raingaging contributed to the award of a National Science Foundation (NSF) grant whose purpose was to develop a rainfall prediction-monitoring system to detect, track, and predict the rainfall associated with potential flash-flood systems approaching metropolitan areas. This project, known as CHAP, was carried out in the Chicago area in 1976-1979.

SEVERE RAINSTORM RESEARCH

The severe rainstorm research went into effect following the field survey and ensuing study of synoptic weather conditions associated with the storm of July 8-9, 1951, which produced rainfall amounts exceeding 13 inches at the storm center. This storm occurred in an area partly sampled by 50 raingages from the Survey's Panther Creek network. In addition, 280 field observations of rainfall amounts were obtained in the storm area. The result was presentation of an extremely detailed isohyetal analysis rarely available from such extreme storm events. There was a lack of information about these rare-event storms, so the potential for accumulating much needed information and knowledge on their spatial and temporal distribution characteristics, and the value of such findings to hydrologists and other users of rare storm events was recognized. Therefore, severe rainstorm research became one of the basic research themes of the Survey's hydrometeorological program.

Floyd Huff assumed a leadership role in this program upon his return from military service in late 1952. Other key staff members in these studies from 1950 to 1970 included Glenn Stout, Stanley Changnon, Richard Semonin, and Douglas Jones, all of whom proved to be long-term members of the Survey's professional staff, and ultimately were responsible for the successful completion of many research studies that contributed to the success of the Atmospheric Sciences Section.

Field Survey Project

A total of 12 severe rainstorms were surveyed in detail during the 1950-1970 period. The value of field surveys to gather detailed storm rainfall data from non-official sources was defined (Changnon, 1958b). Isohyetal patterns were scrutinized, time and space distribution characteristics were investigated, and synoptic weather conditions associated with each storm were defined. These storms resulted in five Water Survey reports (Report of Investigation 14, 24, 27, 35, and 42). The reports covered nine field-surveyed storms in which rainfall amounts exceeded 10 inches in less than 24 hours at the storm centers. These storms spanned the state with occurrences in southern, central, and northern Illinois. Information yielded by the field-surveyed storms also provided important input to several published research papers listed later. Figure 4-1 shows the total rainfall pattern determined for a rainstorm on July 12-13, 1957, and the location of the field data collected by Survey staff to determine the storm pattern. Figure 4-2 shows five Survey staff involved in a field survey of a heavy rainstorm that occurred during August 1989.

As the number and types of research projects multiplied in the Atmospheric Sciences Section, the field survey program received less attention in the 1960s. The program was discontinued in 1970, but the study of severe rainstorms continued under Huff's supervision, based on network data, a six-basin hydrometeorological study (Huff, 1981), analyses of extreme storm events appearing in the records of NWS climatic network, and other sources of data.

Major Publications

The first paper generated by the severe rainstorm program and published in a professional scientific journal appeared in a Meteorological Monograph of the American Meteorological Society (Huff and Semonin, 1960). It discussed an investigation of major flood-producing rainstorms in Illinois during 1914-1957, based on data obtained from published climatic records.

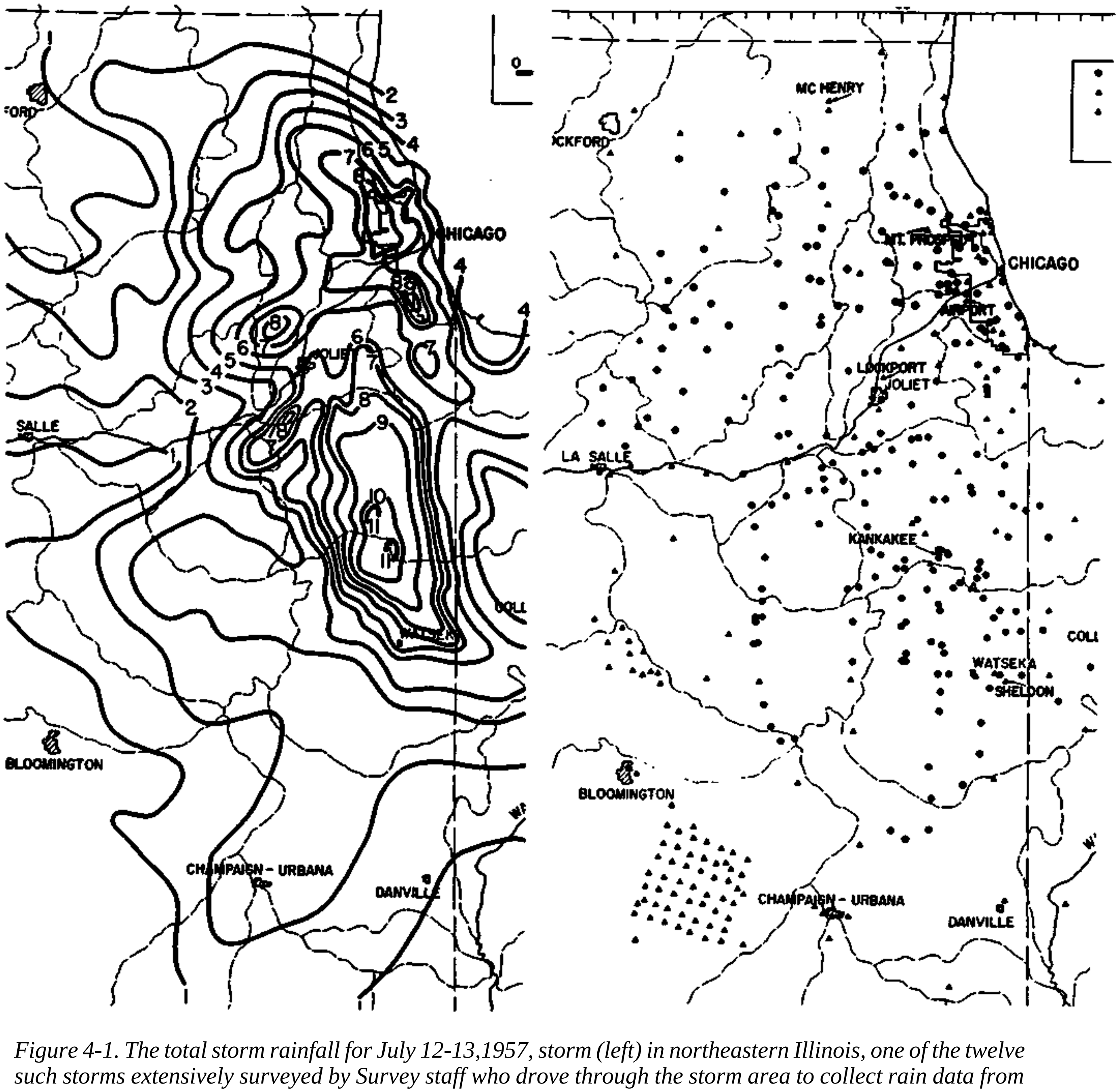


Figure 4-1. The total storm rainfall for July 12-13,1957, storm (left) in northeastern Illinois, one of the twelve such storms extensively surveyed by Survey staff who drove through the storm area to collect rain data from farmers. The sampling density map (right) shows where such field measurements were collected for this storm.

Figure 4-2. Two of the key scientists who were involved in the hydrometoeorlogical research program. Floyd Huff was its director for 50 years and during the last ten years Jim Angel worked with Huff to generate a new series of reports.

Area-depth relations were determined for each rainstorm to obtain a measure of their areal extent, intensity, and rainfall gradients. Other information compiled included storm orientation, shape, and movement, season of occurrence, and synoptic weather conditions associated with each event. Later studies of this type included data dating back to the 1890s, and provided a large amount of data and information on the characteristics of these storms in Illinois and the Midwest.

An update on findings from the severe rainstorm studies was provided in a paper by Huff and Stout in the July 1962 issue of the *Journal of Hydraulics Division* of the American Society of Civil Engineers. This paper summarized research results on severe rainstorm studies in the 1948-1962 period. Results were based on the field survey program, operation of four concentrated raingage networks, the NWS climatic network, and radar observations of storm systems.

Data from the dense raingage networks had been used to investigate area-depth relations on small areas ranging from 5 to 500 square miles (figure 4-3). Empirical mathematical formulas were developed to define area-depth relationships in terms of basin area, storm mean rainfall, and storm duration. The Champaign-Urbana urban network was employed to investigate the distribution characteristics of heavy rainstorms over small urban areas. Other studies were made to determine 1) how spatial distributions are affected by precipitation type, 2) typical orientation and shape characteristics of heavy storms, and 3) synoptic weather conditions under which these storms occur.

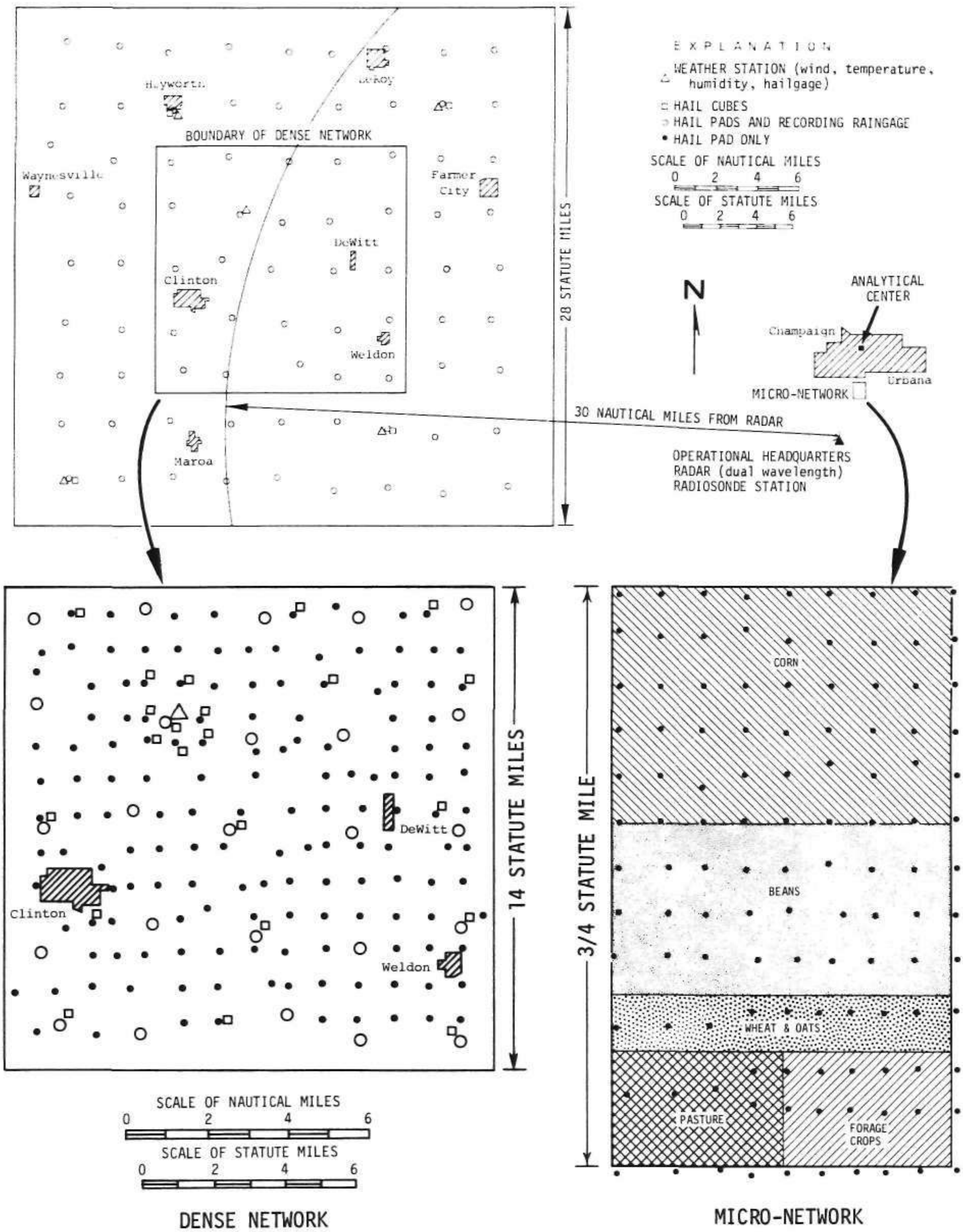


Figure 4-3. Examples of the raingage networks with varying gage densities in operation near Champaign during 1967. Such networks were the source of the data used to perform many of the hydrometeorological studies done by Survey scientists.

The Huff and Stout (1962) paper was not only a significant contribution in the field of severe rainstorm hydrometeorology, but it also focused the attention of an important user group (civil engineers) on the Survey's program and its progress in solving some of the engineering problems related to inadequate information and knowledge available from the meteorological community at that time.

A third important paper resulting from the severe rainstorm studies was published two years later in the *Journal of Meteorology* (Huff and Changnon, 1964b), which presented a statistical model for a typical 12-hour severe rainstorm. The model was derived from comprehensive analysis of ten field-surveyed storms in the 1950s that included physical characteristics and synoptic weather conditions under which the storms developed and matured. Maximum amounts in five of these storms exceeded 10 inches.

The paper also contained a detailed account of a rainstorm that was centered on the Survey's Little Egypt Network in southern Illinois in August 1959. Radar observations were also available for this storm. This combination of observations revealed important information on the meteorological conditions under which these "blockbuster" storms develop, move, and thrive. The importance of this paper was that it demonstrated the diversity of the severe rainstorm studies at the Water Survey, and provided early information on the mesometeorological characteristics of these storms while stressing the importance of mesoscale observations to supplement the macroscale data.

Later studies by Maddox, Survey scientists, and others showed that these storms were associated with mesoscale complexes. One of the major conclusions from the Huff-Changnon paper (1964) stated that "exceptionally detailed information obtained from the raingage network data has aided in establishing a better understanding of the mesoscale structure and movement of such storms". By the late 1970s, mesoscale was the accepted terminology used in describing these storm events.

Mesoscale structures of two severe rainstorms occurring in the 1960s were described in a Survey paper presented at a 1967 Conference on Severe Local Storms of the American Meteorological Society (Huff, 1967c). An unusual amount of detailed data were available for the Leverett storm of 1961 in east-central Illinois and the Mt. Pulaski storm of 1967 in the south-central part of Illinois. Field surveys were conducted after each storm, and radar observations were made at the Survey's Meteorological Laboratory in both cases. Furthermore, the Leverett storm incorporated the 10-gage Boneyard network in Champaign-Urbana (figure 3-1). *These two storms provided substantial new quantitative information on the mesoscale structure of small-area severe convective storms that produce localized flash floods.* Rainfall in the Leverett storm exceeded 6 inches at the storm center in four hours, and 8 inches fell in seven hours in the Mt. Pulaski storm. Amounts in both storms exceeded the 100-year frequency for their durations.

Severe rainstorm research continued on a lesser scale in the 1970s. Scientists who had been closely associated with the hydrometeorology program became involved largely with the

METROMEX inadvertent weather research in the early to mid-1970s. In the late 1970s, the major effort was devoted to CHAP, a large-scale hydrometeorological program in the Chicago area that involved tracking and predicting potential flood-producing storms approaching large metropolitan areas.

However, two important papers summarizing the results of the severe rainstorm research were presented by Huff at a Conference on Hydrometeorological Aspects of Flash Floods (Huff, 1978a), sponsored by the American Meteorological Society in May 1978. Huff discussed characteristic properties of Midwestern flash floods and summarized findings relating to area-depth relations, orientation and shape of severe rainstorm patterns, time distribution of rainfall amounts in the storms, and storm movements. Statistical models for storms of varying areal extent were presented (Huff, 1978b), updating findings presented earlier by Huff and Changnon (1964b). It was pointed out that the information accumulated in these studies should be useful to both hydrologists and meteorologists, but should be especially helpful to those concerned with hydrologic design and/or operational problems on small basins and in metropolitan areas.

The second paper (Huff, 1978b) concentrated on findings relating to the synoptic environment of flash-flood storms. The storm sample was divided into two groups, based on areal extent within the 1-inch isohyet. Analyses were performed in each storm to determine 1) synoptic storm type associated with the rainfall (frontal, nonfrontal, squall line, etc.), 2) low- and mid-level wind conditions, 3) moisture at the surface and aloft, 4) atmospheric stability, 5) time and location of storm development with respect to the synoptic situation, 6) relation to antecedent rainfall, temperature, and cloud conditions, 7) physical properties of the rain systems, and 8) other factors that could provide some degree of prediction guidance. From these analyses, statistical synoptic models were derived and presented in the paper. The models were and still are considered helpful in recognizing the potential development of severe rainstorms by forecasters and in predicting storm location, intensity, areal extent, and duration.

Other important contributions of the hydrometeorology program were contained in papers published in *Water Resources Research* (Changnon and Vogel, 1980, 1981). These papers dealt with the characteristics of isolated severe rainstorms, which were defined as small-area storms that typically produce storm center amounts in a range from 3 to 8 inches, with most of the heavy rain occurring within two to three hours. The storm data were obtained largely from operation of Survey raingage networks in the 1948-1980 period. Results indicated that these events cause localized flash floods that produce excessive storm damage to property and crops and occur, on the average, of once per 1,500 square miles per year in Illinois and elsewhere in the Midwest.

Dam Safely Project

The accumulation of data, information, and the associated increase of knowledge on severe rainstorms provided valuable input to a state-level problem in 1979. The Division of Water Resources of the Illinois Department of Transportation (IDOT) was required to establish new criteria for the design and construction of dams in the state to meet new environmental regulations. Under the dam safety program, extensive information on severe rainstorm occurrences was needed, which the Water Survey agreed to furnish under a contract with IDOT (Huff, 1980).

Three basic tasks were undertaken. The first task was to provide regional estimates of probable maximum precipitation in Illinois for various storm periods and areas. This involved analyses of the maximum observed rainstorms in Illinois to develop a method for adjusting the existing probable maximum precipitation values to provide realistic values for hydraulic structural design in the state. The second task was to provide a set of regional values of 100-year rainfall frequencies for various regions of the state. The third task was to provide time distribution models of rainfall within severe rainstorms. In carrying out the precipitation analyses, relationships were developed for areas ranging from 1 to 300 square miles and for storm periods of 1 to 48 hours. All of the necessary information was provided in a report to the Department of Transportation (Huff, 1980). *Reliable solution of the problems were possible only because of the severe rainstorm research carried out under the Survey's hydrometeorological program.*

Illinois Basin Studies

In the 1960s, another new research program was initiated that involved providing a working guide for hydrologists and engineers concerned with the frequency distribution of point and areal mean rainfall and various characteristics of severe precipitation events in major basins. The objective was to provide quantitative estimates of all the various hydrometeorological factors that could be helpful in the design and/or operation of water control structures. Because of limited personnel and financial assets available to devote to this project, and the comprehensive analyses required to achieve a reliable product, the project became a rather long-term involvement. Studies were eventually completed for six major basins in central and southern Illinois (Kaskaskia, Big Muddy, Sangamon, Little Wabash, Embarrass, and Spoon River). Research results were presented in Report of Investigation 96 (Huff, 1981).

In carrying out the studies, the frequency distribution of basin mean rainfall was determined for return periods of 1 to 100 years and storm periods of 1 to 48 hours for each basin. The frequency distribution of areal mean rainfall was also determined for fixed sub-areas in each basin of 10 to 400 square miles for storm periods of 1 to 48 hours, along with the frequency distribution of sub-area envelopes of maximum rainfall. The frequency of areal mean rainfall is generally of more concern to hydrologists than point rainfall frequencies.

Area-depth relations were determined for all major storms, as were the shape, orientation, and movement of the storms. Also provided was information on the time distribution of rainfall within storms, time lapse between successive severe rainstorm occurrences, seasonal distribution of the severe storm events, and synoptic weather conditions associated with each storm.

Summary Report

The various hydrometeorological projects relating to severe rainstorms resulted in the publication of Report of Investigation 90 (Huff, 1979a), which summarizes pertinent findings. This report provided quantitative information on various subjects of interest to hydrologists and others. For example, a relation was presented between 100-year frequency of storm rainfall and probable maximum precipitation estimates by NWS scientists. The relationship between maximum observed and probable maximum storms was established for Illinois, information that is particularly valuable now because environmental regulations have forced the hydrologic community to consider frequencies of 100 years and longer in the design, construction, and operation of water control structures.

Depth-duration-area relations and statistical models of flash-flood storms derived from the field survey and network data were presented, including the time distribution of severe rainstorms with respect to season of occurrence, intrastorm distributions, antecedent rainfall associated with these events, and characteristics of shape, orientation, and movement.

This report and the six-basin report that followed in 1981 probably marked the end of an era at the Water Survey. Huff retired (to parttime status) in 1979, and other atmospheric research moved to the forefront.

However, the severe rainstorm research provided an answer to one more problem encountered by Survey and state hydrologists in the early 1990s. As mentioned earlier, the hydrologic community is faced with the necessity to incorporate rainstorm events of 100 years and longer into their design considerations. In response to questions from hydrologists, data accumulated in the severe rainstorm research program were utilized to provide some guidance on this problem. Results of the study were published in Survey Circular 176 (Huff, 1993), which has applications for the entire the Midwest since the severe rainstorm characteristics do not vary substantially across the region.

RAINFALL VARIABILITY STUDIES

The rainfall variability studies were based largely on data from several dense raingage networks operated during the 1948-1956 period (see figures 3-1 and 4-4). Results are considered applicable to small basins, urban areas, and other small areas of interest. Much of the information yielded by numerous analyses of network data were combined in Survey Bulletin 44 (Huff and Neill, 1957a), which drew national and international attention to the rainfall research program and is one of the most popular reports published by the Atmospheric Sciences (Meteorology) Section. Detailed rainfall relations for small areas on the scale provided by the Survey network studies had not been available in the literature previously. Some of the more important contributions from the variability studies include rainfall relative variability, variation of point rainfall with distance, areal representativeness of point rainfall measurements, reliability

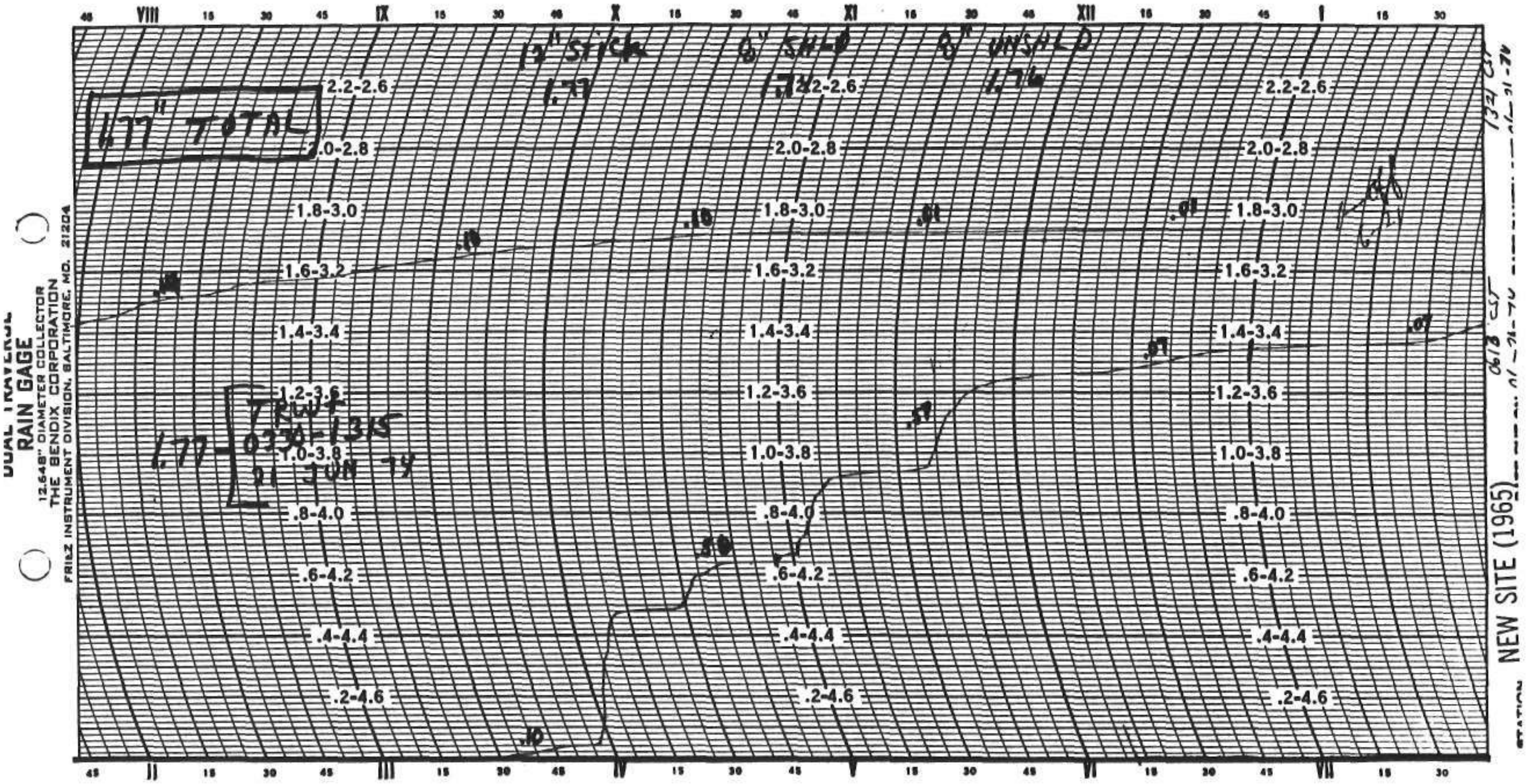


Figure 4-4. One of the thousands of recording raingage charts from a Survey weighing bucket recording raingage. This chart had been operated with 6-hour gear speed to allow determination of detailed (1- and 5-minute) rain amounts, and shows a series of bursts of rainfall.

of storm mean rainfall estimates, frequency of point and areal mean rainfall rates, relation between point and areal rainfall frequencies, and area-depth relations.

Storm Relative Variability

An initial study investigated the magnitude of the relative variability in convective rainstorms (thunderstorms and rain showers) for areas of 100 to 300 square miles and for various levels of storm mean rainfall. The coefficient of variation expressed in percent was the parameter used to determine the spatial dispersion of point rainfall around the areal mean. Results showed that the relative variability increased substantially with increasing area and decreased with increasing mean rainfall. The major reason for this study was to provide quantitative estimates of the degree of variability in convective storms that are the major producer of Midwestern floods. Natural variability is a factor that can affect the design requirements for hydrologic structures. Further details appear in Bulletin 44 (Huff and Neill, 1957a).

Variation of Point Rainfall with Distance

The variation of point rainfall with distance is an important factor in hydrologic and agricultural applications of rainfall data. Due to the ordinary spacing of raingages, estimates of point rainfall are frequently required for locations several miles from the nearest raingage. The literature of the early 1950s provided only very limited information on the subject. Recognizing this void in rainfall knowledge, a study was undertaken to provide a partial answer through analyses of data from the Panther Creek and Goose Creek networks. Statistical analyses were used to develop an empirical relationship expressing departure from the raingage value (sampling error) as a function of distance from and storm rainfall amount at the nearest raingage. Study results were published in Bulletin 44 and the *Journal of the Sanitary Engineering Division* of the American Society of Civil Engineers (Huff and Neill, 1956c).

Areal Representativeness of Point Rainfall Measurements

The accuracy with which a point rainfall measurement represents the mean rainfall for areas of various sizes in the vicinity is pertinent to the design of raingage networks and the interpretation of data from existing networks. This is a problem often encountered by design and operational hydrologists. Again, only very limited information on this subject was available. Therefore a study was implemented using data from the dense raingage networks to provide a partial solution. At that time, data were available from six networks ranging in size from 10 to 400 square miles.

Statistical analyses were used to develop empirical equations relating the differences between point and areal mean rainfall to point rainfall amount at the measurement point (raingage) and size of sampling area (figure 4-5). Such nomograms were presented for conveniently determining the average relationship and the 95 percent confidence bands about the average curves. Empirical relations were derived for storm, weekly, and monthly rainfall.

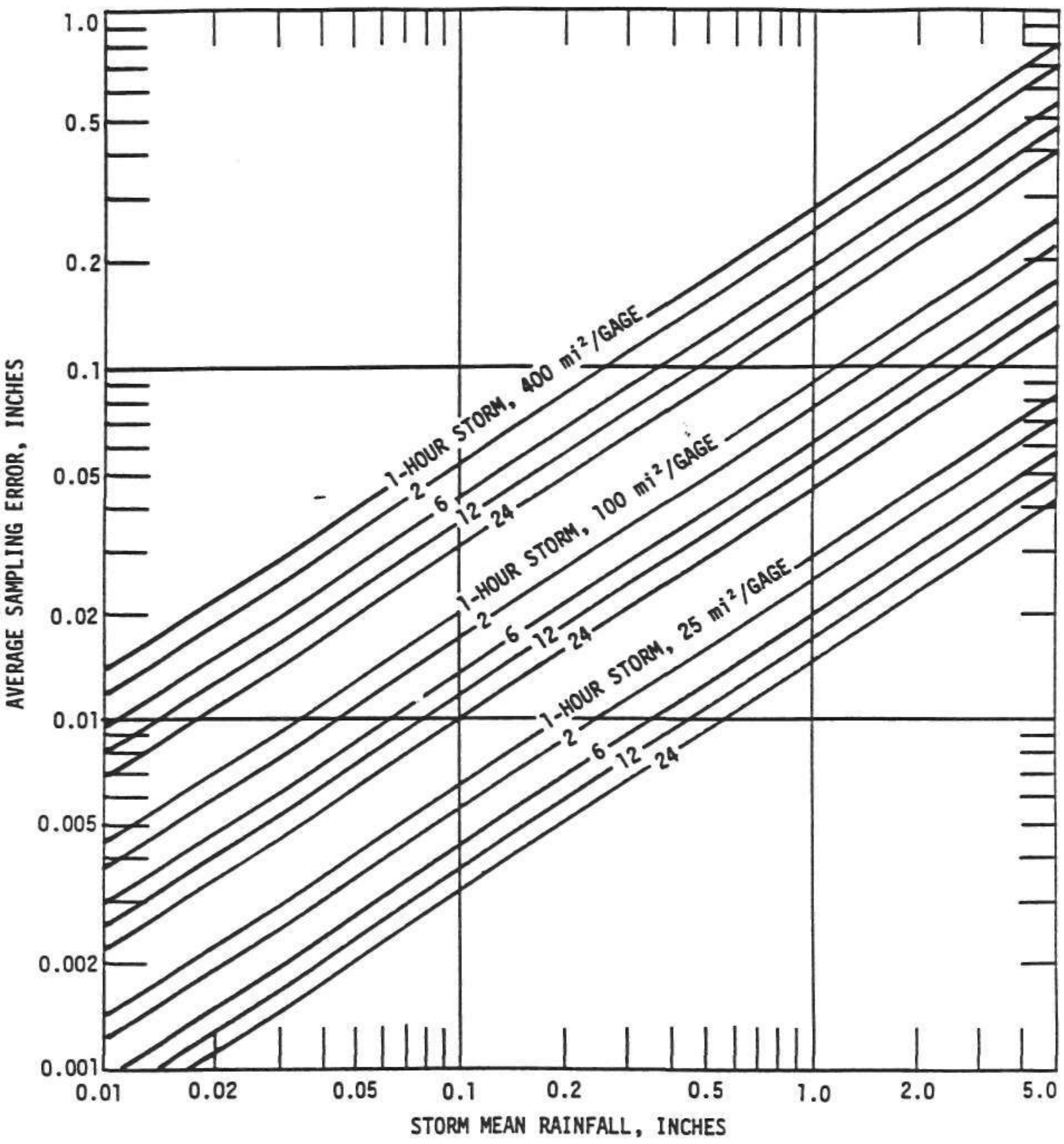


Figure 4-5. Sampling error relations for mean rainfall on a 400-, 100-, and 25-square-mile areas, for selected storm durations (1 to 24 hours) and different raingage densities.

Reliability of Areal Mean Rainfall Estimates

The preceding discussion described a study of the areal representativeness of point rainfall measurements. However, an estimate of average mean rainfall may be required for an area with multiple gages. Consequently, an analysis was made to obtain an estimate of both the average and standard error involved in measuring areal mean rainfall by means of various gage densities within several areas of various sizes. Relations were derived for areas of 25, 50, 100, 200, and 400 square miles using data from the Panther Creek, Goose Creek, £1 Paso, and East Central Illinois networks. Analytical procedures were similar to those used in the study of areal representativeness for which results were presented in Bulletin 44.

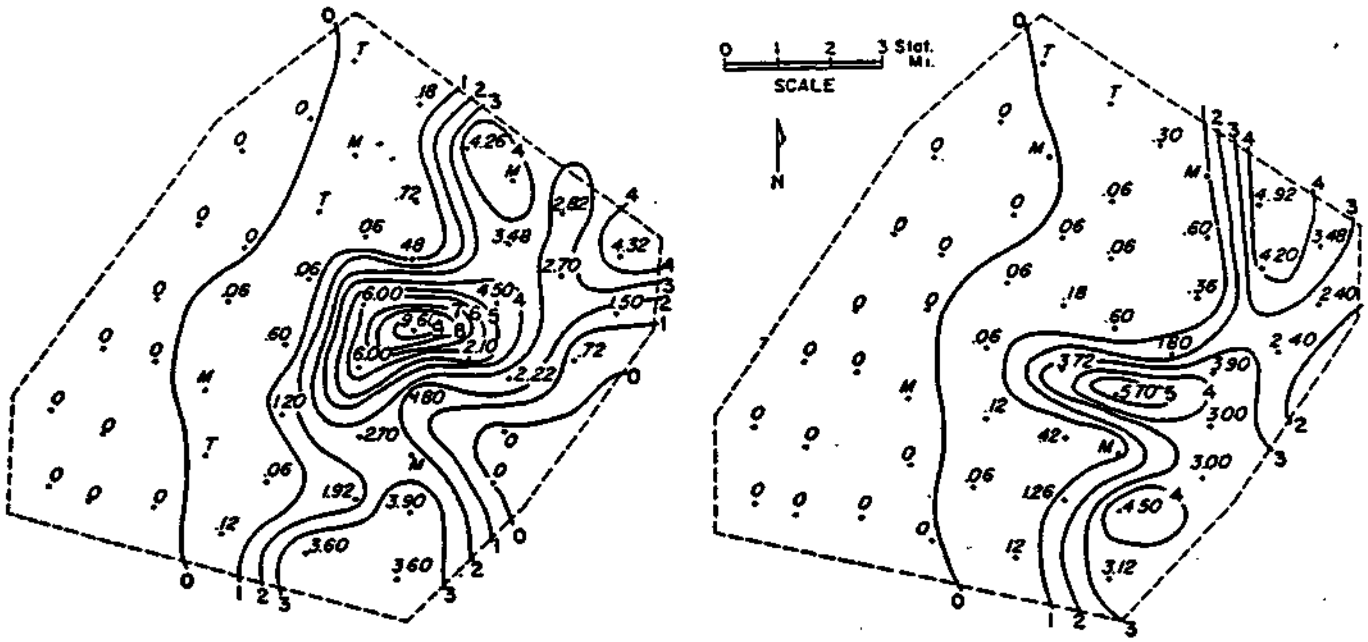
Frequency of Point and Areal Mean Rainfall Rates

As part of the radar meteorology studies in 1952-1953, the 100-square-mile Goose Creek network was outfitted with gages capable of measuring one-minute rainfall rates (figure 4-6). This was the first time that a dense raingage network enveloping such a large area had achieved this capability anywhere in the United States—another first for the Water Survey. By the mid-1970s, knowledge of the spatial distribution characteristics of instantaneous rainfall rates had become pertinent to the communications industry which was shifting from wire-based transmission to line-of-sight atmospheric transmission systems.

The one-minute data were used to develop relations between point and areal mean rates to determine the time distribution of the one-minute rates and to derive other statistics of interest. Results of this study are provided in Bulletin 44 and in a paper published in the *Transactions of the American Geophysical Union* (Huff and Neill, 1956b).

Relation Between Point and Areal Mean Rainfall Frequencies

The literature of the 1950s contained considerable information concerning the frequency distribution of point rainfall. Little data were available on areal mean rainfall frequencies, however, and this is a more important parameter to the design hydrologist and other users of heavy rainstorm distributions. Limited information on this subject was obtained from the data collected on the El Paso and Panther Creek networks between 1948 and 1953. Comparisons were made between point and areal mean rainfall frequencies during the five-year period for 25-, 50-, and 100-square-mile areas. Regression equations were derived for each area. A strong correlation was found between the point and areal frequencies. Indications were that areal mean rainfall frequencies are close to, but slightly less than, equivalent point rainfall frequencies on small areas, results indicative but not definitive of point-areal frequency relations because of the small sample size available for the study. More details on this study are available in Bulletin 44 and in a paper published in the *Bulletin of the American Meteorological Society* (Huff and Neill, 1956a).



c) 1613-14 CST; d) 1617-18 CST;

Figure 4-6. Examples of a sequence of one-minute rainfall patterns (rate in inches per hour) on the Goose Creek Network, as measured for a storm on June 25, 1953.

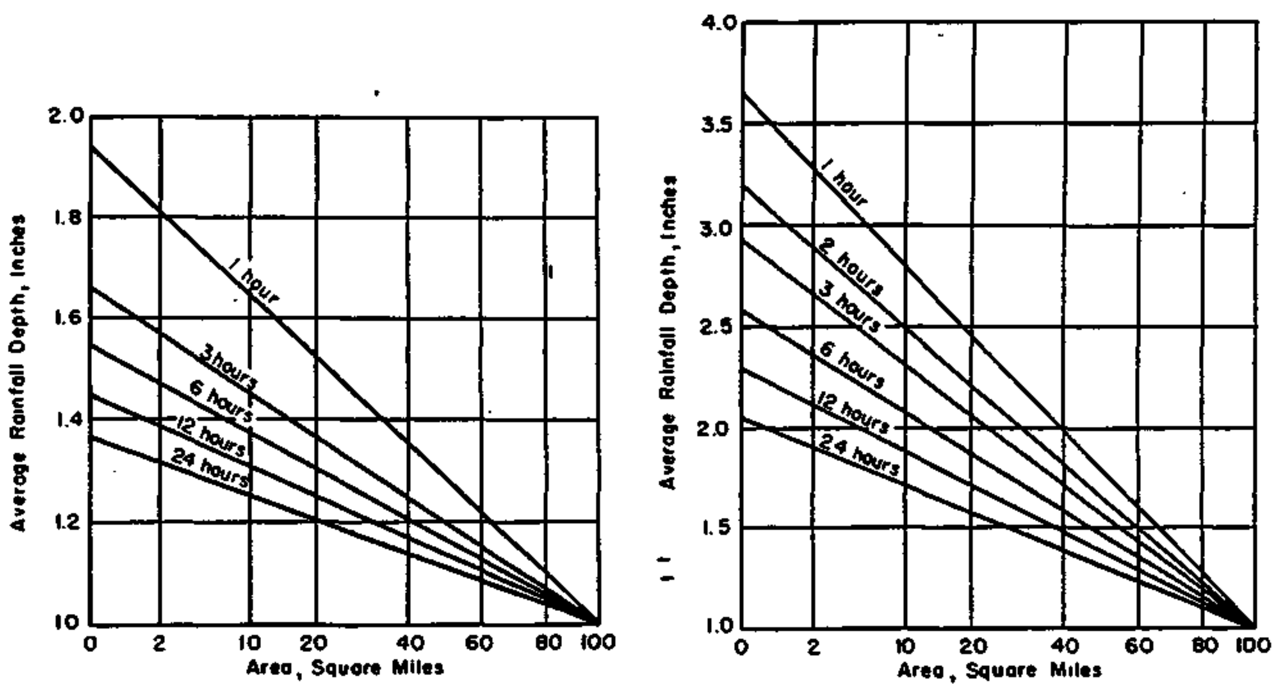


Figure 4-7. Area depth relations on a 100-square-mile area for one-inch storms of varying durations, and for average (left) and extreme events (right).

Area-Depth Relations

Two key factors in hydrological usage of meteorological data are the time distribution of rainfall within heavy rainstorms and the spatial distribution characteristics in these storm events. The method adopted to study the spatial distribution characteristics in the 1950s was area-depth relations, a method still in use today. The area-depth curve provides a measure of maximum rainfall, mean rainfall, and mean rainfall gradient in the storm isohyetal pattern. Early analyses of data from the El Paso and Panther Creek networks led to development of a mathematical expression to define the spatial distribution of storm rainfall in convective storms on small basins (figure 4-7). Study results, the initial contribution from the new hydrometeorological program, were summarized in a paper that appeared in a professional journal, *Transactions of the American Geophysical Union* (Huff and Stout, 1952).

Variability studies provided substantial information on the natural spatial variability in convective rainstorms that was not previously available in the literature. This new information was disseminated through Bulletin 44 and several papers published in national professional journals that recognized the importance of the work. These studies also led to a decision to expand studies on the space-time distribution characteristics of severe rainstorms because of their significance for the design and operation of water control systems.

Mesoscale Spatial Variability

Additional variability studies in the 1960s took advantage of the mounting data sample from the dense raingage networks. Results were summarized in a paper published in the *Journal of Applied Meteorology* (Huff and Shipp, 1968b). Analyses were made of both storm and monthly variability (figure 4-8). Results indicated that storm spatial variability is related exponentially to areal mean precipitation. The relation was not significantly improved by adding other variables, such as storm duration and maximum storm precipitation. The relative variability tends to increase with increasing area and is substantially greater in unstable types of precipitation (RW and TRW) than with steady types (R and S). Grouped by synoptic type, variability was found to be greatest in air mass storms and lowest with low center passages.

Monthly relative variability showed little difference in fall, winter, and spring months, but increased substantially in the summer. It was shown that when spatial variability is averaged over extended periods, it decreases to a relatively constant value for durations greater than two years. The 1968 paper provided additional new quantitative information on the characteristics of the spatial distribution of precipitation that can be useful to climatologists and hydrometeorologists. *And like all Survey hydrometeorology studies, the results were based on real data, not personal suppositions.*

Hydrology of Precipitation

During the 1968-1970 period, an extensive study of the precipitation hydrology of Illinois and the Midwest was carried out under a research grant from the National Science Foundation

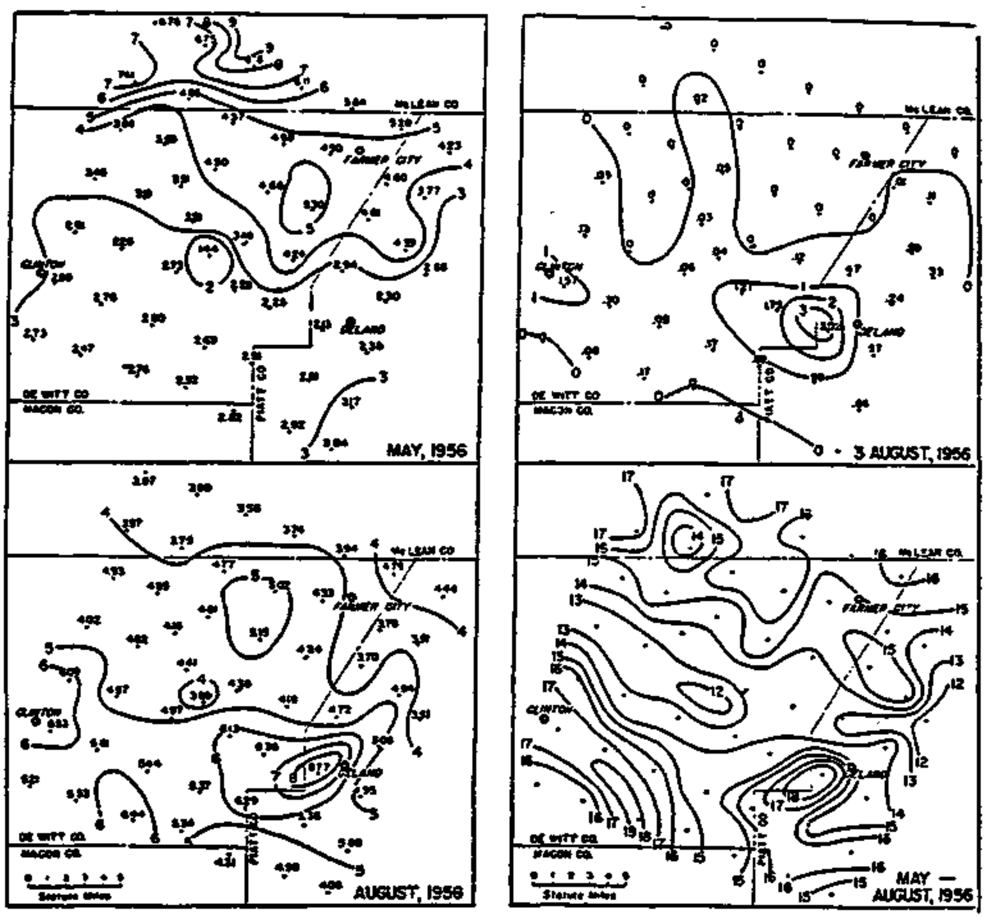


Figure 4-8. Examples of storm (August 3, 1956), monthly (May 1956 and August 1956), and seasonal rainfall patterns across a dense network (400-mi^2) in central Illinois. Extreme variability is shown on all time' scales.

(Huff, 1970; Huff and Schickedanz, 1970). Whereas the other Water Survey studies concentrated on heavy rainfall, this study involved nearly all aspects of precipitation. all levels of precipitation intensity were evaluated in this investigation. The study was oriented toward applications in weather modification, but yielded a wealth of information useful in hydrology, climatology, and other fields involved in the use of precipitation data. In addition to two major reports, several papers describing the results of various phases of the study were published in professional journals.

At the invitation of Dr. Helmut Landsberg, Huff wrote a chapter for *Advances in Geophysics,* which summarized much of the information contained in the two NSF reports, plus other pertinent results from the hydroclimatic studies (Huff, 1971d). This 76-page document provided further recognition of the important research being conducted under the Survey's hydrometeorology program.

Other than the spatial distribution studies as part of the severe rainstorm research, the variability studies were terminated in 1970. The additional rewards from continuation of these studies were considered minimal, and other aspects of the hydrometeorology research needed more attention.

TIME-SPACE DISTRIBUTION CHARACTERISTICS OF HEAVY RAINSTORMS

Accurate design and effective operation of water control structures is dependent upon reliable assessment of the temporal and spatial distribution characteristics of flood-producing rainstorms. The need for more comprehensive knowledge of these storm parameters expanded rapidly in the 1960s and 1970s with the advent and widespread acceptance of computerized runoff models. This need for more hydrometeorologic information was especially acute in the design of water control structures for urban areas and small basins.

In the mid-1960s, the Survey's hydrometeorological program devoted a large portion of its endeavors to alleviating the hydrometeorological information gap with respect to urban and small-basin hydrology problems. Data from the Survey's dense raingage networks were used. The time-space studies are really an extension of the rainfall variability studies discussed previously, and the results of these studies are summarized below.

Time Distribution of Rainfall in Heavy Storms

Data from the 11-year operation of the East Central Illinois Network of 49 recording gages in 400 square miles was the primary source of information for the time distribution study. The network was subdivided to provide relations for areas of SO, 100, 200, and 400 square miles, and the Boneyard Creek Urban Network was used to derive relations for 10-square-mile areas. Therefore, it was possible to determine time distribution relations for point and storm mean rainfall on areas of 10 to 400 square miles. As indicated earlier in this chapter, *mean rainfall* statistics are very important to the design hydrologist and other users of heavy rainstorm information.

Only storms in which one-inch or greater amounts had been recorded were used in the study. This provided a sample of 261 qualifying storms with durations of 3 to 48 hours. Appraisal of the sample led to the development of four basic types of curves showing the time distribution of rainfall in which the maximum rainfall occurred in the first, second, third, or fourth quarter of the storm (Huff, 1967d; 1990). Families of curves (statistical probability curves) were then computed for each quartile to provide the user with a measure of variability that would occur about any average curve derived from the data (figure 4-9). These statistical time distribution models provided the design hydrologist (or other user) with information that allows the user to determine runoff characteristics that could occur under various types of storm time distributions.

A paper summarizing the findings from this study was published in *Water Resources Research* (Huff, 1967d), and the models have since been used by various design hydrologists in the Midwest to investigate small-basin runoff characteristics. The time distribution models have

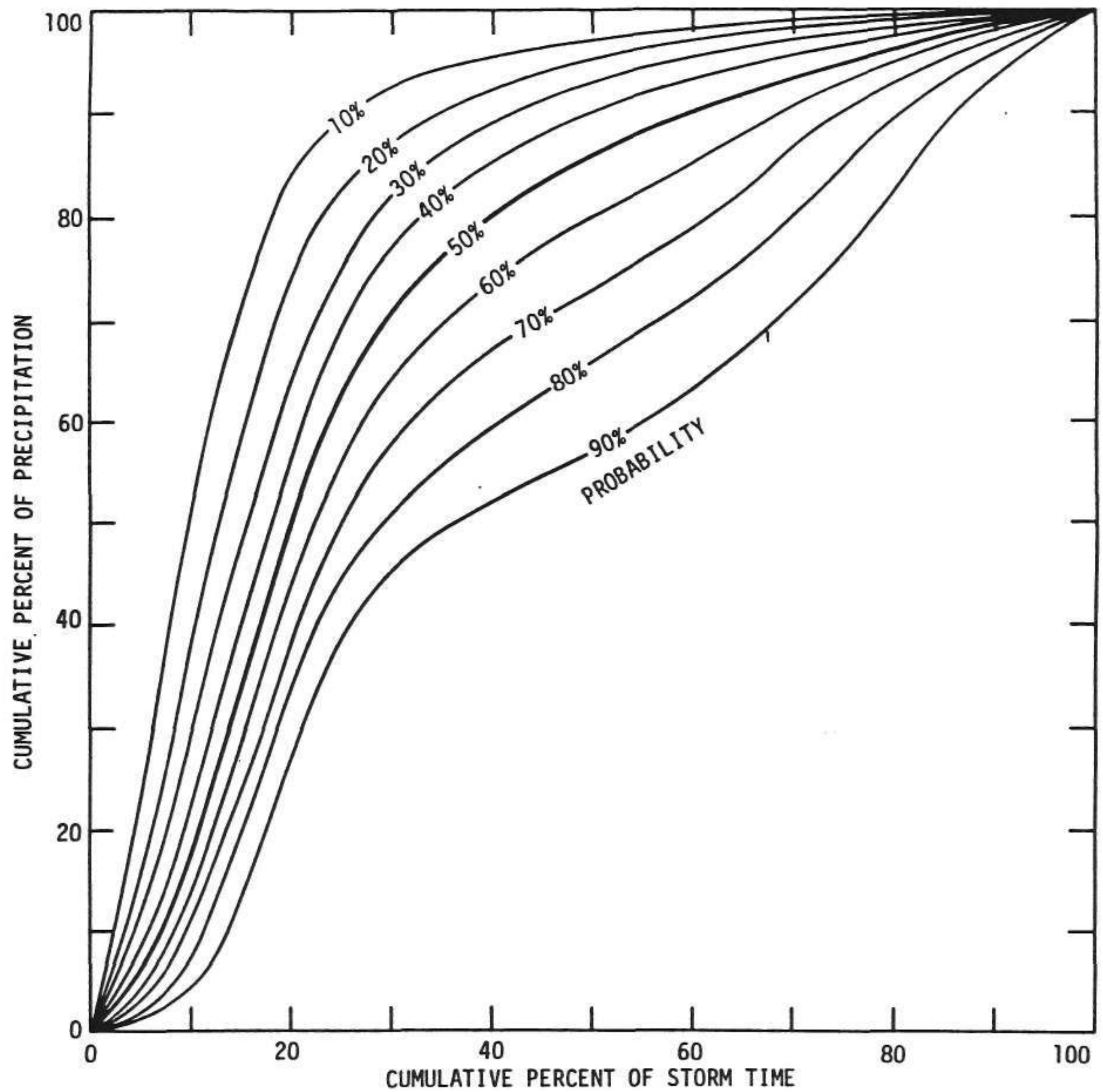


Figure 4-9. A statistical model of the time distribution for heavy rainfalls on small basins (10 to 400 mi^2) infirst-quartile storms (those with more than 50 percent of their rain in the first 25 percent of the storm's duration.

also been adopted by the Water Resources Division of the IDOT for application in all state-regulated water control projects.

This was the first published paper to provide both point and mean rainfall relations and variability measures for the time distribution of rainfall in heavy rainstorms. Minor revisions to the original *point rainfall* relations were made after a 1976 analysis of data from a long-term urban network of raingages in the Chicago area. An important factor in support of the Illinois time distribution models is that they are based on *real data*—no hypothetical assumptions were made in their derivation. Experience has shown that in general, the hydrologic community is more receptive to findings developed from actual data observations rather than those that are largely based on hypothetical assumptions.

Spatial Distribution of Rainfall in Heavy Storms

The dense raingage network data were used also in a study of storm spatial distribution characteristics applicable to small basins, urban areas, and other small areas of interest. The 11-year record from the East Central Illinois Network was again the primary source of data. The study was limited to excessive rainfall periods of 30 minutes to 48 hours for areas of 50, 100, 200, and 400 square miles. Excessive rains were defined as those producing rainfall amounts in the sampling area that equaled or exceeded the two-year frequency values for a given duration. Area-depth curves were used to define the spatial distribution characteristics.

Eight general equations were statistically tested in an effort to find a best-fit solution, which was found to vary with size of sampling area, mean rainfall, and storm duration. Because of the high degree of variability in me area-depth relations between storms, study results were presented as the probability distribution for given sets of conditions with respect to area, storm duration, and rainfall volume. The user was provided with both average curves and curves applicable to patterns of more extreme rainfall (figure 4-10).

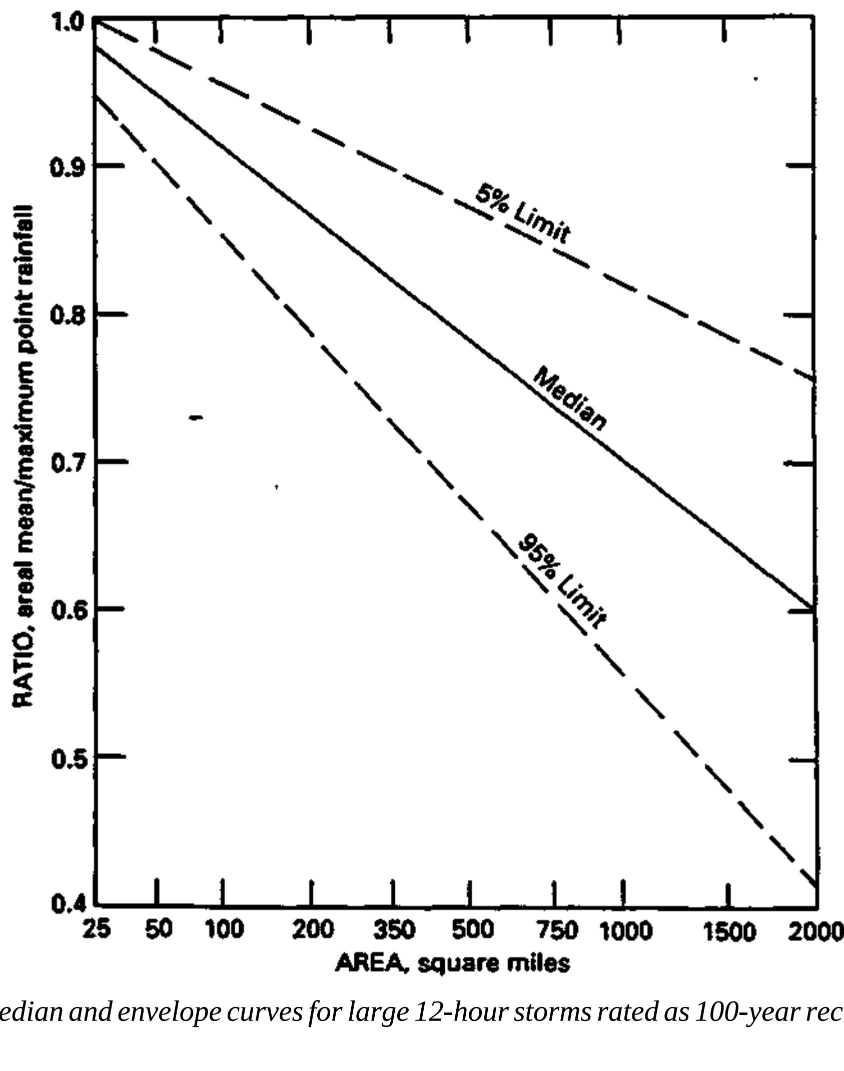


Figure 4-10. Median and envelope curves for large 12-hour storms rated as 100-year recurrence interval events.

A paper summarizing the results of this study was published in *Water Resources Research* (Huff, 1968a). The combination of the time distribution and space distribution papers provided a means to develop models incorporating both of these important factors for hydrologic application in the Midwest and other areas of similar rainfall climate and topography.

As indicated earlier in this chapter, area-depth relations were developed for all severe rainstorms analyzed by the Water Survey in Illinois, including those obtained from the climatic network, field surveys, and network records. These area-depth relations were very useful in later years when information was needed regarding severe rainstorms over larger areas, in conjunction with increasing environmental requirements pertaining to the development of water resources and water-control structures.

RAINFALL FREQUENCY RELATIONS

Entry into the development of point rainfall frequency relations for Illinois occurred under the hydrometeorology program in the late 1950s. Initial efforts were confined to the development of frequency relations for storm periods of one to ten days in Illinois. Previous frequency relations on the national scale had been limited to storm periods of 24 hours or less (Yarnell, 1935; U.S. Weather Bureau, 1955). However, it was considered likely that there would be future needs for information on longer storm periods, and this was verified by consultation with practicing hydrologists in Illinois.

The Late 1950s Study

Two relatively new methods of developing frequency relations were introduced into the first Illinois frequency study. One was the use of daily precipitation data from the cooperative observer network of the U.S. Weather Bureau. Previous studies had been based almost exclusively on the use of first-order data, which resulted in a relatively small number of samples in any state. For example, in 1955 there were five first-order stations in Illinois. However, it was possible to use an additional 39 cooperative stations with excellent long-term records by developing methods to make them applicable to frequency analysis.

The second innovation (made possible by the first) was to present frequency relations as average rainfall in selected areas of approximately homogeneous heavy rainfall events. However, some hydrologists were skeptical of the new method that changed mean rainfall, so it did not gain complete acceptance for many years. The 1950s study was published and distributed as Water Survey Bulletin 46 (Huff and Neill, 1959a). This bulletin also provided results of several associated studies of frequency-related factors that were performed as part of the investigation, such as statistical fitting procedures for frequency analysis (Huff and Neill, 1959b).

Initial Expansion of the 1950s Study

Numerous users of Bulletin 46 requested expansion of the study to include relations for shorter periods. As a result, relations were developed for periods of 5 minutes to 24 hours to supplement those provided in Bulletin 46. These new relations were published in Water Survey Technical Letter 1 (Huff, 1959) and Technical Letter 4 (Huff, 1960). Results of these early frequency studies indicated that existing publications of frequency relations were presenting values for 25-year to 100-year recurrence intervals that were significant underestimates. This resulted in a disagreement between the Water Survey and the National Weather Service (formerly the U.S. Weather Bureau) that persists to this day.

Frequency Study for Northeastern Illinois

In the mid-1970s, a frequency study was carried out for the Chicago metropolitan area and the six surrounding counties. By that time, urban effects on precipitation had been verified in the Chicago area (Changnon, 1968; Huff and Changnon, 1973). Furthermore, some Chicago area hydrologists had experienced problems that led them to doubt the veracity of NWS Technical Paper 40 (Hershfield, 1961) being used by the Chicago Metropolitan Sanitary District in design and operations of the urban sanitary and storm drainage systems. Bulletin 46 alerted users to this problem (Huff and Neill, 1959a). In addition, increased frequency of flooding in the Chicago area during recent years had also become a concern. Therefore, a detailed investigation of flood-producing rainstorms and the derivation of new frequency relations was undertaken after interested groups and agencies indicated the need for such a study at a conference sponsored by the Water Survey in 1971.

A comprehensive study was undertaken that made use of all possible sources of data that related to the frequency of heavy rainstorms and/or frequency-related factors pertinent to the design and operation of a water-control system in northeastern Illinois. As expected, the new frequency relations verified the underestimates in existing frequency relations indicated by the Bulletin 46 study (Huff and Neill, 1959a). The new relations provided more realistic values for the longer recurrence intervals through use of the most comprehensive data sample ever assembled for northeastern Illinois (and most other places). Despite the findings, the Chicago Metropolitan Sanitary District continued to use Technical Paper 40, but the Water Resources Division of IDOT (which regulates water-control activities in Illinois, except in the Chicago metropolitan area) and the majority of private sector hydrologists accepted the Water Survey findings.

In addition to the new frequency relations, quantitative information was provided concerning point-area relationships, frequency distribution of storm centers, diurnal and seasonal distribution of heavy storms, orientation and shape of heavy storms, synoptic weather conditions associated with severe rainstorms, time between successive occurrence of heavy rain events, and time distribution characteristics of rainfall during heavy storms. Results of the project were published in Report of Investigation 82 (Huff and Vogel, 1976), which provides a wealth of information on hydrometeorological factors that influence the flooding potential of heavy rainstorms in urban areas or small basins.

The 1980s Study

The impetus for a new Illinois frequency study was provided by Water Survey Chief Changnon in a 1983 meeting with John Vogel and Floyd Huff. The last Illinois frequency studies had been made more than 20 years earlier (Huff and Neill, 1959a;Hershfield, 1961). In the meantime, evidence indicated that the frequency of floods was increasing in Illinois (Changnon, 1980, 1983). Needs for more comprehensive frequency relations had escalated as more sophisticated hydrologic models were developed and put to use. The last national-level publication on the subject (NWS Technical Paper 40) was not only inadequate for these new needs, but it appeared to underestimate rainfall for long-period recurrence intervals, as Survey scientists had indicated in Bulletin 46 and Report of Investigation 82. However, recurrence-interval values for SO to 100 years and longer had become very important to the hydrologic designer because of more restrictive environmental regulations imposed by Federal and State governments.

Although the needs were recognized, pressure of other research projects caused continuous delays, and a major effort to complete the new frequency study did not occur until 1986-1988. Retiree Floyd Huff, who had returned to the Survey part-time, was assigned to supervise the project with able assistance by Jim Angel.

Frequency relations were developed for the new study for time periods ranging from 5 minutes to 10 days and for recurrence intervals ranging from 2 months to 100 years. These wide ranges, which had not appeared in previous publications, were considered necessary to meet all user needs in the foreseeable future. The data sample consisted of records from 61 Illinois daily precipitation stations (cooperative observer network) and 34 recording raingage stations in Illinois and surrounding states. Frequency relations were determined on both a seasonal and annual basis, because seasonal data are required for some hydrologic purposes.

The frequency relations were presented in two forms (point rainfall frequencies and mean relations) to satisfy the preference of users. Point rainfall frequencies were provided because these had been used mostly in the past. Mean relations were provided for ten regions of Illinois in which the heavy rainstorm climate is approximately homogeneous. The second method was recommended by the scientists participating in the study to help minimize the influence of sampling vagaries, which are almost unavoidable when dealing with a highly variable natural parameter (rainfall).

Included in the frequency study was an update of the Chicago area relations published in Report of Investigation 82 (Huff and Angel, 1993). Other related studies included the time distribution of rainfall within heavy storms; the shape, orientation, and movement of severe rainstorms; the distribution of non-representative observations (commonly referred to as "outliers") in large samples; and the dispersion of point rainfall values near the mean in areas of similar rainfall climate.

The results of this comprehensive study of Illinois rainfall frequency relations and related subjects was published in Water Survey Bulletin 70 (Huff and Angel, 1989c). An abbreviated version was published in Circular 172 (Huff and Angel, 1989d) for those users not interested in the details of the development of the frequency relations. The new frequency relations have been accepted by most users in the State, including the Water Resources Division of IDOT, which furnished some financial support for the project.

The Nine-State Project

After completion of the Illinois frequency study, a similar study was carried out for the nine Midwestern states that constitute the Midwestern Climate Center: Illinois, Indiana, Iowa, Kentucky, Michigan, Minnesota, Missouri, Ohio, and Wisconsin. The project was jointly sponsored by the Midwestern Climate Center and the Illinois State Water Survey.

The methods and techniques developed and employed in the Illinois study were used to develop the nine-state relations. Using primarily 275 long-term daily reporting stations of the NWS cooperative observer network supplemented by 134 stations with shorter records, rainfall amounts were determined for recurrence intervals from 2 months to 100 years and for durations of 5 minutes to 10 days. The results were presented as isohyetal maps of point rainfall and as climatic division averages in tabular form. The report also examined the time distributions of heavy rainfall within heavy storms, the seasonal distribution of heavy rainstorms in the Midwest (Angel and Huff, 1995), and other storm characteristics such as storm orientation and movement.

Results of the frequency study of heavy rainstorms and other studies related to the application of the frequency relations were summarized in Survey Bulletin 71 (Midwestern Climate Center Report 92-03) by Huff and Angel (1992).

Highlights of the Frequency Studies

The frequency studies made six major contributions.

1. The studies provided more realistic estimates of storm rainfall for recurrence intervals of 25 to 100 years in Illinois and the Midwest. Long recurrence intervals have become a subject of major concern with respect to water control activities in recent years.

2. The application of daily reporting precipitation data in the frequency studies provided a means for obtaining a much larger data sample, and, consequently, more reliable determination of frequency relations. These relations for heavy rainfall use only about the upper 1 percent of a station's precipitation observations, thereby introducing a serious sampling problem.

3. The use of areal means helps to minimize the sampling error in computing frequency relations, a situation made possible by the much larger samples obtained by using the

cooperative network data.

4. A wealth of quantitative information was provided on hydrometeorological factors that influence the time-space distribution characteristics of heavy rainstorms in urban areas and small basins. These factors influence the flooding potential of convective storms, the most common source of flash floods in the warm season, and they must be considered in flood prediction for hydrologic operations and other purposes.

5. An urban-related rainfall increase in the Chicago area was verified, and its location was defined. This provided a quantitative measure of the effect of the increase on the regional frequency relations.

6. The frequency studies provided recognition for the Survey in another important hydrometeorological area.

URBAN HYDROMETEOROLOGY

Urban hydrometeorology at the Water Survey has dealt with two meteorological factors that can influence the time-space distribution characteristics of precipitation and thus the runoff characteristics in heavy rainstorms. The two weather-related factors are natural rainfall variability and inadvertent weather modification. Of these, inadvertent weather modification has stimulated by far the most attention in the meteorological and hydrological communities.

The Survey's Atmospheric Sciences Section has established itself as a leader in the field of inadvertent weather modification (see Chapter 7). The Survey's interest dates back to 1968 when Changnon published a controversial paper relating to an apparent precipitation anomaly at La Porte, IN, resulting from inadvertent weather modification by the Chicago industrial area (Changnon, 1968). Since Chapter 7 deals with the inadvertent weather research in detail, the present chapter will be limited to summarizing the application of those findings relevant to urban hydrologic problems. Inadvertent weather modification may affect numerous fields of endeavor. However, the urban hydrologist's interest is mostly in how it may affect runoff with respect to intensity, duration, spatial distribution, and other hydrologic factors.

Initial Urban Study

The Water Survey's first formal entry into the field of urban hydrometeorology occurred in 1959-1960 when Huff and Changnon (1960) undertook a study of the distribution of excessive rainfall amounts over a small urban area. They used a 10-year record of storm precipitation from a network of 11 recording raingages in the 10-square mile urban area of Champaign-Urbana, Illinois. One or more raingages of all storms in the study recorded amounts that exceeded the two-year average recurrence interval of point rainfall for durations ranging from 30 minutes to 24 hours.

Results of this study provided new information on the *natural variability* of heavy rainfall within small urban areas and small basins that should be considered in hydrologic problems relating to such areas. Information was provided concerning the frequency of excessive amounts in small areas compared with occurrences at any given point, the percentage of the area experiencing excessive amounts during individual storms and the frequency distribution of this percentage, the adequacy of a single point record to define the frequency distribution of areal mean rainfall over the surrounding area, and the frequency with which excessive amounts for periods of 30 minutes to 24 hours occur within the same storms. Significant evidence of inadvertent weather effects was not found in this small urban area. A paper summarizing the results of this study was published in the *Journal of Geophysical Research* (Huff and Changnon, 1960a).

Little was accomplished in the urban hydrometeorology program in the early and mid-1960s because of personnel assignments to more pressing tasks in other Survey meteorological programs. This emphasis changed, however, after Changnon's 1968 La Porte paper.

Eight-City Climatic Study

In the 1969-1971 period, Changnon and Huff (1972), with support from the National Science Foundation, made an extensive climatological analysis of possible urban effects on precipitation in and around eight major cities in the central and eastern United States. These included St. Louis, Chicago, Indianapolis, Cleveland, Washington, Houston, New Orleans, and Tulsa. Cities were chosen to reflect differences in climate, population, industrial complexes, and topographical features.

Urban-induced increases in precipitation were identified at six of the eight cities. Increases varied from 9 to 17 percent, and the maximum effect occurred primarily in urban centers or within 30 miles downwind of them. Of major hydrologic importance was the finding that the urban-induced increases appeared to occur most often on days when the natural rainfall was moderate to heavy. In general, the urban effect was most pronounced in late spring and summer. The frequency of hail and thunder-days were also influenced by the urban environment. Overall, the findings indicated the urban effect was sufficient to be of concern to the urban hydrologist.

Results of the eight-city study were presented in detail in the grant reports, and were summarized in two papers published in the *Journal of Applied Meteorology* (Huff and Changnon, 1972c) and in the *Bulletin of the American Meteorological Society* (Huff and Changnon, 1973). The study was instrumental in both the planning and initiation of METROMEX, a major field study of inadvertent weather modification at St. Louis in the 1971-1975 period (Changnon et al., 1971).

Hydrologic-Related Findings from METROMEX

Chapter 7 provides a complete description of the METROMEX study. The discussion here is limited to those findings that are most relevant to hydrologic problems. METROMEX results verified the earlier conclusions of the eight-city climatic study (Huff and Changnon 1972c, 1973) that the urban effect occurs most often and is most pronounced in naturally-occurring storms of moderate to heavy intensity crossing the urban area. For example, the METROMEX analyses at St. Louis indicated the anomaly occurred mainly in storms producing average rainfall exceeding one inch on the 2,000-square-mile network.

The detailed observational program showed the urban effect to be substantially greater at its center (approximately 30 percent in summer) than indicated for St. Louis and the other cities in the climatic study. This finding is partially due, at least, to the raingage density in METROMEX, about one gage every three miles. The climatic data network used in the eight-city study used spacing on the order of one gage every 15 to 20 miles except in special cases. The urban effect was greatest in summer and late spring. The urban-induced rainfall increases were found to result most often from enhancement of the natural atmospheric rain processes in organized weather systems (fronts, squall lines, and squall zones).

As part of the METROMEX program, detailed analyses were made of raincells (rain intensity centers) within heavy convective storms (Huff, 1976c). This was made possible by the combination of radar observations and raingage data from the 225-gage network. These cells in combinations are responsible for the heavy rainfall produced by convective storms (usually thunderstorms). Results indicated a substantial increase in water yield from cells exposed to potential urban effects, compared with those exposed only to the surrounding rural environment. Naturally occurring heavy cells were found to undergo the greatest enhancement from urban exposure (as opposed to new cells forming over the urban area).

In summarizing urban effects on storm rainfall in the Midwest, Huff (1977b) pointed out that "hydrologically, the five-year study (METROMEX) indicates that the frequency distribution of heavy rainfalls of 5-minutes to 2-hour duration may vary significantly between urban, suburban, and rural areas in large urban-industrial regions, and this variation should be considered in the design and operation of urban hydrologic systems." When summarizing impacts of the METROMEX findings, Changnon et al. (1977) showed that urban-induced increases in precipitation have influence on several aspects of water resources. In addition to their effect on rainfall frequency distributions, there are impacts on water supply, sewage treatment, surface water pollution, and ground-water quality.

The massive amount of hydrometeorologic information accumulated under the METROMEX program and other urban-effect studies has emphasized the need for the hydrological community to evaluate the implications of these findings in the design and operation of water control systems and other hydrologic endeavors. The question is whether the hydrologic community is inclined to accept and apply the findings. The need to coordinate knowledge and information between the meteorological and hydrological communities was emphasized further by Huff (1986) in the Robert E. Horton Lecture at the Sixth Conference on Hydrometeorology of the American Meteorological Society, but the degree of coordination still remains questionable. Applications of the new information and knowledge accumulated in recent years from hydrometeorological research to hydrological problems could be expensive and therefore probably unacceptable to some in the hydrologic community and their clientele.

The Chicago Project

A major hydrometeorological research program was carried out in the Chicago metropolitan area during 1976-1979 by the Atmospheric Sciences Section with financial support from an NSF grant. The Survey's expertise in radar meteorology and hydrometeorology (original areas of research) were undoubtedly helpful in obtaining the relatively large grant needed to pursue this project.

Major objectives of this research were to 1) develop a real-time, prediction-monitoring system for storm rainfall using a combination of weather radar and telemetered raingage data, 2) determine the precipitation requirements for hydrologic design, operation, and modeling purposes, 3) define the time-space characteristics of severe rainstorms in the Chicago area, and 4) establish methods for applying the Chicago findings to other cities (Huff and Changnon, 1977). Basic components of the field measurement program were a network of more than 300 recording raingages encompassing 4,000 square miles in and around Chicago, plus two sophisticated radar systems for obtaining real-time information on storm parameters pertinent to optimizing operations of urban water resources systems.

All of the above objectives were completed successfully except number 4, which had to be omitted because funding problems made it necessary to reduce the project duration by one year. The prediction-monitoring system was described in detail in a paper appearing in the *Journal of Water Resources Planning and Management Division of the American Society of Civil Engineers* (Huff et al., 1981). A detailed description of the research and findings were also presented in Water Survey Circular 146 (Changnon et al., 1980) and the Final NSF Report (Changnon et al., 1980).

Recent Activities in Urban Hydrometeorology

In 1988-1989, a new urban raingage network was established in the Chicago urban area in cooperation with the U.S. Army Corps of Engineers. This network replaced an older, smaller, urban network initiated in 1949 that consisted of raingages operated by several government agencies. The Corps' was concerned with the determination of water supplies withdrawn from Lake Michigan on an annual basis, as prescribed by law (Peppier, 1991). The Survey's interest was primarily research in urban hydrometeorology. The network consists of 25 recording raingages in an urban area of approximately 800 square miles that should provide a large amount of new information on the urban precipitation climate in future years.

Data from the new network and the old urban network, described by Huff and Vogel (1976), have been used to investigate an apparent increase in the frequency of floods in the Chicago urban area in the last thirty years. This apparent increase has been disturbing to city and state officials, area hydrologists, and property owners who suffered substantial property damage from the floods.

A comprehensive analysis of the data led to the conclusion that the increase in flood frequency has resulted primarily from 1) an upward trend in heavy rainstorm frequencies since the early 1900s (Huff and Changnon, 1987), and 2) the use of frequency relations in hydrologic design problems that substantially underestimate the frequency and magnitude of severe rainstorms. The frequency errors are due partly to failure to adjust for the urban-induced rainfall factor in earlier frequency computations. The foregoing problems have been overcome in the new Survey frequency relations for Illinois (Huff and Angel, 1989c). A paper describing this project and its findings was published in the August 1995 issue of the *Water Resources Bulletin.*

SUMMARY

Major Achievements

1. *Major increases in information and knowledge on the various distribution characteristics of heavy rainstorms*—a. subject that became increasingly important over time.

2. *Development of statistical models for severe rainstorms that exceeded the 100-year frequency of rainfall at their centers.* These are the storms of major interest to design hydrologists at the present time.

3. *Accumulation of massive amounts of data and information relating to time and space distributions in heavy rainstorms,* including the development of statistical models to provide input to hydrologic models.

4. *Accumulating and publishing a large amount of new quantitative information on the small-scale natural variability in convective rainstorms that are usually associated with flash-flood storms.* Bulletin 44 summarizing early findings was probably the most popular Water Survey report or paper published in hydrometeorology and also received national and international acclaim.

5. *Development of a comprehensive precipitation hydroclimatology applicable to Illinois and the Midwest.* Although oriented toward applications in weather modification, this study yielded considerable information on precipitation characteristics that is useful in hydrology and other fields concerned with precipitation.

6. *Development of improved frequency relations for heavy rainstorms in Illinois and later the nine-state Midwest.* The studies were expanded to provide other pertinent information such as storm shapes, orientation, movement, time distribution of rainfall,

   area-depth relations, antecedent rainfall associated with heavy storms, time between successive excessive rainfalls, and other factors.

7. *Application of information and knowledge on inadvertent weather to the hydrology of major urban areas,* particularly to the increased flooding problem in the Chicago metropolitan area in recent years.

Pivotal Papers and Reports

Bulletin 44 (Huff and Neill, 1957a) focused national and international on the Water Survey's hydrometeorological program. It was also the source for five papers published in professional journals. This report and the associated papers, based on data from the dense raingage networks, provided new quantitative information on the distribution characteristics of heavy storm rainfall applicable to small basins and urban areas.

A paper by Huff and Semonin (1960) appearing in an American Meteorological Society Monograph brought initial attention to the severe rainstorm studies. This paper presented the results of a hydroclimatic study of major flood-producing storms in Illinois from 1914 to 1957. A paper in the *Journal of the Hydraulics Division of ASCE* updated the Huff-Semonin paper and incorporated new information from the dense network and radar operations (Stout and Huff, 1962). A third important paper on severe rainstorms was published two years later in the *Journal of Meteorology* (Huff and Changnon, 1964b), which provided the first statistical model for extreme storm events, along with mesoscale analyses of a 10-inch rainstorm centered on our southern Illinois raingage network and observed by radar. This paper provided details never before available on a storm of this intensity and its mesoscale structure and synoptic features.

A very important hydrologic paper by Huff (1967d) was published in the *Journal of Water Resources Research.* Based on the dense raingage network data, the time distribution of rainfall during heavy rainstorms was defined by a series of statistical models that are adaptable as input to hydrologic design models. This met a major need in the hydrologic community, and the models have had relatively widespread usage. For example, the use of the distribution curves is required for all state-regulated projects in Illinois.

A 76-page chapter in *Advances in Geophysics* (Huff, 1971), summarizing major results of the hydroclimatic studies, brought expanded recognition and prestige for the hydrometeorological program.

The Changnon-Vogel paper (1981) in *Water Resources Research* provided new and important information on the hydrometeorological characteristics of isolated severe rainstorms and their spatial distribution.

The Huff (1993) report summarizing the distribution characteristics of storms having a frequency of 100 years or longer was an important contribution to the hydrologic community which must consider these storms in most of their water control structural designs at the present time.

Major Projects

The field survey and analysis program during 1950-1970 is considered a critically important project. Although limited in scope, it provided a vast amount of data and information on the distribution characteristics of severe rainstorms never before available. This has proved invaluable in later years when information on the distribution characteristics of storms having a return period of 100 years or longer became a major need of the hydrologic community in order to meet stricter environmental regulations regarding the design of water-control structures. It was the single most important source of information in the database that permitted development of Survey Circular 176 (Huff, 1993), which helped to alleviate this need for information in Illinois and the Midwest.

A second major project that helped meet an expanding need in the hydrologic community was a comprehensive study of the time and space distribution characteristics of heavy rainstorms applicable to small basins and urban areas. The primary source of data for this project was the Water Survey's dense raingage networks. Storms were used in which rainfall for periods of 1 to 48 hours exceeded the 2-year recurrence interval for a given storm duration. Statistical models applicable to hydrologic models were especially welcomed by hydrologists, because these characteristics are an important controlling factor in storm runoff.

A third major project was the NSF-sponsored research during 1968-1970 involving quantitative evaluation of convective rainfall characteristics pertinent to weather modification activities (research, operations, and evaluation of results). Although aimed primarily at weather modification applications, the study produced a wealth of hydroclimatic information very useful to hydrologists, climatologists, and other users. The importance of this project is reflected in the invitation to summarize the findings in *Advances in Geophysics* (Huff, 1971d).

The identification and assessment of urban effects (inadvertent weather modification) on precipitation was a very important hydrometeorological research activity that began with the La Porte findings of Changnon (1968), and continued with the eight-city study of potential urban effects (Huff and Changnon, 1973), the large-scale METROMEX program (Changnon et al., 1977), and the CHAP project in the late 1970s to develop of monitoring-prediction techniques for incoming heavy rainstorms in large metropolitan areas (Huff et al., 1981). These were all major contributions in the field of inadvertent weather modification.

The development of new rainfall frequency relations for Illinois, and later the Midwest, was a major contribution from the hydrometeorological program (Huff and Angel, 1989c; Huff and Angel, 1992). The 1989 study introduced new analytic techniques, expanded frequency relations, and provided supplementary information designed to meet new and expanding user needs.

Key Staff

Those scientists involved most frequently in this program included Floyd Huff, Stanley Changnon, James Neill, John Vogel, and James Angel (fig. 4-11). Other significant contributions came from Glenn Stout, Richard Semonin, Douglas Jones, Homer Hiser, and Bill Shipp. Analysts involved to a substantial degree included Elmer Schlessman, Phyllis Stone, and Marion Adair. Marvin Clevenger, Bob Sinclair, and Herb Yuen provided valuable contributions in data reduction and programming procedures. Carol Verseman, a University of Illinois student, was involved part-time for three years and provided valuable assistance to the scientists.

Others who became involved during the CHAP project included engineers Eugene Mueller, Donald Staggs, and David Brunkow. Neil Towery was associated with both the field operations and data analyses, and Nancy Westcott was involved in the analysis activities.

Figure 4-11. In 1971 the Atmospheric Sciences Section launched the first in a long lasting series of annual retreats. Those attending the 1971 retreat in Monticello were (front row, l. to r.) Terry Flack, Oscar Anderson, Stan Changnon, Griff Morgan, and Bob Beebe. Second row: Elmer Schlessman, Bob Cataneo, Harry Ochs, Doug Jones, Floyd Huff, and Dick Semonin. Top row: Paul Schickedanz, John Wilson, Mark Edington, Bill Ackermann, Jack Adam, Tony Rattonetti, Gene Wright, and Art Sims.

Chapter 5

CLIMATE RESEARCH AND SERVICES

Stanley A. Changnon and Floyd A. Huff

INTRODUCTION

The concept of a program focusing on climate research and services developed in 1953 as a result of a nationwide call from the U.S. Weather Bureau for states to join in a national climate program and establish cooperative projects between the Weather Bureau and agencies in each state. The goal was to create an analyzable digitized database for each state and thus for the nation by editing and entering historical weather data prior to 1949 onto punch cards for all the weather stations in the state. The Weather Bureau had begun entering all weather data on cards starting with the 1949 data but did not have the resources nor personnel to do the historical data.

Stanley Changnon, who was finishing his assignment as head of the University of Chicago's Cloud Physics project at the Survey in the fall of 1954, appealed to Chief Arthur Buswell for state support to launch a cooperative project to enter the Illinois historical data on punch cards. The project was expected to last two to three years. An important factor affecting the decision was the severe 1952-1955 drought then in progress in Illinois, which had produced numerous requests for information related to the state's climate and the drought's severity. Chief Buswell approved the endeavor as part of the Meteorology Section's activities, making Changnon Director of the Illinois Cooperative Climate Punch Card Project, which provided an invaluable database and effectively launched the climate research endeavors at the Water Survey. However, a program of climate services can be traced back to 1948 when the Water Survey agreed to take over the operation of the local Urbana weather station (see Chapter 2), an act that provided data for local information and climate services.

The initial concerns of the evolving program in 1954-1955 were data quality and reporting project progress to the U.S. Weather Bureau. Attention to climate data issues, including analytical techniques for climate research, was to become an area of continuing, albeit intermittent, attention from 1955 on.

The earliest climate research at the Water Survey focused on descriptive climatologies of various locations in Illinois and various weather conditions such as rainfall, evaporation, thunderstorms, and clouds. The drought of the mid-1950s became another subject of the early climatological research. Many of the initial studies were intended to provide information wanted by Survey hydrologists or to answer inquiries from the public. Climatological studies of severe weather including severe winters were another form of descriptive research that developed in the early 1960s.

The punch card data for 70 Illinois weather stations were a "gold mine" for performing research that had been prohibitively difficult before. Data included daily temperature and precipitation values for each station from 1901-present. Opportunities for funding from federal agencies enabled Survey climatologists Huff and Changnon to pursue research of how natural surface conditions such as the hills of southern Illinois or Lake Michigan affected the climate. Closely allied were studies focusing on the causes for the climate features found in Illinois. This type of research expanded in the 1980s when better data were available in digital form and staff like Peter Lamb had interest and expertise in studies of the larger scale conditions affecting the Midwestern climate.

Opportunities for funding from the weather insurance industry to study the hail climate of Illinois and elsewhere developed in 1959 as a result of the Illinois hail climatology study (Huff and Changnon, 1958). This launched a long-term research effort that still persists today concerning the climatic aspects of severe storms. In 1957, new Water Survey Chief Ackermann chose to have Changnon's 1956 University of Illinois masters thesis about Illinois' thunderstorms and rainfall published as one of the Survey's Reports of Investigation, another decision that fueled the severe storm climatology endeavors. Attention in subsequent years was directed to the climatology of Illinois tornadoes, severe rainstorms, high winds, and lightning. Research focusing on the climatic aspects of droughts and floods (extended wet periods) also continued, largely on an event-driven basis after 1960, and it is important to appreciate that until 1980 the climate research was heavily oriented to Illinois conditions. Research on climate change conducted primarily after 1975 is described elsewhere (see Chapter 7). In addition, there has been extensive research relating the effects of climate on the physical world and socioeconomic conditions (see Chapter 10) and work in hydroclimatology (see Chapter 4).

In 1954, Helmut Landsberg, Head of the Weather Bureau's Office of Climatology, made a bold move by establishing a "state climatologist" in each state to help state agencies and university scientists with climate data and information. The Weather Bureau sought a "home" for Paul Sutton, the first Illinois State Climatologist, and the Water Survey proffered an office and support typing services. From 1955 until the Weather Service ended their state climatologist program in 1972, a total of five people held the title, including Bill Harms, Al Joos, and Bill Denmark. They worked closely with Changnon, who became the Survey's staff climatologist in 1957, but their presence required a close interaction and coordination with the Survey's climate services activities. When the federal program ended in 1972, Changnon became the Illinois State Climatologist through a cooperative arrangement with the National Climatic Data Center, and the Survey has funded and maintained the position ever since.

Assumption of the state climatologist function in 1972 led to more emphasis on climate services, which expanded greatly in the late 1970s and 1980s as the Water Survey undertook a major role in working with Senator Adlai Stevenson to help get the National Climate Program

(NCP) Act established. The act called for enhanced climate services and a strengthening of the state outreach programs, and since 1980 the Survey has sustained a very active research and assessment program relating to climate services. This interest led the Survey to pioneer and promote the concept of regional climate centers as a means to improve climate services between the national and state levels. Climate conditions typically assume regional dimensions, and needs for climate information typically are at the regional scale. An assessment of the value of a potential regional climate center during 1981-1985 established the value of these centers, and the first of the nation's six regional climate centers was located at the Water Survey in 1987.

The Survey's diverse climatic research has continued to expand over time, partly as a result of the enhanced services endeavors and the regional climate center's presence (figure 5-1). For example, the ever-growing assessments of users of climate information revealed the strong desires for climate forecasts, long-term outlooks for conditions months and seasons ahead. Consequently, Survey scientists initiated climate forecast research in the late 1970s, including testing and development of statistically based climate techniques.

Table 5-1 shows the number of climate-related publications from 1951 onward. More than 190 publications were issued over a 40-year period, 1955-1994. These values do not include those dealing with climate change (Chapter 7) or those concerning impacts of climate (Chapter 10). The number of publications related to climate research and services exceeds

Table 5-1. The temporal distribution of publications related to climate research and services.

		Reports		
Year	Papers	State series	Contract	Total
1951-1954	0	2	0	2
1955-1957	1	6	0	7
1958-1960	3	2	3	8
1961-1963	3	3	3	9
1964-1966	5	1	3	9
1967-1969	3	4	0	7
1970-1972	5	2	0	7
1973-1975	2	3	1	6
1976-1978	2	2	1	5
1979-1981	4	5	6	15
1982-1984	21	8	7	36
1985-1987	13	11	6	30
1988-1990	20	4	0	24
1991-1993	18	6	0	24
1994-1995	3	0	0	3

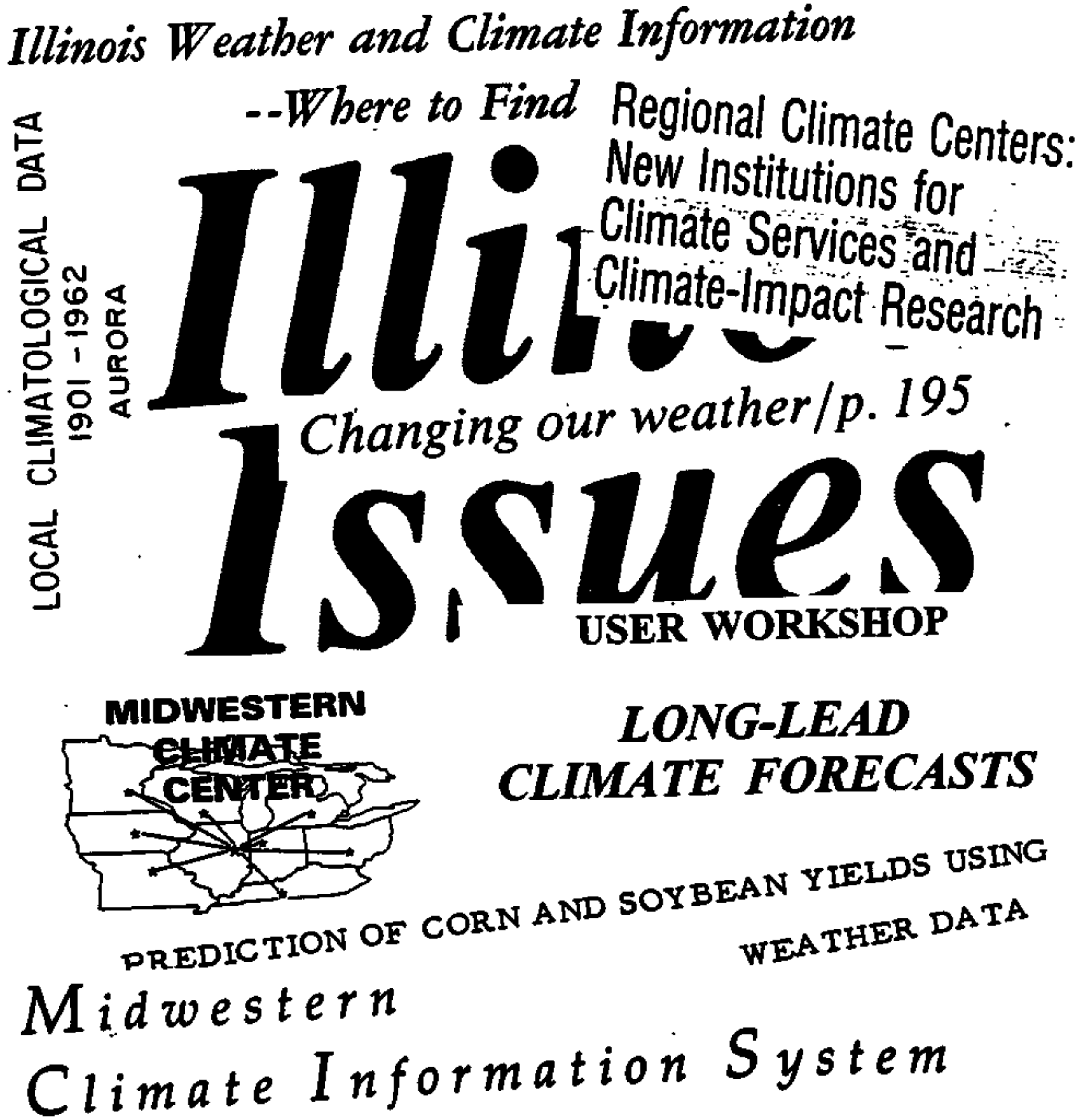


Figure 5-1. The titles of several publications which help illustrate the climate services efforts of the Water Survey.

those written in any other major atmospheric sciences program area. Review of the state reports addressing climate shows a spurt during the 1955-1963 when many studies defining the climate of Illinois were done. The nine contract reports during 1958-1966 were related to insurance-funded studies of hail and severe storm climatologies.

A second surge in the issuance of a series of Illinois-focused climate publications came during 1980-1990 and was related to alternative energy analyses, studies of a series of severe winters, and analyses of users of climate data and information. The sizable growth in scientific papers after 1981 was related to Chief Changnon's desire to increase climate research efforts at the Water Survey. Climatologists Wayne Wendland and Peter Lamb were employed in 1977 and 1979, respectively, and a Climate Section was established in 1980. Also in 1980, the Board of Natural Resources and Conservation approved Chief Changnon's request to reorganize the large Atmospheric Sciences Section as three sections: a Meteorology Section headed by Bernice Ackerman, a Climate Section headed by Wayne Wendland, and an Atmospheric Chemistry Section headed by Donald Gatz. A Climate Information Unit headed by John Vogel was established in 1980 to enhance climate services but was later dissolved in 1987 when the Midwestern Climate Center was created. Further shifts occurred in 1984 with the formation of the Climate and Meteorology Section headed by Peter Lamb and the dissolution of the Meteorology and the Climate Sections in 1990 when an Office of Applied Climatology headed by Kenneth Kunkel was established. A reduction in organizational attention and support for pure climate research was reflected by the decrease in publications since 1993, although considerable research has been directed to the areas of climate impacts (Chapter 10) and climate change (Chapter 7).

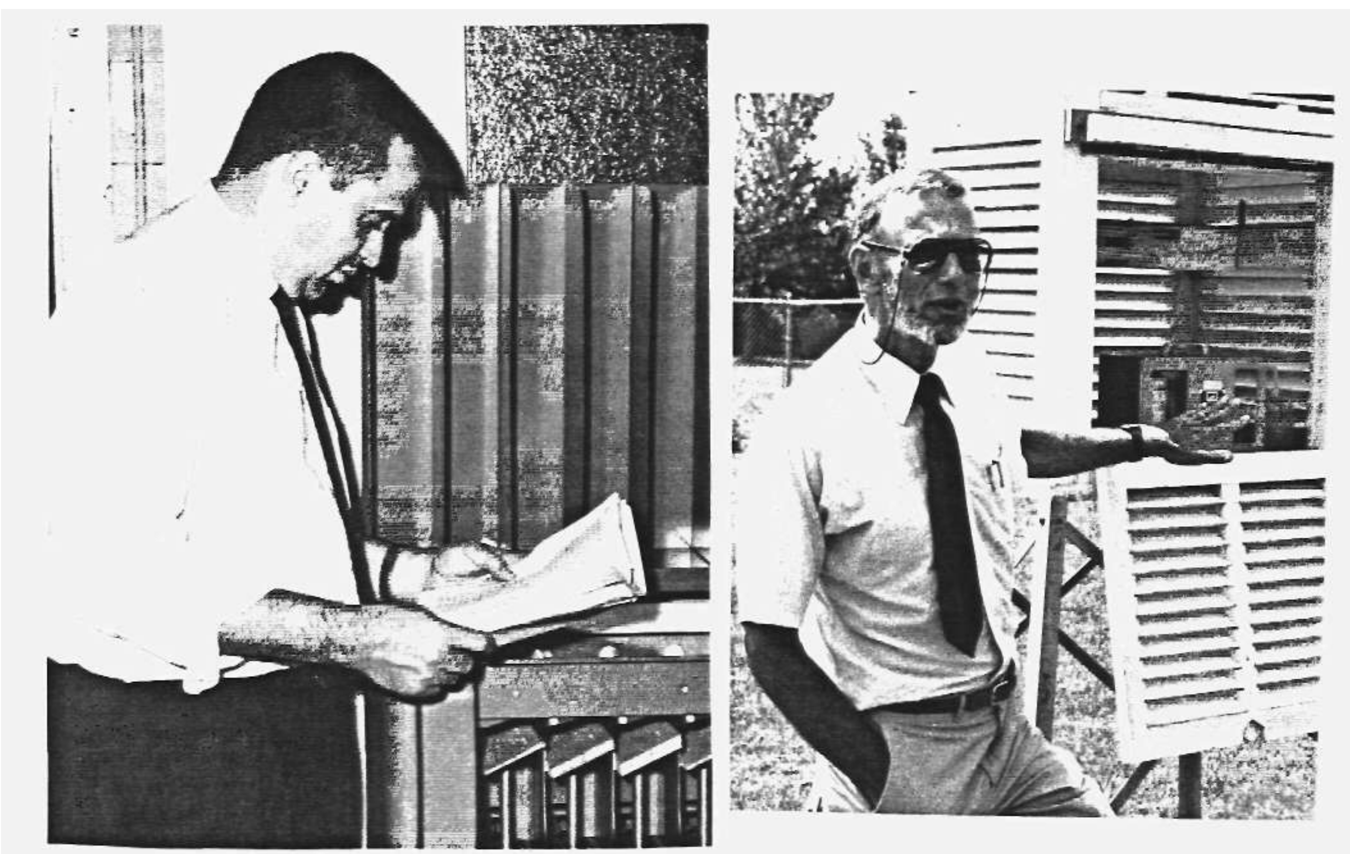


Figure 5-2. The Survey's climate research pioneered the use of punch cards beginning in 1954 as a means for storing and analyzing climatic data. On the left, Stan Changnon is at the card sorter (1960). On the right is Wayne Wendland who followed Stan as State Climatologist, explaining weather instruments to visitors.

Careful review of the climate research and services activities revealed eight major themes: climate services, assessment of data, and research describing the climate, climatic extremes, severe storms, causes of climatic conditions, the influence of surfaces on climate, and climate forecasts. Climate services is an area involving the provision of information on how to access climate information, profiles of users of information, and descriptions of climate products and delivery systems. The Survey's mandate includes provision of data and information "about the state's water and atmospheric resources"; hence, developing climate services was an expected and necessary function of the Water Survey. Assessment of *climate data and methods for analyzing climatic data* undergirds the services and research. This work began with the start of the climate program in 1954, as part of the punch card project that launched the climate research endeavors at the Survey (figure 5-2).

The wide interest and calls for information about severe local storms common in Illinois (thunderstorms, hail, tornadoes, lightning, and straight-line winds) led to continuing *climatic studies of severe storm conditions*, often with external funding (figure 5-3). The Survey's water resource focus also led to extensive *analyses of climatic extremes* such as droughts, flood-producing wet periods, and seasonal extremes such as severe winters (figure 5-4). A frequent need is for a *description of the climatic conditions for a particular place and/or time.* For example, a hydrologic assessment of potential reservoir sites in southern Illinois required a des-

Figure 5-3. Titles of various Water Survey publications describing the severe storms of Illinois.

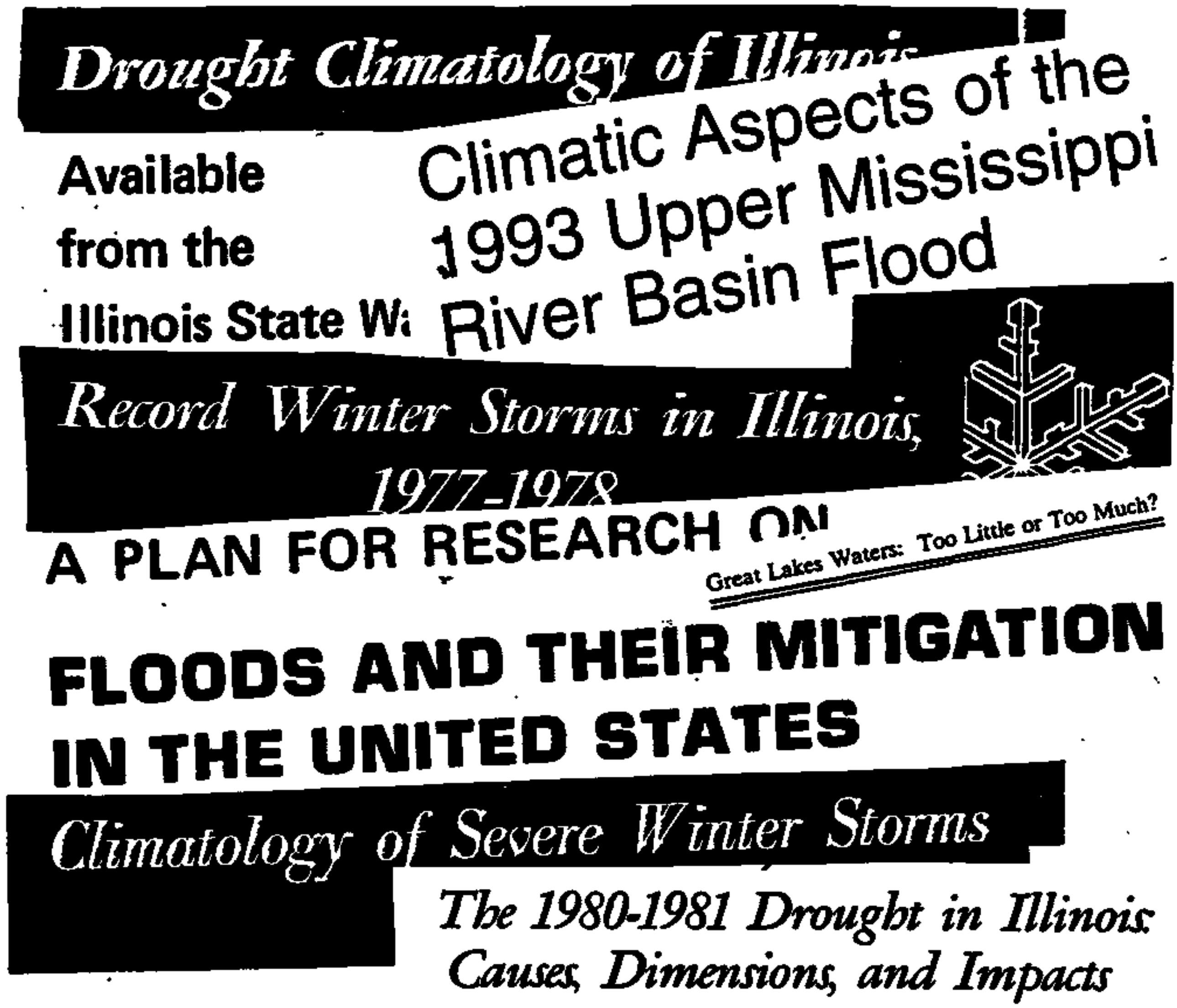


Figure 5-4. Titles of selected Water Survey publications concerning climatic extremes.

cription of the area's climate, both averages and extremes, and special information on the frequency of wet and dry years that affect reservoir storage and hence their design (Changnon, 1957a). These types of needs led to a series of descriptive studies of climatic conditions in Illinois, the Midwest, and other regions. These three themes were largely descriptive and statistical in nature.

To further explain their findings, say, about the features in the average pattern of hailstorms across Illinois, a series of studies addressed the underlying physical causes of these climatic variations in both space and time. These *causative studies* formed a sixth theme (figure 5-5). Closely allied was a seventh theme, *investigations of how natural surfaces such as lakes and hills affect climate.* This was motivated by needs to explain unusual climatic variations in parts of Illinois. Furthermore, the importance of Lake Michigan as the water supply for 66 percent of the state's population led to studies of that lake's effect on clouds and precipitation over the lake.

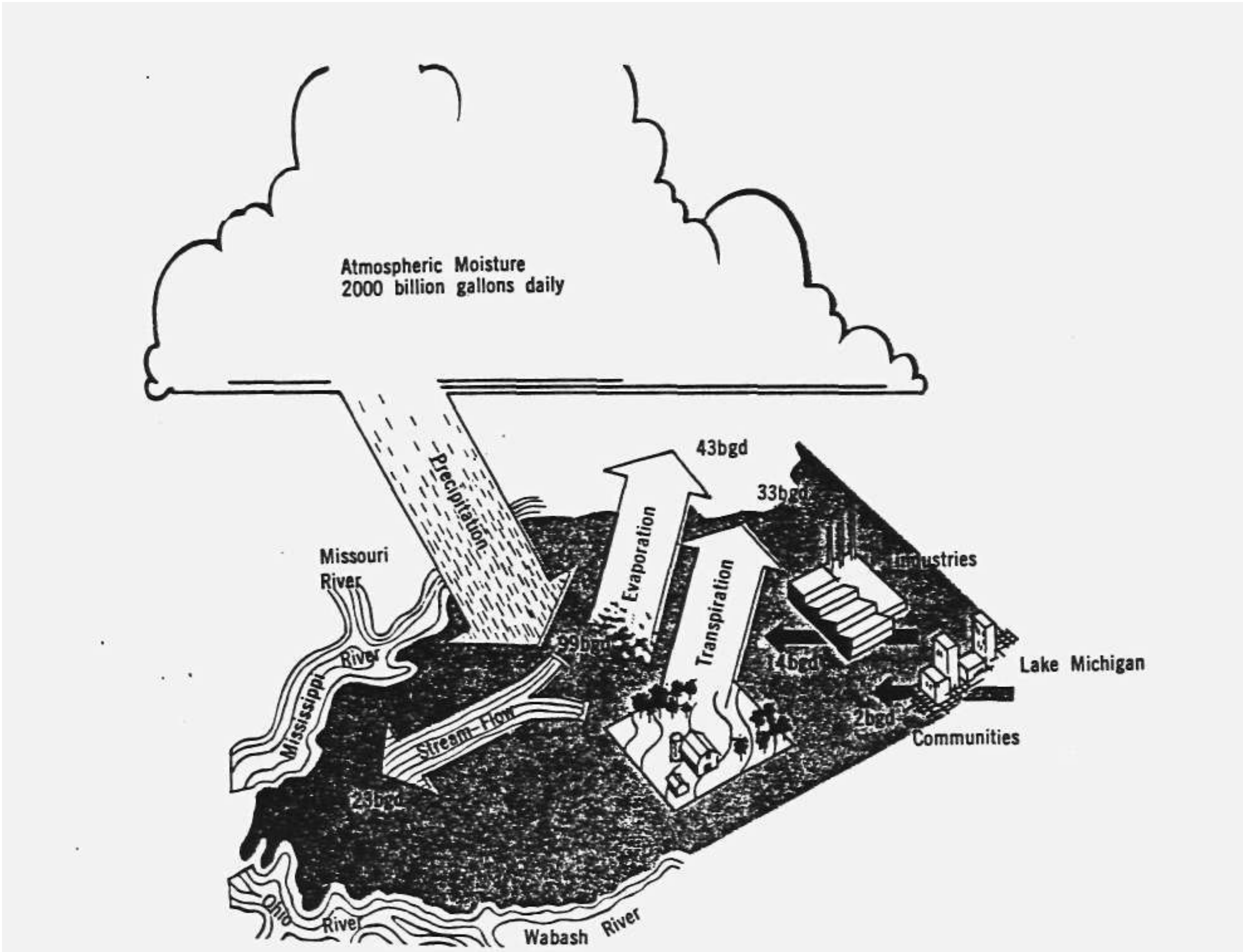


Figure 5-5. An important early analysis defined the major components of the hydrologic cycle for Illinois. The various quantities of water are shown here with 99 billion gallons per day (on average) being precipitated.

Climatic information of extremely high value is that which *predicts or allows estimation of future climate conditions months, seasons, and years ahead, theme 8.* Survey scientists responded to this need and did research to assess the needs for climate forecasts and then-accuracy, to develop user-oriented forecasts and methods for testing forecasts. Much of this work was supported by research grants.

CLIMATE SERVICES

As described in the introduction, climate services were and are fundamental to the Survey's mission, and they it was also effected from 1954 to 1972 by the presence of the Weather Bureau's State Climatologist housed at the Survey. The State Climatologist's main responsibility was to provide climatic services in Illinois, with a special focus on helping University of Illinois staff and students. Survey climatic services during this period were primarily in support of other Survey research and in developing information presented in a series of reports that documented most aspects of the state's climate including thunderstorms

(Changnon, 1957b), hail (Huff and Changnon, 1959), droughts (Huff and Changnon, 1963), clouds (Changnon and Huff, 1958), tornadoes (Changnon and Stout, 1957), the climate conditions of 14 Illinois communities (Changnon, 1955a, 1964a), and evaporation in Illinois (Roberts, 1953). Continuing studies of Illinois droughts, lasting from the late 1950s through the 1980s led to a user-oriented report on how to detect a developing drought (Changnon, 1987a).

Operation of the Morrow Plots Weather Station in Urbana, as mentioned in Chapter 2, became the responsibility of the Water Survey in 1948 (figure 2-1). Operation and maintenance of this station have been one of the fundamental climate services of the Water Survey. The station was one of 100+ "cooperative weather stations" of the NWS in Illinois, and data on temperatures and precipitation were routinely reported. Moreover, the Urbana weather station was one of the state's oldest stations (Changnon and Boyd, 1963), at which many more weather conditions were measured than at other stations, including winds, humidity, solar radiation, evaporation, and soil temperatures in a full-fledged monitoring effort. The station's unique climatic data, collected from 1888 to 1947 by University of Illinois staff and by the Survey thereafter, was a treasure trove for climatic investigations (Changnon, 1959). Later in 1963 the NWS selected the Urbana station as one of 20 benchmark stations in the United States to monitor climate change. This identification of the Urbana station was terminated when the University of Illinois refused to provide the guaranteed site security that was required for a permanent site into future years.

The Survey's climate services program blossomed after the Weather Bureau's State Climatologist program ended in 1972, and Stanley Changnon became the Illinois State Climatologist through a cooperative agreement between Illinois and the National Climatic Data Center. The Survey has supported the position ever since with Stan Changnon (1972-1980) and Wayne Wendland serving from 1981 to present (fig. 5-2).

The growing national interest in how climate was changing and desire for information about how climate affected activities during the 1970s drove the expanding services and research program, largely through federal and private sector grants to Survey scientists. To facilitate use of climate information in Illinois, the Survey issued publications informing potential users in Illinois about where to get information (Changnon, 1975b) and what was available (Changnon, 1979b), as illustrated on figure 5-1. Survey scientists also began the first of several climate information access systems with a system to access hail information (Clark and Wildhagen, 1979). To facilitate climate services, a Climate Information Unit was formed in 1980. In 1982-1983, a series of *Climate Calendars* for 20 areas covering the state were developed (Hilberg and Sinclair, 1983). These were designed for use by the news media. During the 1980s the Water Survey also pursued two parallel efforts to boost its climate services and those of the nation.

The National Climate Program Act of 1978 was promoted by Survey leaders (Ackermann, 1977; Changnon, 1977b, 1978b, 1982a) and called for improved climate services in the "national interests" because climate information was not being effectively used to improve the nation's economy (then slumping) and environmental management. However, there was a struggle to get the new national climate program to help fund the states' efforts in climate services, one proviso of the National Climate Program Act. In 1978, Changnon began a multi-year effort to persuade responsible federal parties of the value of state services (Changnon et al., 1980a). This became a crusade led by members of a North Central Agricultural Committee who proposed in 1979 to the National Climate Program Office (NCPO) to develop the concept and plan of a "regional climate center" to help facilitate state services by serving as a middleman between the monolithic national data center and the struggling, often under funded State Climatologists. NCPO funded this proposal and, after a plan was developed by this regional committee, the Water Survey submitted a proposal to establish a trial center named the Regional Climate Coordinating Center (RCCO). This trial institution was operated from 1981 to 1986 (Vogel et al., 1982, 1984, 1985, and 1986) and developed a real-time data collection and distribution system for Illinois as a test of a regional-scale system (Changnon et al., 1982c, 1984a). RCCO also sampled users of climate information (Changnon et al., 1983b; Lamb et al., 1984), and concluded its four-year term showing that this "proof of concept experiment" for regional climate centers was highly successful (Wendland et al., 1985).

During 1986-1987, efforts to get permanent regional climate centers (RCCs) established across the nation and funded adequately by the National Oceanic and Atmospheric Administration (NOAA) failed, leading to the development of arguments for their unique role in providing near real-time climate information (Changnon, 1986a) as well as a plan for them (Changnon, 1987a). A group of the nation's leaders in climate services developed a plan for a national climate information system, and it was issued as a Water Survey report (Changnon et al,, 1987).

Frustrated by the lack of NOAA funding for a regional center, Water Survey leaders, joined by interested scientists from Nevada and New York, turned to Congress in 1987 with practical arguments for enhancing the nation's climate services by establishing RCCs. Congress agreed and added funds for three centers to NOAA's FY1988 budget, and thus the Midwestern Climate Center (MCC) was established at the Water Survey in 1988 (Kunkel et al., 1990). By 1990, six RCCs providing climate services throughout the nation had been established (Changnon et al., 1990). Under Ken Kunkel's leadership, the MCC quickly developed a regional real-time climate information system modeled after the trial system developed by RCCO for Illinois in 1984 (Kunkel et al, 1990), and the Midwestern Climate Information System (MICIS) was a model copied by several RCCs.

During the 1980s, a second parallel activity sought to enhance climate services through a systematic assessment of the informational needs of users and the diverse applications of climate information. These market-type assessments began with a major national scale assessment of users in the U.S. agribusiness industry during 1981-1983 (Lamb et al., 1985) Changnon and Fosse (1981) assessed the many uses of climate information in the hail insurance industry and showed highly valuable applications. As the result of an invitation from NOAA, Changnon (1981k) assessed what was known about the needs of agricultural and water resource managers for climate data and information. This was followed by assessments of climate information users in government agencies (Wendland and Changnon, 1985) and at universities (Vogel et al., 1986). A series of regional workshops was conducted in the Midwest to define the needs of users for near real-time climate information in both the private and public sectors (Wendland and Changnon, 1986). Changnon et al. (1987a) continued in-depth assessments of the uses and needs for climate forecasts among six sectors of the agribusiness industry, and Changnon et al. (1995a) assessed climate information users in Midwestern power utilities, thereby discovering their major needs for climate forecasts. MICIS contains crop yield-weather models that allows users to make their own prediction of future weather conditions and how these choices would affect crop yields (Kunkel et al., 1990).

Such marketing studies helped the Survey services program, leading to user-friendly delivery systems and tailor-made products such as the soil moisture values for the Midwest determined using a model developed by the MCC staff (Kunkel, 1990a). An important feature of this 1980-1995 user assessment thrust was to determine the kinds of applied research products needed for the Midwest, a prime factor driving the MCC research program. This has included studies of hourly weather data (Peterson, 1991), the development of a climate-agricultural atlas (Reinke et al., 1993), and calculation of mean or normal temperature and precipitation values for the Midwest (Wendland et al., 1992).

CLIMATE DATA AND ANALYSIS

As noted above, the early era of the Survey's climate program involved evaluating historical data for Illinois and then entering it on punch cards, the first effort at the Water Survey to digitize data and to use computers, including the University's famous ILLIAC computer, for analyses as early as 1956 for a study of sequences of wet and dry periods (Changnon, 1960b). Thus, the Meteorology Group took a giant step forward in their approach to data analysis. Because the punch card project was a cooperative one, annual reports were prepared that described data entered, editing of the data, problems encountered, and initial research findings (Changnon, 1955b, 1956a, 1957e, 1963c). The first research-services report relying heavily on digitized data was a climate summary based on data from the Urbana station (Changnon, 1959a).

Editing of the daily data for 63 Illinois stations, each with data for 1901-1948, allowed an assessment of the quality of the volunteer observers for these stations. This led to the discovery that certain observers had faithfully reported thunderstorms, hail, ice storms, and other weather phenomena in addition to what they had to measure and report: daily high and low temperatures and precipitation. A process for evaluating these records to determine the reliable records of thunderstorms and hail was developed (Changnon, 1967a) which would prove useful in later research for the crop insurance industry (Changnon and Changnon, 1987).

Certain research projects required specialized and/or unavailable data sets. This led Survey scientists to create data sets. For example, Richman and Lamb (1985, 1989) in their studies of the climate conditions in the central United States, used historical precipitation and temperature data to create a gridded data set for the central U.S. and southern Canada. For her research dealing with the climatology of solar radiation in the Midwest, Mary Petersen developed specialized solar data sets (Petersen et.al., 1995). The Midwestern Climate Center, faced with the lack of digital data for most Midwestern stations prior to 1949, launched a major project, in concert with state climatologists in the region, to edit and digitize much of the region's historical data. This now allows long-term regional studies that could not be accomplished before.

The addition of staff with statistical expertise during the 1970s led to several analytical studies and development and testing of statistical methods for analyses. Schickedanz (1977) investigated the use of power spectra, and many of his other climate-related analyses are described in the Chapters 7 and 8. Beginning in 1983, Michael Richman launched a series of statistical studies related to climatic data analyses in which he assessed various uses of principal components (1983, 1986, 1988a), use of eigenvectors (1985), and multivariate analysis (1988b), largely for applications in defining climate relationships. The principal component approach was used to define climatic regions of the nation (Richman, 1991), and thunderstorm regions were defined using cluster and bi-plot analyses (Gabriel and Changnon, 1989).

The bias in mean temperature values induced by the time of observations was defined (Head, 1985), and an inventory of the available climate data for the Midwest was done as part of the regional center activities (Wendland et al., 1987). Reinke and Taylor (1991) assessed management of historical climate data, and Wendland (1991) prepared a history of the weather observations in Illinois. Lamb and Richman (1991) assessed the uses of cooperative weather station data. Wendland and Armstrong (1993) identified the thermometer problems affecting maximum and minimum temperature records. Kunkel and Court (1989) collaborated in a study comparing means and normals, and Angel et al. (1993) assessed various averaging periods used to define climate normals.

DESCRIPTIVE CLIMATOLOGICAL RESEARCH

Descriptive climatologies of climatic conditions for various locations but with a focus on Illinois have been the Survey's longest running research theme. Roberts (1953) launched this research with a study of evaporation based on Illinois pan evaporation data. Descriptive climatologies for four Illinois cities (Monmouth, Mt. Vernon, Rockford, and Urbana) were developed based on the newly available punch card database (Changnon, 1955a). A comprehensive description of the extensive historical weather data at Urbana was prepared and issued in a major Survey report (Changnon, 1959a). The state of Illinois developed a series of natural resource atlases during 1958-1959, and the one on water resources and climate contained an extensive analysis describing what was known about most Illinois climate conditions at that time (Changnon, 1958a). A subsequent, more definitive description of the state's weather and climate conditions was prepared for *Water for Illinois* (Changnon, 1967d). In 1964, climatic data summaries for 12 additional Illinois cities (Changnon, 1964a) were prepared. Attention to Illinois' evaporative climate conditions occurred in the 1960s with Jones (1966) completing a study of evapotranspiration, and Roberts (1966) delving into the amount of evaporation from lakes. The diurnal distributions of clouds, thunderstorms, and other weather conditions were investigated using hourly data on punch cards (figure 5-6), and resulted in a report based on first-order weather stations in Illinois and adjacent states (Changnon, 1968). Huff (1971b) followed with similar analyses of the diurnal variations in Illinois precipitation values.

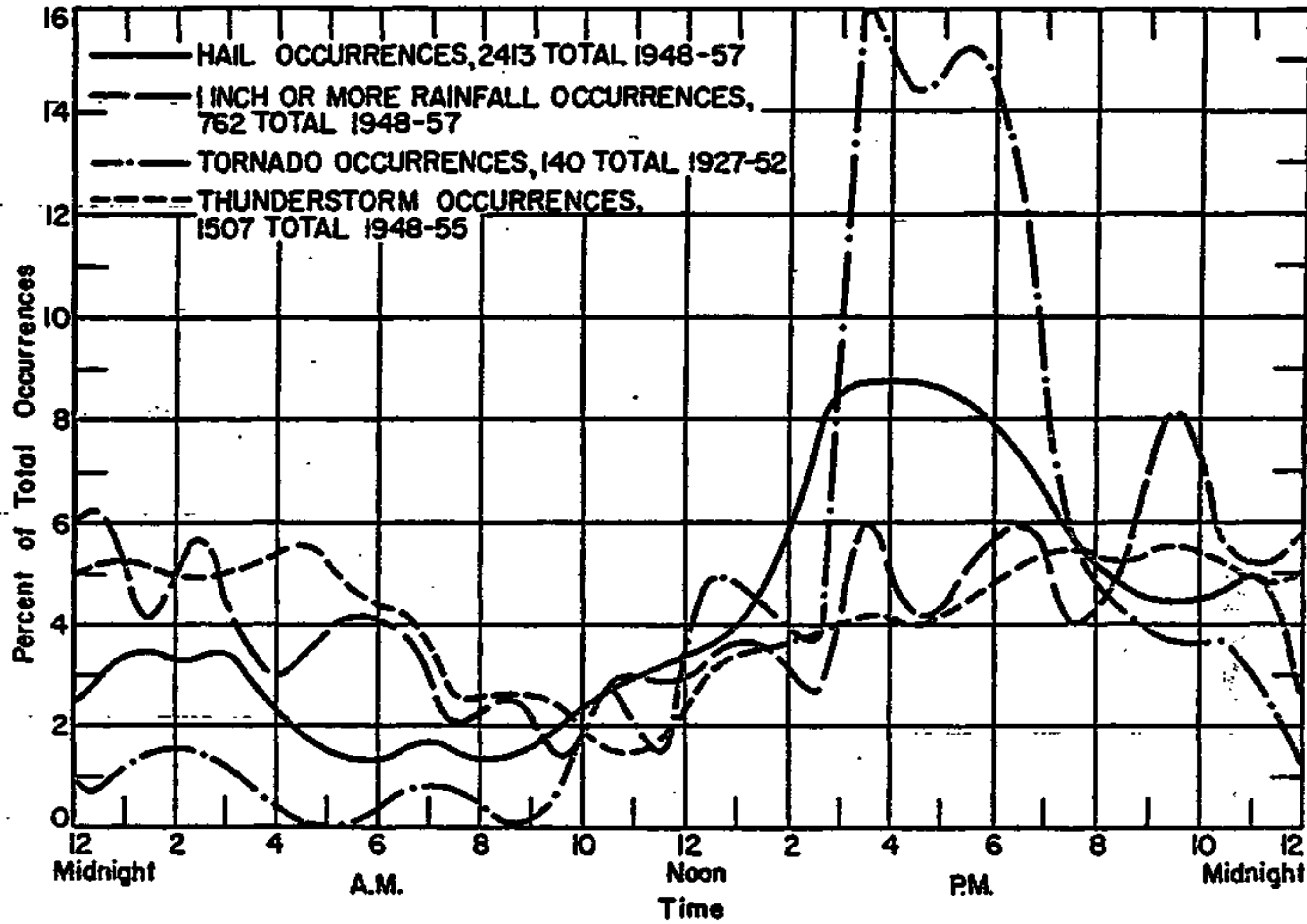


Figure 5-6. Diurnal distributions of important severe weather conditions in Illinois, as based on an early study using punch card data.

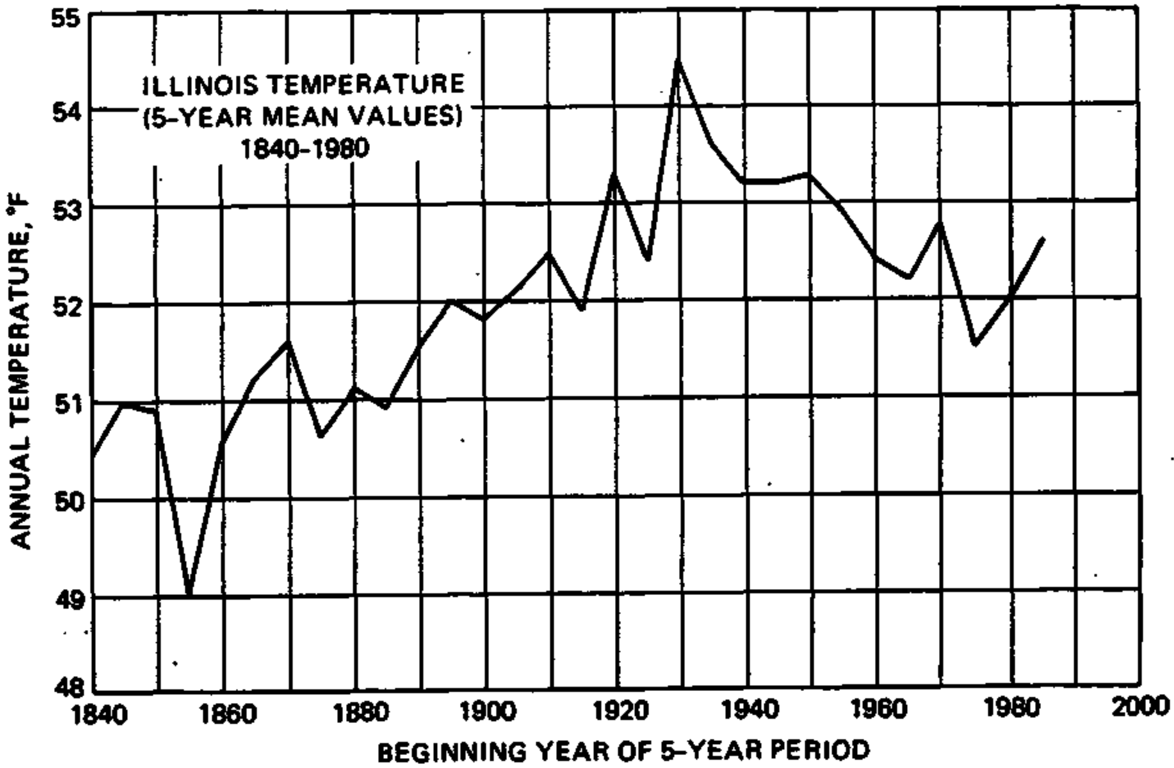
The 1970s ushered in studies funded by federal agencies of climate conditions in other regions. Survey scientists wrote a report (Changnon and Huff, 1975) describing the climatic conditions of the High Plains (see Chapter 6), and Lamb (1982, 1985a, 1991a) conducted studies of the climatic conditions over Subsaharan Africa. Attention to the Midwestern precipitation distribution in time and space (the result of recommendations from Helmut Landsberg who served as a program consultant) became a major NSF-funded study involving Lamb and his staff who prepared a series of publications from 1984 to 1989 (Richman and Lamb, 1985a, 1985b, 1989; Richman, 1986a, 1986b; Lamb and Richman, 1986). These descriptive studies were integrated with causative studies described below.

National concern over energy supplies developed with the energy crisis of the 1970s and led Survey climatologists into several investigations of alternative energy sources (wind and solar power). Changnon (1978c) summarized what was known about the state's solar energy climatology using historical data sources. Research projects launched in 1980, with grants from the Illinois Department of Energy and Natural Resources Agency, further assessed and described the solar energy and wind energy statistics for Illinois (Hendrie, 1980, 1983; Wendland, 1981, 1982).

Attention to Illinois' precipitation climate never abated. Huff and Changnon (1963) developed the climatology of precipitation lines in Illinois, as detected by weather radar (Changnon, 1960e). Huff (1970a) defined sampling errors in measuring rainfall across various sized areas using data from two Survey raingage networks. Jones and Sims (1978) developed statistical distributions of instantaneous rainfall rates for the Midwest and three other climatic zones. Later, Huff (1979b) defined the spatial and temporal correlations in monthly and seasonal rainfall across the state. Unusual rainfall conditions during 1979 including the wettest August on record at many state locations, followed by the driest September on record was the topic of another study (Changnon and Vinzani, 1980). The important results of many Survey studies of rainfall conditions since the early 1950s were brought together in a single comprehensive review document (Changnon and Huff, 1980). Bryan and Wendland (1993, 1994, 1995) generated a third set of station climatologies for eight Illinois locations.

The growing scientific interest in the possibility of climate change led to a major analysis of the 1901-1980 historical variations of all climatic conditions in Illinois (Changnon, 1984d). Figure 5-7 illustrates the long-term variations in the state's precipitation and temperature since 1840. Changnon (1987c) measured and reported on the regional shifts in visibility over time, and on the 100-year fluctuations in climate conditions, as measured at the Urbana station (Changnon, 1990c). As part of a grant from the U.S. Geological Survey to assess possible effects of changes in climate, Kunkel et al. (1993) assessed the relationship between heavy rain periods over 7-day periods and seasonal precipitation amounts in the Midwest, finding no relationship.

Ever expanding regional interests in climate conditions, fueled by the regional climate center developments beginning in 1980, ushered in more studies of the region's climate. Several climatologists determined the Midwestern mean climate conditions for 1951-1980 (Wendland et al, 1985b), and these were updated for 1961-1990 period (Wendland et al., 1992). Peterson (1989) developed a solar radiation model for the Midwest and defined the climate of solar radiation (Peterson et al., 1995). Agricultural interests in soil moisture led to the development of a soil moisture model for the Midwest (Hollinger et al., 1990). Soil moisture climatologies were developed for the Midwest (Hollinger and Reinke, 1990) and for Illinois (Hollinger and Isard, 1994). A regional study of spring freezes was also completed (Kunkel and Hollinger, 1995). Angel (1995) reported on his study of severe winter storms on the Great Lakes basin, showing how the lakes alter and intensify storm conditions.



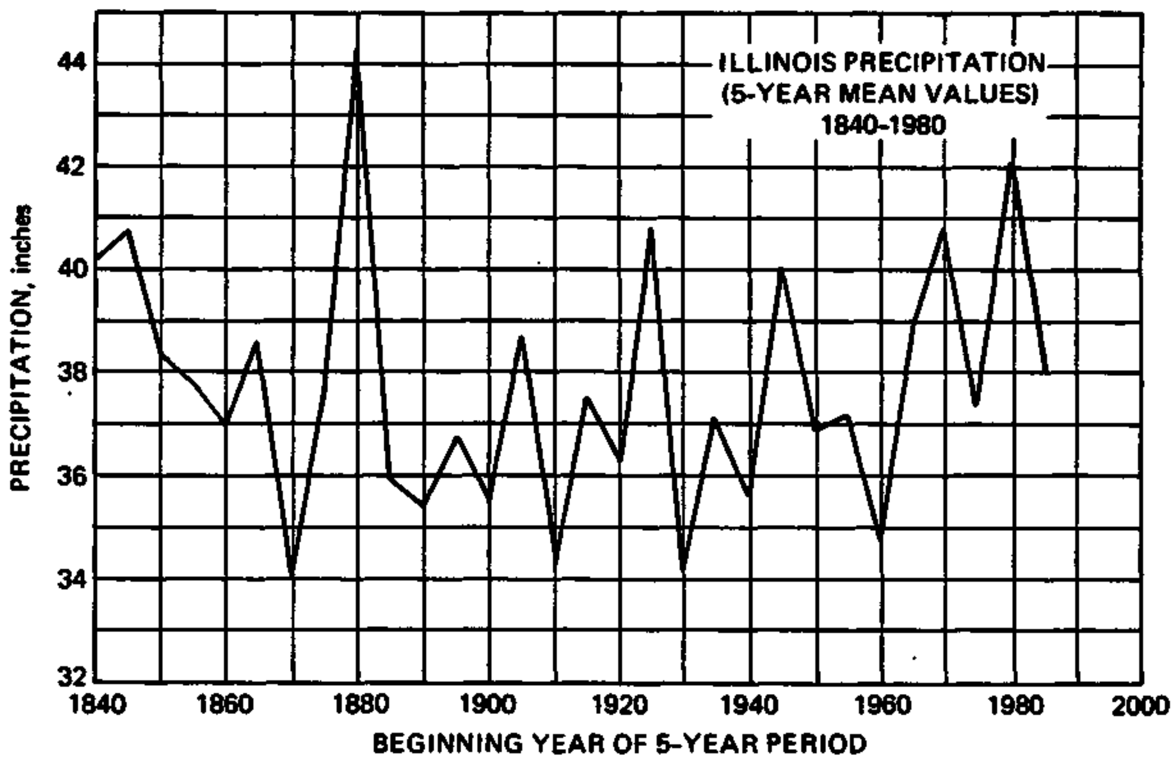


Figure 5-7. The 5-year average values of precipitation and temperature for Illinois since 1840.

CLIMATIC EXTREMES

A sizable research effort sustained since 1960 has focused on the climatological conditions associated with droughts, floods, prolonged wet periods, and other forms of severe weather lasting for months, seasons, and years. Public and hydrologic interests in these events and the design and operation of many weather-sensitive facilities have driven research aimed at describing these conditions in great detail.

The severe drought of 1952-1956 helped launch the climate research program, and there were several studies of this drought and others (Huff and Changnon, 1960b). Changnon (1960b) defined the probabilities of dry periods in Illinois for an engineering meteorology conference. Huff and Changnon (1963) collaborated on a major analysis of past precipitation droughts in Illinois, providing drought frequency information. A comprehensive analysis of its climatological aspects of the 1980-1982 drought in south-central Illinois included its causes and impacts (Changnon et al., 1982a). A public information brochure about droughts was issued (Hilberg and Changnon, 1984). A comprehensive interdisciplinary project during 1985-1987 involved scientists from the Natural History Survey and led to a comprehensive document designed to help detect the onset and ending of droughts in Illinois, always a difficult problem (Changnon et al., 1987b). Easterling and Changnon (1988) revisited the history of Illinois droughts during the 1901-1985 period and developed a new climatology of droughts. A severe summer drought in 1988 led to a series of climatic investigations (Kunkel et al., 1989; Kunkel and Angel, 1988), and an in-depth assessment by an interdisciplinary team (Angel et al., 1992). Ken Kunkel's studies (1990b) of the surface energy budget included investigation of conditions during the 1988 drought, showing how dry surfaces had increased near-surface air temperatures.

Severe floods in Illinois during 1983 became the subject of a climatic-meteorological analysis (Changnon et al., 1983). Involvement in flood research led to an invitation from the NSF to perform a national needs survey of flood-related research involving a group of national experts (Changnon et al., 1983). Record Midwestern flooding in 1993 led to a study of the flood's climatic aspects (Bhowmik et al., 1994; Kunkel et al., 1994).

Cold winters and winter storms were also extensively investigated. Changnon (1964f) performed case studies of three unusual winter storms which included thunderstorms, and a later study addressed a very long-track winter snowstorm that began in Illinois and went to the East Coast (Changnon and Vinzani, 1981). A major climatological analysis was made during 1966-1968 of all severe winter storms in the state since 1901 (Changnon, 1969c). Ironically, this study and its design-related findings which led to the development of the winter storm model shown in figure 5-8, were presented just a few years before a series of very severe winters in Illinois began. The first of these, in the winter of 1977-1978, was the subject of a major climatic analysis (Changnon, 1978a). The unique severe storms of that winter became the subject of a special study (Changnon and Changnon, 1978). The next severe winter (1978-1979) was fodder for a comparable investigation (Changnon, et al., 1980), and the third bad winter (1981-1982) underwent similar scrutiny (Changnon et al., 1983a). Wendland performed an assessment of the high temperatures and dry weather in summer 1983 (Wendland et al., 1984).

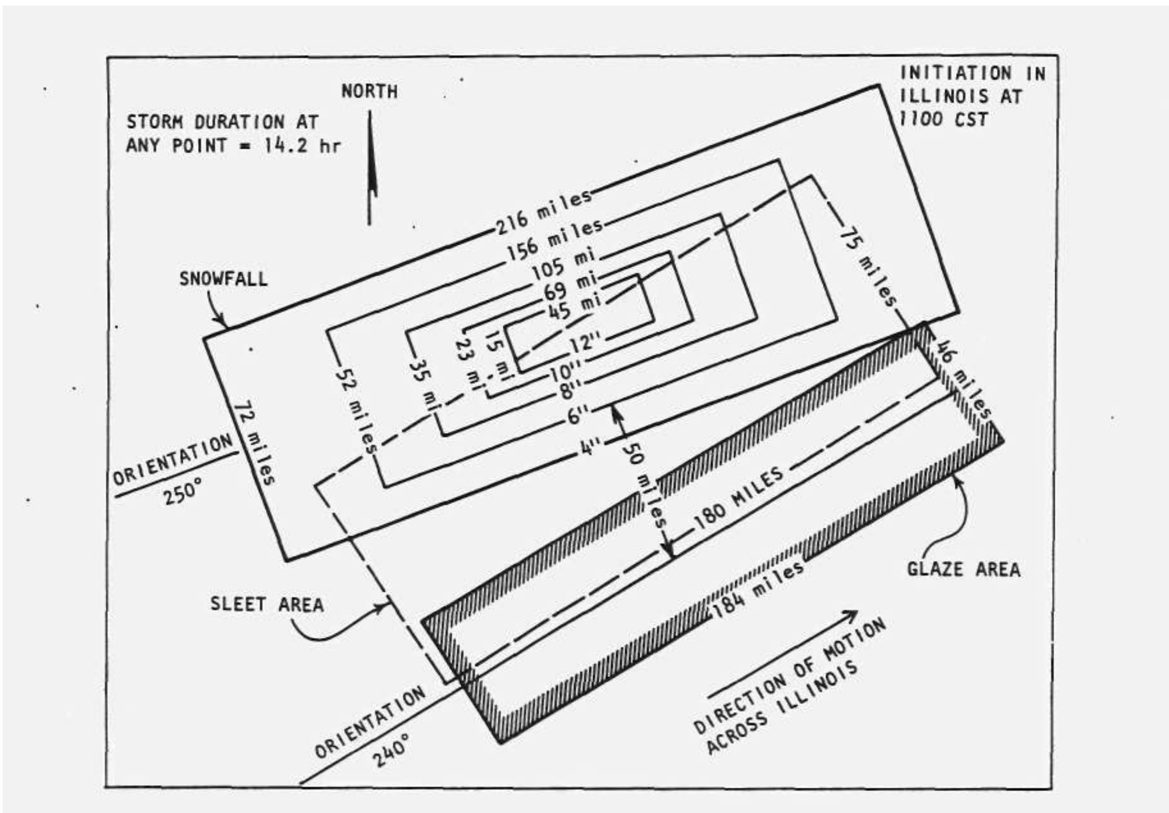


Figure 5-8.. The surface model of severe winter storms in Illinois, showing the orientation and dimensions of the areas of heavy snowfall (4 to 12 inches), sleet, and freezing rain.

CLIMATOLOGY OF SEVERE LOCAL STORMS

Illinois' climate in the warm season is marked by numerous severe local storms, including thunderstorms and lighting, hail, heavy rains, tornadoes, and high winds, all of which produce extensive damages to crops and property and cause between 10 and 25 deaths each year. Understanding the climatology of these events is important in the design of structures and for the protection of human lives so research delving into these events began early and has continued to 1995. *Extensive research in severe local storm climatology has thoroughly defined the climatologies of these events in Illinois and many other states.* The initial investigations began in 1956. Changnon (1957b) defined the climatology of thunderstorms in space and time across the state. Changnon and Stout (1957) produced a climatology of Illinois tornadoes.

Hail

Huff and Changnon (1959) collaborated for a comprehensive investigation of hailstorms in Illinois. Based on support from the crop-hail insurance industry, Changnon launched further climatic investigations of hail in Illinois and adjacent areas. First, all the severe hailstorms during the 1915-1950 period were identified and measured (Changnon, 1960a), and a climatic study was made of the state's 25 most severe hailstorms on record (Changnon, 1960d). Changnon (1962a) compared the areal distributions of thunderstorms and hailstorms across Illinois, and defined the regional characteristics of severe Illinois hailfalls (Changnon 1962b). The frequency of hailstorms across Missouri, Iowa, and Illinois was another climatic topic assessed (Changnon, 1961b). A climatic investigation assessed the singularities found in the historical hail, thunder, and lightning data (Changnon, 1962c), and this study showed favorable periods for maximum storm activity (for example, June 10-15). Using hailstone sizes and associated winds, Changnon, (1967b) delineated the seasonal and areal variations found in hail intensities across Illinois. Changnon and Stout (1967) analyzed the U.S. crop-damage values of hail to map the variations across the nation. Stout and Changnon (1968) prepared a national atlas based on the incidence of hail days. Spatial and temporal relations found in crop-hail loss data were analyzed for 26 states, as a prelude to what future conditions might be (Schickedanz et al., 1977). A comprehensive climatology of all available hail information in the United States was created in 1977-1978 (Changnon, 1978d). Temporal changes in hail frequencies across the upper Midwest from 1901 to 1980 were the subject of another hail study for the insurance industry (Changnon, 1984a), and an educational brochure about hailstorms was prepared (Changnon, 1987).

Thunderstorms and Lightning

The first comprehensive climatology of Illinois thunderstorms and the rainfall they produce was completed in 1957 (Changnon, 1957b). The patterns of thunderstorms and hailstorms across Illinois were then compared (Changnon, 1962a). A climatic investigation of damaging lightning incidences in Illinois was completed (Changnon, 1964b). The Illinois lightning data were then used to test the reality of a suspected latitudinal distribution across the state (Changnon 1970e). A model of the structure of thunderstorm rainfall, designed for hydrologic applications, was developed using the historical data from the networks (Stall and Huff, 1971). A study of historical reports of damaging lightning across the state attempted to assess how localized influences on cloud-to-ground lightning affected its areal distribution. A public information brochure about thunderstorms was issued (Changnon, 1985d).

Extensive studies concerning the temporal and spatial characteristics of thunderstorms in the United States were conducted during 1984-1988 (Changnon, 1988a, 1988b) as part of two NSF grants. Historical fluctuations in thunder events across North America were assessed (Changnon and Hsu, 1983a). These studies showed major shifts in frequency since 1900

(Changnon, 1984). Various features in the time distributions of thunderstorms in different regions of the United States were compared (Gabriel and Changnon, 1989). The relationship of thunderstorm reports, as based on audibility of thunder at weather stations, and lightning occurrences was defined using data from the new national lightning-sensing network (Changnon, et.al., 1988b; Changnon 1989f; Changnon and Gabriel, 1989) showing that weather station observations of thunder missed about 25 percent of all passing storms.

Tornadoes and High Winds

An exhaustive, updated study of Illinois tornadoes was completed in 1971 (Wilson and Changnon, 1971), and Changnon and Vogel (1981b) prepared a public information brochure about the tornado threat in Illinois with information about protective measures. Changnon (1982b) analyzed the historical distribution of reported tornadoes revealing that poor record keeping was a major problem in any time-oriented climatic studies. Changnon (1980b) defined the climatological aspects of non-tornadic high winds. Changnon (1982e) assessed the effects of high winds and other climatic conditions that produce damaging dust storms.

Catastrophes

An NSF-sponsored study examined the major weather-caused catastrophes, each producing $100 million or more in losses in the United States since 1948. The highest frequency of these major storms was found in the Midwest (Changnon and Changnon, 1992). The time trends of these catastrophic events causing > $100 million showed two peaks: one in the 1950s and another in the 1980s.

CAUSES OF CLIMATIC CONDITIONS

The early studies describing the climate conditions in Illinois were basically statistical interpretations with little rationale or limited explanations supporting the mesoscale variations found or the temporal fluctuations detected. This was remedied with research that focused on causes for the events and their distributions in time and space. Huff's (1951) early analysis of the atmospheric moisture budget in Illinois was a definitive beginning, placing the conditions that affected the amount of precipitation and evaporation into a useful perspective (fig. 5-5). A second study investigated cloud types in Illinois (Changnon and Huff, 1957). Descriptive findings about hail patterns across Illinois, which were begun in 1957, were explained by Huff's (1960b) comparison of hail patterns and synoptic weather features and by comparisons of the hail pattern with other surface climatic features such as dew point temperatures and thunderstorms (Huff, 1961). Chiang (1964) produced a climatology of synoptic features for Illinois based on analyses of 10 years of surface weather patterns. Ten years later a computer-based study of synoptic features developed a frontal climatology for the entire United States (Morgan et al., 1975). Changnon (1971e) assessed the atmospheric controls exerted by the Great Lakes on the region's climate.

The 1980s brought in a new era of study. Peter Lamb began a series of studies of the atmospheric conditions affecting the climate of northern Africa (Lamb, 1981, 1983, 1988) including the effects of the North Atlantic Oscillation (Lamb, 1987). He also investigated the stability and circulation factors affecting the precipitation distribution across the central United States (Portis and Lamb, 1989; Lamb and Peppier, 1989), including the relationship of precipitation to the Southern Oscillation (Richman et al., 1991, 1992a) and water vapor content (Portis et al., 1992). Kunkel (1989) defined the role of the regional energy budget in causing droughts in Illinois, and he also investigated the role of the upper air flow patterns in the development of heavy rain periods in the Midwest (Kunkel et al., 1993b). Richman et al. (1992b) analyzed the precipitation produced by winter storm tracks. Surface frontal data and pressure data were used to explain the nationwide average annual and seasonal patterns of thunderstorms (Changnon, 1988b). The upper air patterns that lead to heavy rain events across the central United States were assessed by Kunkel and Easterling (1991).

INFLUENCE OF SURFACE FEATURES ON CLIMATE CONDITIONS

Investigations closely related to the studies of causes of climate features of the state were those dealing with the influence of surface features such as hills, land elevation, and large lakes on the climate. This research is treated as a separate theme because of the considerable extent of these studies and their relevance to understanding the climate of Illinois.

Lake Michigan

A series of studies have dealt with Lake Michigan and its influence on climate. The first was a 1962 study that assessed behavior characteristics of precipitation from five squall line cases crossing Lake Michigan to determine the degree of influence on storm structure and rainfall from squall lines (Wilk and Stout, 1962). Huff and Changnon obtained a federal grant in 1964 to study how Lake Michigan affected precipitation. They found that the lake produced a 15 percent decrease in average annual precipitation on the lake's east shore area, as compared to upwind land areas (Huff and Changnon, 1967), and greatly altered severe storm activity (Changnon, 1966c). Further research defined the average amount of precipitation over Lake Michigan (Changnon, 1967e), and in turn, the amount of precipitation being generated around the southern end of Lake Michigan by snowfall and by thunderstorm activity (Changnon, 1968g).

This project helped lead to a comprehensive climatic investigation of precipitation and storms around the Lake Michigan area with estimates of various overlake conditions (Changnon, 1968e). The influence of the Great Lakes on all weather conditions was subject to a broad climatic investigation (Changnon and Jones, 1972), and Jones (1972) developed a basinwide climatic database useful for hydrologic studies. A comprehensive study of the climatology of the Lake Michigan basin was constructed during 1982-1983 (Gatz and Changnon, 1984). Studies of the lake and urban influences on precipitation over and near southern Lake Michigan were conducted in 1977-1980 (Changnon, 1980b, 1984c), as part of a project investigating inadvertent weather modification (see Chapter 7). Lake effects reduced summer rainfall by 10 to 15 percent over the southern end of the lake and acted to reduce the urban effect to increase rainfall. New studies of the effects of the lakes on precipitation showed the average distribution of rainfall over a 3-year period using satellite data (Augustine et al., 1994).

Topographic and Surface Effects

An NSF grant was obtained in 1962 to initiate field studies of the precipitation patterns, temperatures, and winds over the well-defined hills of southern Illinois (Changnon, 1965c). Seven wind sensors and recorders were installed in the hill and valley areas. After five years of data collection using a surface network and exhaustive climatic studies of the local historical data, it was determined that the hills affected the air flow leading to enhancement of convection (Changnon et al., 1975a). This atmospheric impulse was found sufficient to increase average summer rainfall by 10 percent in the hills (Jones et al., 1974; Huff et al., 1975). Topographic influences on summer rainfall in the St. Louis area were also assessed (Huff and Vogel, 1975) showing moderate shifts to higher rainfall west of the city.

Investigations of the surface energy budget have included modeling and surface field measurements done during the 1988 and 1991 droughts in Illinois (fig. 5-9). In addition, diagnostic analyses of upper air data were done for the 1957-1989 period to examine the effects of soil moisture deficiencies on boundary layer heating. A key result of these studies and field measurements revealed that the sensible heat flux in very warm and dry summers caused an increase in daytime temperatures of 2°K, a factor explaining the high temperatures in Midwestern droughts, and a factor promulgating the drought conditions (Kunkel, 1994). Ken Kunkel has also been involved in studies of the surface energy budget, done as part of the national Atmospheric Radiation Measurements (ARM) program. Field measurements of the variability of surface fluxes over dry desert grasslands and irrigated lands were made in an ARM study area (Kunkel, 1992).

CLIMATE FORECASTS

The science of climate forecasting has been fraught with widely varying scientific views, confusion, and controversy, not unlike the world of planned weather modification. Most everyone who is weather sensitive would like to know the weather conditions for weeks, months, and even years ahead, but the scientific capability to produce highly accurate "climate forecasts" has been very limited. The science of climate prediction has made considerable progress since about 1970, and Survey scientists began their involvement in studies of climate forecasts and their utility as the Survey's program of climate services and research grew during the late 1970s.

During 1977-1978 the weather insurance industry and NSF encouraged Survey scientists to test and develop some empirical, statistically based techniques as tools to estimate future annual and multi-year mean values of precipitation, temperature, and storm activity. These funded studies began under Paul Schickedanz's direction, and after his death, they were pursued

Figure 5-9. Ken Kunkel is shown making field measurements of the surface energy budget during July 1988.

by James Neill, Chin-Fei Hsu, Floyd Huff, and others. Changnon et al. (1979e) assessed the capabilities of these methods to predict future mean levels of hail loss, as measured on a state scale, were assessed and found them to be nearly 80 percent accurate. The prediction results for precipitation were less impressive (Neill, 1980) and those for agricultural (crop yield) applications were comparable with low skill (Huff, et al., 1980). Changnon and Sonka (1980) assessed the statistical fluctuations in Illinois corn and soybean yields to determine the predictability of annual values, found to have accuracy after two years of much above or below conditions.

The strong call of key Survey customers for information about climate forecasts led Lamb (1980) to measure their uses and needs. Lamb and Changnon (1982) assessed the best historical periods of data for use in estimating conditions in future years. Changnon (1983g) assessed various applications of long-range outlooks in water resource management. Neill (1982) reported on success with his statistical technique for predicting trends in state hail losses, and

Neill and Hsu (1983) described the underlying spectral analyses technique. The applications of climate forecasts in agriculture became an increasing topic of investigation (Sonka et al., 1983). a subject more fully explored in Chapter 10. Easterling and Angel (1990) assessed how to estimate future temperature conditions with historical data for applications in the gas utility industry. In-depth structured interviews with agribusiness leaders were performed to gather detailed information on their uses and needs for climate forecasts and the limitations in usage (Changnon, 1992b).

The continuing call for conditional, probabilistic forecasts of seasonal precipitation in Illinois led to research during 1981-1982 resulting in the operational issuance of outlooks by the Survey every month during 1983-1986, and assessment showed the outlooks had some useful accuracy (Changnon and Hsu, 1985b). For example, these forecasts were used in making a major water resources decision about how to manage the water in the Kaskaskia basin during a drought (Changnon and Vonnahme, 1987). Since then, however, forecast development research at the Survey has ended because of the lack of staff to pursue this form of research. However, assessment of the uses and needs for climate forecasts has continued. The problems associated with current long-range climatic and hydrologic forecasts issued for the Great Lakes were investigated (Changnon, 1990b). In a recent study, the uses and desires for climate forecasts by managers and engineers working in the electric utility industry have been assessed (Changnon et al. 1995).

SUMMARY

Accomplishments

The climate program has defined and explained the climate of Illinois in much greater detail than exists for any other comparably sized region of the world. Climate studies at the Water Survey have generated more publications than any other program area, and have been the central and most productive Atmospheric Sciences program. Survey scientists have conducted extensive climatic investigations of severe local storms, contributing to their definition in Illinois and elsewhere along with methods for analyzing and interpreting these data. Innovative work has been conducted by Paul Schickedanz and Mike Richman in the use of statistical methods to analyze climate data and develop predictions. Much of the existing knowledge about how Lake Michigan affects the weather and climate has come from Water Survey studies. The Survey has also done innovative work in defining the climate of droughts and floods.

The Water Survey has conducted the most extensive and successful climate services program of any state in the nation over the past 50 years. The Survey was instrumental in the National Climate Program Act and in developing an improved climate services program in the United States. These efforts have included conception and testing of the RCCs concept, establishing the Midwestern Climate Center at the Survey, and helping to form a national RCC program. The Survey's services program has been designed and enhanced by pioneering work in applications of climate information and user assessments. The Survey has also pioneered the development of computer-based real-time systems for acquiring weather data, for manipulating these data quickly to generate hundreds of climate products and for easy access, computer-based information updated daily. The development of MICIS and its Illinois prototype was a special accomplishment.

Awards

The Atmospheric Sciences Section received a special award from the American Meteorological Society (AMS) in 1974 for "its innovative applied research." Nine staff members (Angel, Changnon, Huff, Kunkel, Lamb, Richman, Schickedanz, Vogel, and Wendland) have been asked to serve on AMS scientific committees that deal with climate, statistics, and applied climatology. The AMS recognized Changnon's climate work by presenting him with their 1991 award for "Outstanding Contributions to the Advancement of Applied Meteorology."

Major Projects

The first key project that helped launch the climate program involved a cooperative project during 1955-1958 with the U.S. Weather Bureau. They provided the initial project guidance, all the raw historical data, and blank punch card supplies, while the Survey provided the expertise and staffing to evaluate the data and enter it on cards.

A series of research projects from 1960 to 1970 funded by the Crop-Hail Insurance Actuarial Association were of great importance in providing funds for support of the hail climate studies. These studies were the starting point for comprehensive research dealing with the climatology of severe local storms.

The Department of Energy and Natural Resources funded important projects on alternative energy sources during 1980-1983. The National Science Foundation supported the initial and important project to assess the Midwestern climate conditions and their causes during 1985-1988, as well as six years of studies of the effects of the southern Illinois hills on clouds and precipitation. The Department of the Interior funded climatic studies of the influence of Lake Michigan.

The series of grants from the National Climate Program Office that supported the development of the RCCO and testing of the regional climate center concept were pivotal in enhancing the Survey's climate services during 1981-1987. A series of eight grants from NOAA for the Midwestern Climate Center provided significant funding of $3.5 million for this center's development.

Last but certainly not least was the continuing state support of the climate research and services program. Most of the state funds directed to the atmospheric sciences since 1960 have been devoted to climate studies and services.

Pivotal Publications

The more pivotal publications in climate program, and the reasons for their selection follow.

•*The atmospheric moisture budget of Illinois* (Huff, 1951). This initial climate publication produced invaluable information for understanding the state's climate controls.

•*The hail climatology of Illinois* (Huff and Changnon, 1959). This extensive bulletin helped attract insurance industry funding for ten years, and was the springboard to a major effort in climatic studies of severe local storms.

•*Precipitation droughts in Illinois* (Huff and Changnon, 1963). This monumental study established a long-term program of studies of droughts and made the Survey staff national experts on droughts.

•*Methods to evaluate thunder and hail records* (Changnon, 1967a). This paper presented an new and innovative method for assessing cooperative station records and allowed new, definitive climatological studies of the nation's hail and thunder occurrences.

•*Precipitation climatology of Lake Michigan* (Changnon, 1968e). This report was the most extensive treatment of lake effects on precipitation and storms, and established the Survey as national leaders in lake effect climatology.

•*The best climatic normals* (Lamb and Changnon, 1981). This paper launched the Survey's program in climate predictions and provided the basis for further studies and information still used to estimate future conditions.

•*The solar and wind climatology of Illinois* (Hendrie and Wendland, 1981). This established very useful information for alternative energy development.

•*Climate fluctuations in Illinois* (Changnon, 1984). For the first time a definitive description of the historical fluctuations in all aspects of state's climate were presented, providing a basis for assessing climate change in the state.

•*The space and time characteristics of hail in the U.S.* (Changnon, 1984d). This national compilation of all that was known about hail on space scales from inches up to thousands of miles, and from time scales of minutes to decades.

•*The assessment of users of climate information in agribusiness* (Lamb et al., 1985). This report served as a major milestone in marketing style activities and set the tone for several subsequent studies of uses of climate information.

•*Development of a soil moisture model* (Kunkel, 1990). This paper and the work it represented provided the "working model" needed to provide for the first time, updated regional information on the current status of soil moisture in the Midwest.

Key Staff

The principal scientific leaders and principal investigators of important grants included Stanley Changnon, Floyd Huff, Kenneth Kunkel, Peter Lamb, John Vogel, and Wayne Wendland. Others who significantly contributed to the climate research included former Chiefs Arthur Buswell and William Ackermann, as well as James Angel, Keith Hendrie, Chin-Fei Hsu, James Neill, Randy Peppier, Mary Petersen, Michael Richman, W.J. Roberts, and Paul Schickedanz.

Several persons outside the Water Survey also provided strong support and interest in the climate program. They included Ray Fosse, Phil Brown, and Dick Roth, Crop-Hail Insurance Actuarial Association; Alan Hecht, Director of the National Climate Program Office: David Rodenhuis, Chief of the Climate Analysis Center; Ronald Taylor and Eugene Bierly, National Science Foundation; Al Joos, former Illinois State Climatologist from the National Weather Service; and Helmut Landsberg, a long-term friend and consultant to the program.

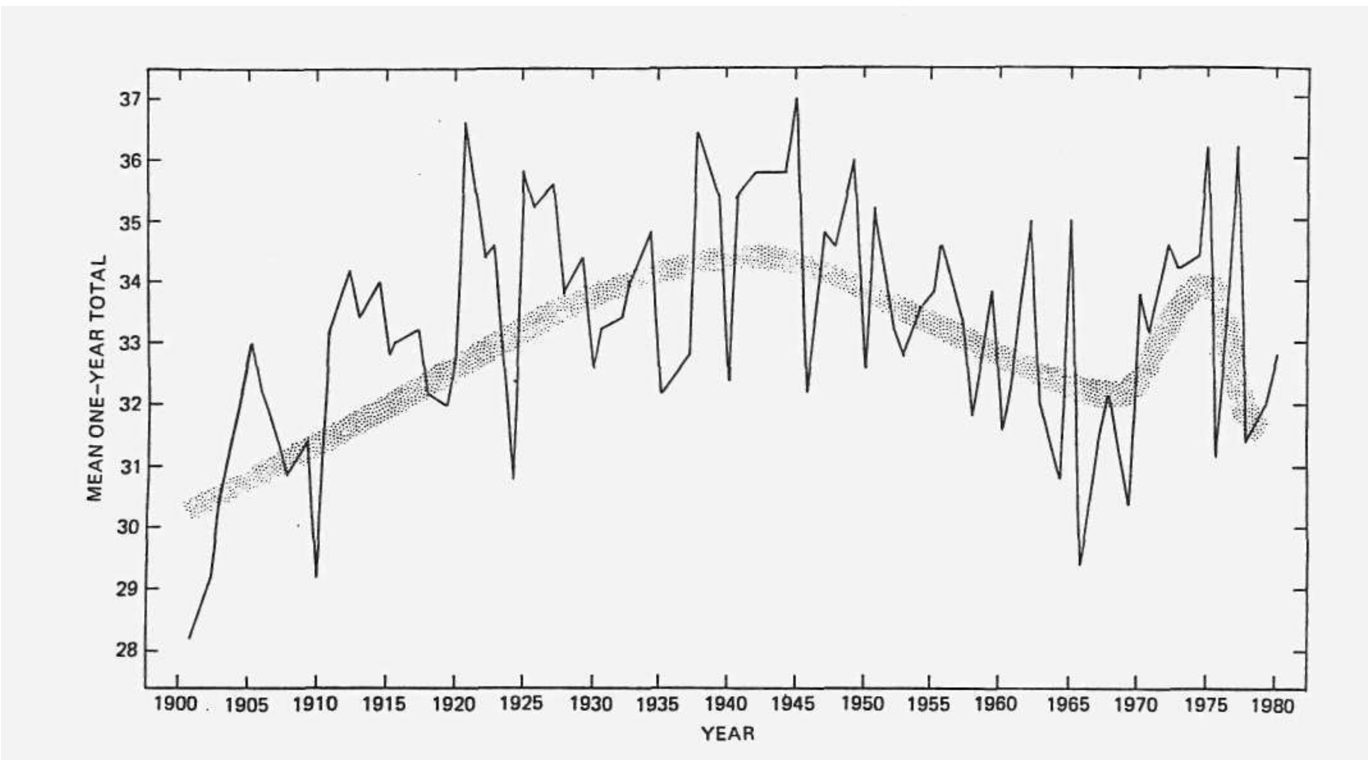


Figure 5-10. The research in climate included numerous studies of severe storms. One project investigated the historical fluctuations in thunderstorms, and this graph shows the national mean annual frequency of thunder for each year from 1901 through 1980. The general trend is similar to the temperature curve for the nation.

Chapter 6

PLANNED WEATHER MODIFICATION

Stanley A. Changnon and Floyd A. Huff

INTRODUCTION

The development of the Water Survey's meteorology program came about because an influential Illinois seed grower Lester Pfister wanted to enhance rainfall over his seed farms in central Illinois. His interest and the Survey's decision to work with him and develop staff and support facilities helped launch an applied weather research program in 1948 (see Chapter 2). When Pfister gave up on his cloud-seeding dreams in 1949, the fledgling Meteorology Group at the Survey forgot about weather modification for several years and turned to other topics: rainfall measurement with radar and raingages and to hydrometeorology.

In 1957, Richard Semonin was assigned to serve as the Meteorology Group's cloud physicist. He was asked to study weather modification as tool to improve the state's water resources. At this time, Illinois and the Midwest was recovering from a severe drought and much interest in the use of cloud-seeding to make rain had been expressed in Illinois. Weather modification was an emerging scientific field at the time and little was known about the physical processes that led to summer convective rainfall. The emerging research endeavors were to lead Semonin along several paths including following up on the previous work during 1953-1954 to examine the chemistry of precipitation water and aerosols (see Chapter 8). Semonin got an NSF grant in 1958 to sample airborne particulates so as to help identify the nuclei associated with summer rains, one the key unknowns facing cloud seeding. These activities ultimately led to the establishment of a Cloud Physics Laboratory that is still functioning (see Chapter 8).

The impetus to return to field experimentation in planned weather modification was developed around the concept that one could influence the electrical field of the atmosphere and the electrical charging of cumulus clouds. This concept was pioneered by Bernard Vonnegut and Charles Moore, two free-thinking atmospheric scientists affiliated with the Arthur D. Little Company. In 1960, they enlisted the help of Semonin and the Survey's instrumented aircraft which had been used for the particulate sampling in 1958-1959, to conduct a field experiment in central Illinois.

The renewal of weather modification field research at the Water Survey in 1960 was also tied to the emergence of a national effort in weather modification research and development. Widespread use of operational cloud-seeding projects by commercial firms in many parts of the United States during the 1950s had raised many questions about whether cloud seeding really worked, and the subject piqued the interest of the meteorological community and the leaders of science programs at several federal agencies. Although the early attitude of the U.S. Weather Bureau was epitomized by the position that "weather modification does not work," science leaders at other federal agencies were definitely interested. A group at the U.S. Department of Agriculture wanted to learn more about using cloud seeding to suppress lightning and limit forest fires. With its focus on water management for the dry western states, the Bureau of Reclamation began rain-making and snow-enhancement studies in various states with encouragement from Congress. The Department of Defense saw weather modification as a technology needed for national defense and conducted and funded diverse research about fog dissipation and rainmaking. By 1960 the newly formed National Science Foundation recognized that the science of weather modification required monetary support and focused on supporting varied types of research (Changnon and Lambright, 1987). By the mid-1960s, the newly formed National Oceanic and Atmospheric Administration or NOAA (institutional home of the National Weather Service) had also become active in weather modification research, including cloud and rain modification research in Florida and cloud seeding to reduce hurricane winds. After 1960, these diverse interests of the federal agencies resulted in substantial funding for weather modification research at universities and institutions such as the Water Survey.[1]

With its continuing need for federal funds to sustain and build its meteorology program, the Survey embraced weather modification research during the 1960s, a decision further fueled by events in the Vandalia area during 1963-1964. That area of Illinois had undergone a localized drought in 1962-1963, and a commercial cloud-seeding firm operated by Irving P. Krick convinced several local farmers to fund a cloud-seeding project during parts of 1963 and 1964. Certain local interests asked the Water Survey for scientific opinions on the likelihood that the ground-based seeding generators used in the project could create rain, and for help in assessing whether the seeding had actually done so, and, if so, how much. Survey scientists soon realized they needed more knowledge to provide answers to such questions. Consequently, they launched a research endeavor about *the evaluation of weather modification projects* (fig. 6-1).

Evaluation became a major and long-lasting theme of the Water Survey's research dealing with weather modification. Rain evaluation was a natural subject because Survey scientists since 1948 had done pioneering studies of rainfall measurement techniques with radar and raingages (see Chapter 3), and what counted to farm interests was "more water in the raingage." By 1964 Survey scientists had already intensively studied the variability of rainfall with its raingage network databases (Huff and Neill, 1959a). A key to evaluation of possible cloud seeding effects on rain rested in sorting the "signal from the noise of the high natural variability" found in Illinois precipitation (Changnon, 1979c). Another impetus came from a 1965 invitation to present a major scientific assessment about the rain evaluation at a special weather modification

[1] The Water Survey conducted extensive research during the 1950s to test the suppression of evaporation from lakes using fatty alcohol compounds and other substances. This research under the leadership of W.J. Roberts (1959, 1961 was related to "climate modification" and was done by the Hydrology Section, not the Meteorology Section.

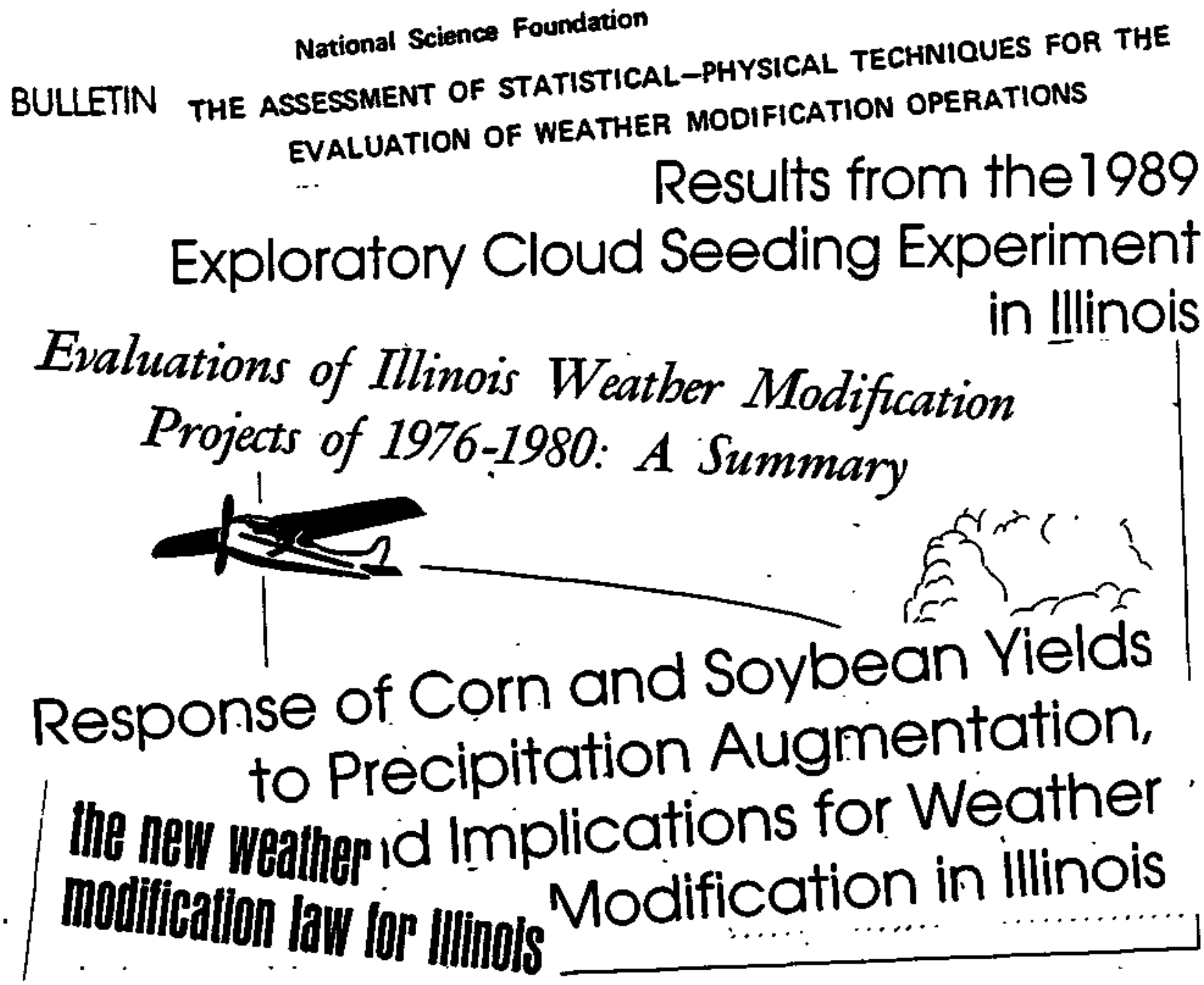


Figure 6-1. Some Water Survey publications addressed various aspects of planned weather modification in Illinois including project evaluation.

symposium at the 1966 national conference of the American Association for the Advancement of Science (Changnon and Huff, 1968).

The Water Survey began research focusing on hail in the late 1950s. This included three endeavors: 1) a study of the statewide climatology of hail (Huff and Changnon, 1959), 2) an Air Force-sponsored project in 1959-1961 focused on use of radar to detect hailstorms (Wilks, 1960), and 3) a series of projects funded by the hail insurance industry examined surface hail characteristics (Changnon and Stout, 1962, 1963e; Changnon, 1964c, 1966c). This track record and expertise put Survey scientists in a strong position to join in the new national program to study hail suppression, an NSF programmatic thrust that began in 1966 largely as a result of Soviet claims that they had developed a highly effective hail suppression technology (Changnon and Lambright, 1987). Fueled by the special interests of several mission agencies, rapid growth of the federal research programs in weather modification led the Bureau of Reclamation to contact Survey scientists in 1969 about the potential for a major rain enhancement project in Illinois. This signal coupled with ever growing federal attention on the development of weather modification brought the Water Survey into a bona fide program in weather modification by 1970. The program was the Precipitation Enhancement Program (PEP) and was designed as an effort expected to require at least ten years to complete.

By this stage of the development of a Survey weather modification program, a major thrust was considerable research concerning the socioeconomic, environmental, legal, and public policy ramifications of weather modification. Purposeful changes in the weather could create controversy between diverse interests, and by 1970 the national concern with the environment was growing. As a hydrologist, Chief Ackermann was deeply interested in the potential of weather modification for additions to water resources, and he and Section Head Changnon chose to pursue a careful course in developing the research program by laying a base of understanding about the ramifications of changed weather. This work showed the types of potential benefits and the cautions necessary in conducting a field experiment. This chapter addresses the meteorological aspects of the weather modification research so all weather modification "impacts research" is described as part of the Survey's impacts research program (Chapter 10). Chief Ackermann was interested and extremely helpful during 1972-1973 to inform agricultural and water interests about the Water Survey's emerging Precipitation Enhancement Program (PEP). Then during 1977-1978 under an ensuing program named the Precipitation Augmentation for Crops Experiment (PACE) Chief Ackermann was again heavily involved in PACE promotion when he and Sylvan Wittwer (Director of the agricultural experiment station at Michigan State University) helped influence the heads of the Agricultural Experiment Stations at Midwestern land grant universities to join with the Survey in developing the Precipitation Augmentation for Crops Experiment (PACE).

Another series of events extremely important to the Survey's involvement in weather modification began in 1976. Dry conditions during 1975 and early 1976 in central Illinois again led several leading farmers, two agribusinesses, and a bank in the Coles County area to organize a group that raised $65,000 to conduct a cloud-seeding project to make rain. Section Head Changnon and Dean Glenn Salisbury, Head of the Agricultural Experiment Station, conferred with the Coles County group in May 1976 and promised information and assistance with their project, and the Illinois Weather Modification Control Board (formed as a result of the 1975 legislation developed by the Survey, as part of PEP, and promoted by the Illinois Farm Bureau) reviewed and approved its first project application, the Coles County Weather Modification Project. Changnon had been appointed chairman of the Board by the Director of Registration and Education.

A cloud-seeding project was conducted in a five-county area centered on Coles County in the summers of 1976 and 1977 with Survey scientists monitoring the operations, and evaluating the end-of-project radar and rainfall data (Changnon and Towery, 1976, 1977), and frequently conferring with local sponsors and the news media. Similar endeavors were made for seven other cloud-seeding projects conducted elsewhere in Illinois during 1977-1981, and Survey weather modification experts worked closely with the local groups and the media to answer myriad questions about weather modification. This six-year period (1976-1981) of major scientific services to Illinois helped fulfill the Survey's mid 1960s decision to become proficient in weather modification as a future issue that would face Illinois. This action fit former Chief Buswell's philosophy that a major role of the Water Survey was to anticipate major water issues and do the necessary data collection and research "to be prepared".

The 141 publications written by Survey scientists and devoted to weather modification illustrate the timing in the development of attention to the field (Table 6-1). This number excludes 33 publications having to do with impacts research (see Chapter 10).

Table 6-1. Number of Scientific Papers and Reports Written by Water Survey Scientists about Planned Weather Modification (Excludes Publications Dealing with Impacts, see Chapter 10)

		Reports		
Year	*Papers*	*State series*	*Contract series*	*Total*
1960-1962	4	0	2	6
1963-1965	0	0	1	1
1966-1968	3	0	2	5
1969-1971	8	0	6	14
1972-1974	7	0	7	14
1975-1977	21	2	3	26
1978-1980	9	3	6	18
1981-1983	7	2	8	15
1984-1986	8	0	3	11
1987-1989	7	0	4	11
1990-1992	4	0	3	7
1993-1995	8	2	3	13

The temporal distribution of the publications reveals a small but constant level of attention to planned weather modification during the 1960s, followed by a major spurt during 1969-1971. The 1960-1963 publications were related to field experimentation led by Richard Semonin seeking to modify the electrical charge inside clouds. The 1965-1969 endeavors were largely related to the issue of evaluation of rainmaking projects. The spurt during 1969-1971 occurred as two new programs developed under Changnon's direction: 1) the Survey's involvement in hail suppression research focused on Illinois and on the National Hail Research Experiment (NHRE) in Colorado, and 2) the Survey's own program to develop PEP, an experiment involving rainfall enhancement in Illinois. Attention to hail suppression research continued through 1977, and after PEP ended in 1975, staff led by Bernice Ackerman focused on the design of HIPLEX, a project being developed by the Bureau of Reclamation for the High Plains.

Floyd Huff, Paul Schickedanz, and Chin-Fei Hsu continued to provide staff expertise for the statistical and physical evaluation of weather modification projects, both experimental and operational, which resulted in several NSF-funded projects during the 1975-1986 period. In 1978, the Survey's major focus on weather modification turned to PACE, an Illinois-based experiment for rain enhancement funded by NOAA. This project has been sustained through 1996 under the direction of Changnon and Bob Czys, but the project's name was changed in 1990 from PACE to Precipitation, Cloud Change, and Impacts Project (PreCCIP).

Four major research themes developed within the weather modification program area during the 1960-1995 period. The earliest interests, and the two major research themes, centered around 1) *rain enhancement in Illinois,* and 2) *the design and evaluation of weather modification projects*. The latter included design of a *hail suppression experiment in Illinois,* an endeavor sustained by a series of NSF grants over a 10-year period beginning in 1967. . Both themes persisted 25 years or longer.

A third theme concerned sporadic interests in *other forms of weather modification including cloud and fog modification.* After the Survey program developed and had gained national acclaim, Survey scientists also eventually became involved in a fourth theme, the *programmatic issues and government policies related to weather modification.*

DESIGN AND EVALUATION OF PROJECTS

The oldest and longest lasting area of research involved the design and/or evaluation of weather modification projects. At the root of this research was staff expertise and invaluable databases in both rainfall (from dense raingage networks operated since 1948) and in hailfalls (from networks of hail pads and hail observers during 1960-1961 and again during 1967-1970 in central Illinois). This work was led by Huff and Changnon in the mid-1960s, and then Paul Schickedanz, hired because of his meteorological/statistical expertise, became a major contributor from the late 1960s until his death in 1977. State funding supported the early work, NSF funded the hail studies after 1967, and the support for the rain design and evaluation work came largely from federal agencies in a series of grants from 1968 through the mid-1980s.

Precipitation Research

The first study concerned the impact of rainfall variability on the verification of rain enhancement projects (Huff, 1966). A major early paper concerned the use of rainfall data to evaluate cloud seeding (Changnon and Huff, 1967). Huff (1968b) explored the use of area-depth curves, a tool of hydrologists, for assessing storm rainfall modification. The use of rain rates as a tool for evaluation was also assessed (Huff et al., 1969) as part of the Survey's first grant from the Bureau of Reclamation. Techniques developed were employed to assess the rainfall results from Project Whitetop, a five-year modification experiment conducted in southern Missouri during the 1960s (Schickedanz and Huff, 1970). The scientists then collaborated to examine various rain evaluation techniques (Schickedanz and Huff, 1971). NOAA scientists interested in developing a seeding experiment to enhance and redistribute precipitation on the Great Lakes funded a Survey study to assess the hydrologic (and economic) effects (Stout and Ackermann, 1974). The developing research in this area led to an invitation to present a comprehensive paper on the design and evaluation aspects of weather modification at an international conference in the Soviet Union (Changnon, 1973i).

Two new activities in 1976 affected the Survey's design-and-evaluation research dealing with rainfall modification. A two-year contract awarded by the Bureau of Reclamation to prepare the design for the High Plains Experiment (HIPLEX) led to comprehensive studies by several Survey staff of the physical and statistical aspects (and impacts) of the proposed experiment (Ackerman and Changnon, 1977). Schickedanz (1977b) who had become nationally recognized for his statistical methods and analyses of weather modification projects, addressed the statistical aspects including the use of covariates (Schickedanz and Sun, 1977), and Achtemeier (1979) investigated the impact of severe storms on the HIPLEX field project. Schickedanz (1977c) launched studies of the broader issues of factor analyses in evaluating rainfall modification. The HIPLEX project work culminated in two major design documents (Ackerman et al., 1976, 1977).

Other rainfall-related evaluation endeavors launched in 1976 resulted from the need to respond to a series of cloud seeding projects that began in Illinois. Survey scientists finally had the opportunity to apply the findings of their research in a way that would prove important to Illinois. Technical Letter 27, a brochure providing guidance to these field operations was issued. Eight summer rainmaking projects in various parts of central and southern Illinois during 1976-1981 (fig. 6-2) were evaluated by Survey scientists (Changnon and Towery, 1976, 1977). The meteorological staff met frequently with the cloud seeders and the projects' local supporters and promoters. All the projects were funded by local subscriptions of funds. Several state reports were prepared for individual projects (Changnon et al., 1979f; Changnon and Hsu, 1979, 1980; Hsu and Changnon, 1981). Evaluations of these projects were then interpreted and summarized in a major state report (see figure 6-1, Changnon and Hsu, 1981) that said the results suggested rain enhancement had occurred in the better operated projects.

These evaluations of the eight Illinois cloud-seeding projects helped bring Survey scientists into a new arena, the evaluation of operational, nonrandomized cloud-seeding projects (Changnon et al., 1979a, 1979g). Various techniques for use in evaluating operational cloud seeding projects were identified and assessed (Changnon et al., 1980g). This work began with a grant issued to Paul Schickedanz, but upon his untimely death, the work was shifted to a new staff member, Chin-Fei Hsu, Floyd Huff and Stan Changnon.

The concept of "piggybacking" scientific evaluation on such commercial projects was defined (Changnon et al., 1980e; Gabriel and Changnon, 1981) and included the delineation of the operational process necessary during weather modification projects to allow meaningful evaluation (Huff and Changnon, 1980). This research also led to a series of NSF-funded projects dealing with the physical and statistical evaluation of operational weather modification projects (Hsu et al., 1981; Hsu and Changnon, 1982). Changnon and Hsu investigated the use

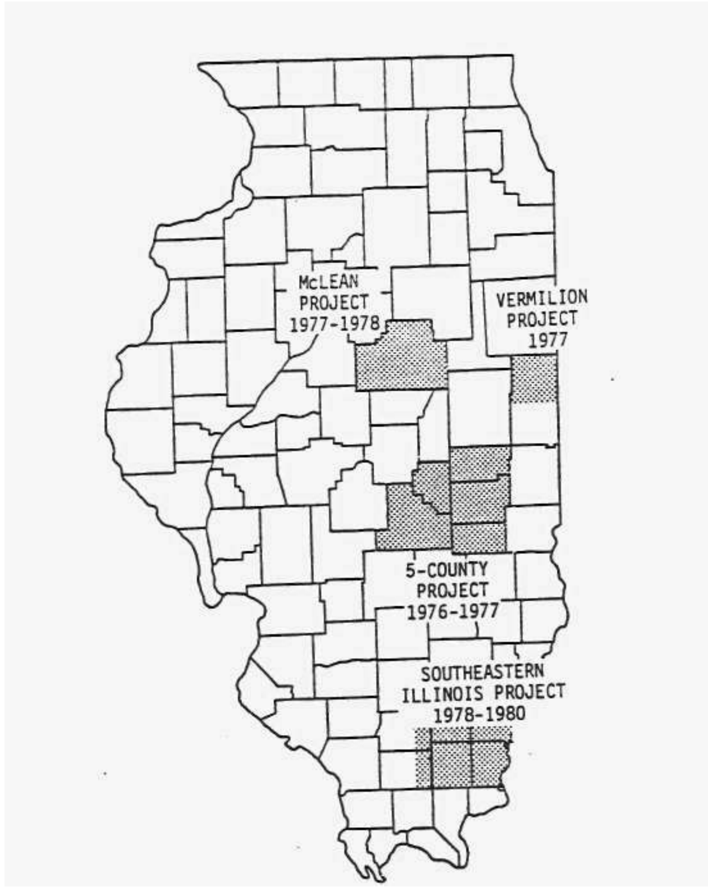


Figure 6-2. The locations of the eight cloud-seeding projects conducted during 1976-1981 to enhance summer rainfall. These were supported by local funds and Survey scientists monitored and evaluated each project.

of historical precipitation and hail data, always a controversial issue, in evaluating operational projects (Changnon and Hsu, 1983c), and results were presented to the hydrologic community who was vitally interested in rain enhancement (Changnon and Hsu, 1983b). The work culminated in a major final report to NSF (Hsu et al., 1984). Statistical techniques for evaluation were assessed in a separate publication (Huff et al., 1985), and specific operational projects around the nation were tested and evaluated (Changnon and Hsu, 1985a). Much of the evaluation work has been summarized (Changnon, 1986a).

Research in design and evaluation by 1979 was also applied to PACE, the new rain enhancement project developing in Illinois (Changnon and Ackerman, 1980). Other design and evaluation research related to PACE and done since 1980 is presented in the next section on the rain enhancement experiments in Illinois.

Hail Research

An NSF-funded three-year project awarded to Changnon in 1968 focused on hail suppression studies including the design and evaluation of projects with specific reference to Illinois. A large 8,000-square-mile network of hail observers was established in central Illinois. Historical hail data from the U.S. Weather Bureau stations and crop-hail insurance records were gathered and analyzed. Various evaluation approaches and types of data for possible use in evaluating hail suppression experiments were assessed (Changnon, 1968b). By 1969, papers about the design and evaluation of hail suppression began to emanate from this research, including assessments of hail data for the design and evaluation of projects (Changnon and Schickedanz, 1969, Changnon, 1969d; Schickedanz and Changnon, 1970). The results generally indicated that hail suppression would require a long time, more than 10 years, of experimentation to detect. The Illinois-based project also addressed the use of RHI radar echo measurements to detect hail-bearing storms as an operational tool, and for the evaluation of seeding to suppress hail (Changnon and Staggs, 1970). The series of projects during 1967-1975 concerning hail research in Illinois and elsewhere led ultimately to the design of a potential hail suppression experiment for Illinois (Changnon and Morgan, 1976b). We also were leaders of a major technology assessment of the national development of a hail suppression technology, a 2-year NSF funded project (Changnon et al., 1977d).

In 1969, Survey scientists also became involved in the National Hail Research Experiment (NHRE), which was gearing up for a major national field experiment in northeastern Colorado. This project had been preceded by the involvement of Changnon and Stout in the national Hailswath Project in South Dakota during the summer of 1966 (Changnon, 1966d, 1966e). The areal spread of damaging hail was assessed as a tool for evaluating hail suppression efforts (Changnon, 1971f). Subsequent involvement of several Survey staff in NHRE was based on funding for three projects. One designed the field project (Schickedanz and Changnon, 1970, 1971). A second used the Survey's brand new dual wavelength CHILL radar for field operations in Colorado, and the collection of data for evaluation (Changnon and Mueller, 1974). A third NHRE-related study addressed the small-scale variability of hail falls based on data from an NHRE hail network and the implications of the large spatial variability for evaluating hail suppression were assessed (Morgan and Towery, 1974, 1975). A hail cube device, developed by Survey scientists, was used in Colorado to collect data allowing a count of the hailstones that fell, the size of each hailstone, and the direction of any windblown hailstones, as measured on the sides of the cube.

Continuing research aimed at a potential national hail suppression experiment in Illinois led to further studies of the project's ultimate design (Changnon, et.al., 1974, 1975; Changnon and Morgan, 1975). A Survey report summarized what had been learned about radar's capability to detect hail (Changnon, 1972a). Survey evaluation techniques were then applied to the evaluation of an ongoing hail suppression project in west Texas (Changnon, 1975d). The nine-year project in Illinois culminated in a comprehensive design of a hail suppression project for Illinois (Changnon et al., 1976b and 1976c). Morgan and Towery (1977) addressed the various ways to measure surface hail and their implications for use in suppression evaluation. The status of hail suppression efforts across the nation was reviewed (Changnon, 1977c), a survey done as part of the technology assessment project (see Chapter 10 for further details). Changnon, in response to a WMO invitation, presented an in-depth paper discussing the uses of crop-hail data (presented at an international conference in the Soviet Union) for assessing hail suppression (Changnon, 1985b). Much of the Survey's work with hail suppression ended in 1977 as the national effort and federal support for research ended.

ILLINOIS RAIN ENHANCEMENT EXPERIMENTS

A major goal of the Survey's meteorological program since 1968 was to conduct well-conceived and scientifically sound experiments to define the potential for enhancing rainfall in Illinois. This began with the PEP project, which lasted from 1971 to 1975, ending with a loss of Bureau of Reclamation funding due to "territorial agency wars" between them and NOAA (Changnon, 1973b, 1975e). The next major effort was the PACE project, which began in 1978 with grants from NOAA and was expected to become a major joint experiment between NOAA and Water Survey scientists (fig. 6-3). Unfortunately, however, NOAA terminated all their weather modification research in 1981. After a one-year lapse of funding for PACE in 1981, the Survey, with the permission from the Governor's office, joined three other states in seeking and gaining congressional financial support for their research projects (see Chapter 12). PACE resumed in 1982 and research has continued to date although the project's name changed to PreCCIP in 1990 to allow for a broadening of the research to include inadvertent weather modification.

The first study that examined the potential for rain enhancement in Illinois focused on weather conditions during short-term dry periods (Semonin, 1960). The efforts related to the first actual project began a decade later when PEP developed in 1971 to determine the feasibility and desirability of rain enhancement in Illinois. The first project report (Water Survey, 1972) documented the planning and the beginning of the impact and meteorological research that embraced ten topics. It included cloud and mesoscale modeling (Ochs and Ceselski, 1973), studies of weather conditions during droughts (Huff, 1973), the amount of seeding material (silver iodide) found in rain (Gatz, 1975), and the potential for extra-area effects (Schickedanz, 1973), the possibility of a change in rain beyond or downwind of the target area of the experiment addressing the eternal concern with "stealing rain". We established our concepts about the feasibility and necessity of enhancing rain in Illinois (Changnon, 1972c), and we also informed the hydrologic community about our well-designed program (Changnon, 1973g). Ackerman et al., 1977 summarized what Survey scientists had learned during PEP. Weather modification research described in this chapter also used the findings generated by the Survey's long-running cloud physics program and the studies of mesoscale weather conditions affecting rainfall. These research endeavors are described in Chapter 8.

A second and more major rain enhancement project began with studies of the legal issues facing weather modification projects (Changnon, 1977d) and investigations of the Illinois seeding opportunities as determined from cloud models (Semonin, 1977). A public information document describing PACE was prepared and widely distributed across Illinois (Changnon and Ivens, 1979). The front page of this document appears as figure 6-3. Ackerman et al.(1979) used a NOAA P-3 aircraft to penetrate Illinois clouds to gather data and assess the suitability of Midwestern clouds for modification. Potential seeding materials were also under investigation, including the use of hygroscopic materials (Johnson, 1980). A fully executed plan for the seeding experiment in PACE was prepared (Ackerman and Changnon, 1980) and called for a three-phase effort involving a pre-experimental data collection-analysis effort, exploratory seeding experiments, and finally a confirming experiment if justified by the prior two phases.

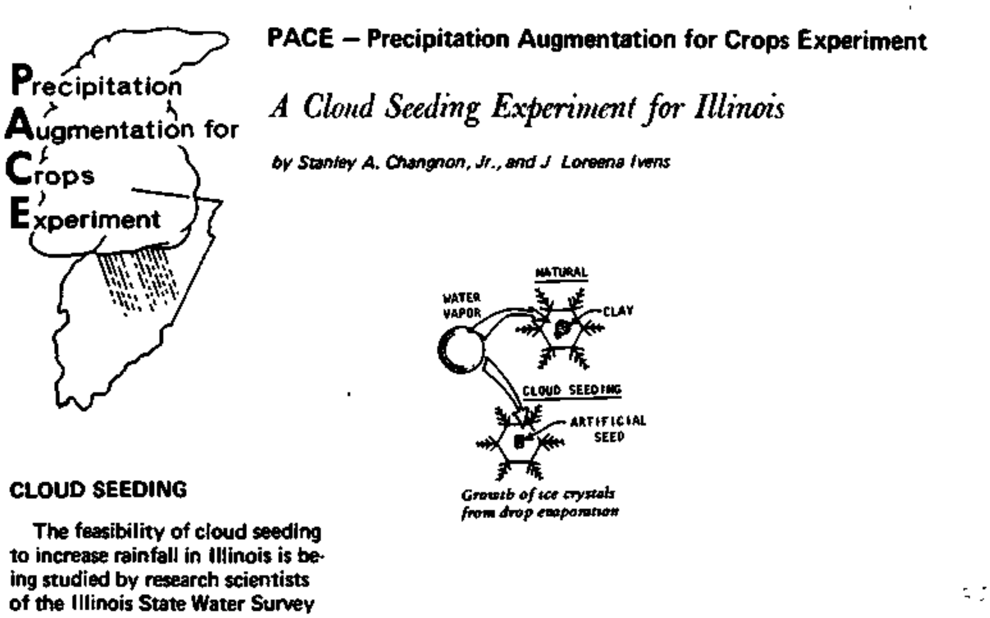


Figure 6-3. The Precipitation Augmentation for Crops Experiment (PACE) began in 1977 as a joint NOAA-Water Survey project. This is the first page of the information flyer was prepared for wide distribution in Illinois to help explain the project including its objectives and dimensions to the lay public.

The detailed initial design of the "pre-experimental" phase of PACE was also executed (Changnon, 19801). The relationship between surface weather conditions and rainfall development was studied to improve project forecasting and evaluation of the results (Achtemeier, 1981). Much of the cloud and echo research done as part of the pre-experimental research of 1977-1980 was summarized (Changnon et al., 1980e).

A project report (Achtemeier et al., 1983) documented the varied research conducted during 1980-1982, which included new studies of the impacts of added rainfall (see Chapter 10). Progress in analyses of Illinois convective clouds was made during 1982-1985 with more cloud modeling (Ackerman and Westcott, 1985; Westcott and Ackerman, 1985), studies characterizing Midwestern clouds (Ackerman, 1986), and investigations of Illinois convective cells as revealed by radar (Huff, 1976c). After these studies were completed, a seeding hypothesis involving dynamic seeding at mid-cloud levels of growing convective clouds, which had performed well in Florida, was selected as the best for PACE experimentation (Ackerman et al., 1985a; Changnon et al., 1986b). The seeding approach used in PACE is illustrated in figure 6-4.

PACE gained national visibility (Changnon, 1986b; Changnon et al., 1991a), and the first exploratory seeding experiment was designed and conducted under Bob Czy's leadership in the summer of 1986 (Changnon and Huff, 1987). An innovative forecasting and nowcasting system was designed for the summer field experiment (Scott and Huff, 1987; Ochs and Kidder, 1989). The experimental period in 1986 was plagued by unusually dry weather, but a limited evaluation

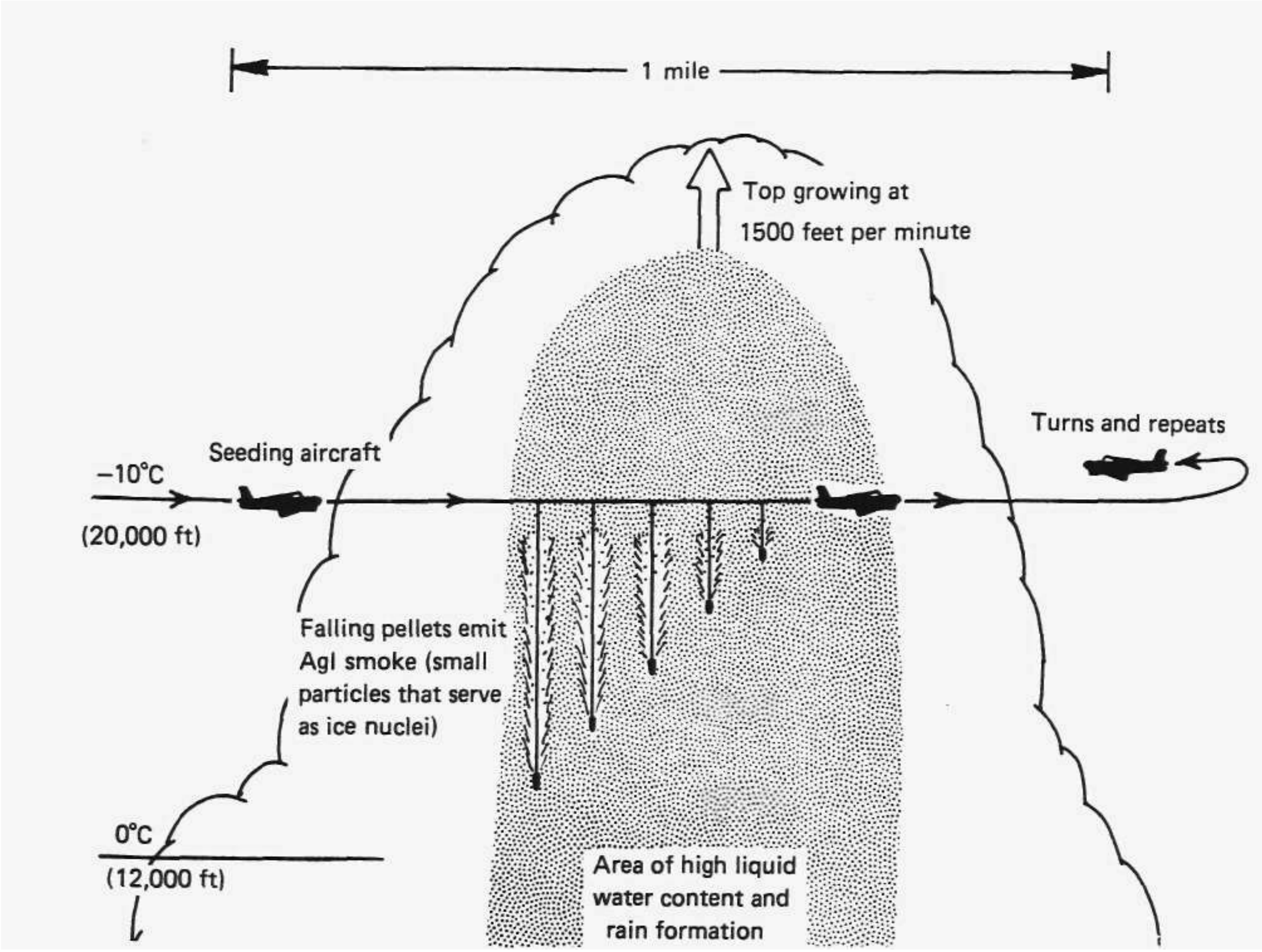


Figure 6-4. A schematic showing the PACE seeding approach. The aircraft penetrated growing cumulus at the -10°C level and dropped flares containing silver iodide or sand (the placebo) into the growing cloud's updrafts. The AgI was expected to increase cloud buoyancy and growth, the "dynamic seeding" hypothesis. A rapidly growing cumulus congestus cloud was selected for experimentation and then the seeding officer on board the aircraft drew an envelope that told him which group of flares to drop.

of the few seeded cases was made and reported in the literature and at conferences (Changnon et al., 1987c; Westcott, 1990).

A second and more successful randomized seeding experiment was conducted for eight weeks during the summer of 1989 (see PACE staff and equipment photographs on fig. 6-7). Czys (1991) who directed the 1989 project, analyzed the updraft structures found in the clouds studied (fig. 6-5). Czys assembled a major report which documented all the data collected during the 1989 trials (Czys, 1993). Changnon and Czys (1992) and Changnon et al. (1992) presented the initial findings from the 1989 experiment.

The project's final results were carefully summarized and presented in a sizable state report (Czys, et al., 1993), and in scientific papers (Czys, et al., 1994; Changnon et al., 1994a). The cloud growth results did not support the dynamic seeding hypothesis, although there was weak evidence that rainfall had been enhanced (Changnon et al., 1994b). Examples of the scientifically conflicting findings are illustrated in figure 6-6. A complete assessment of the seeding results, coupled with operational limitations inherent in the dynamic seeding approach

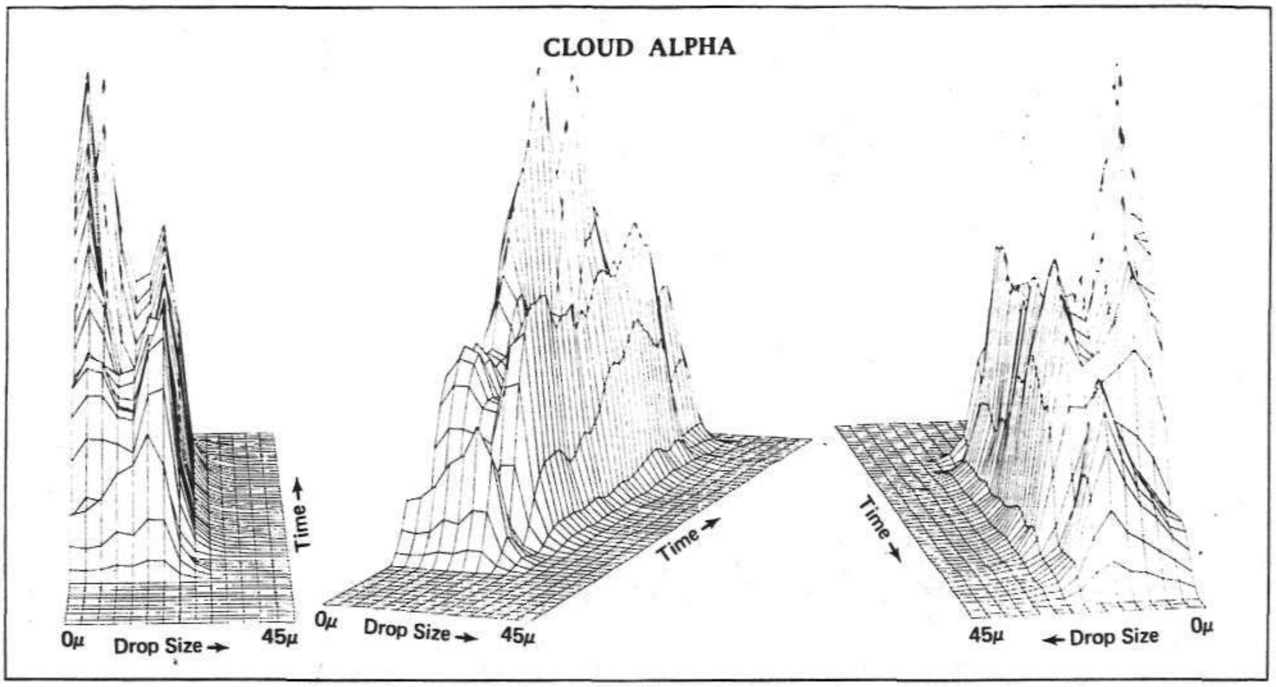


Figure 6-5. A three-dimensional drop distribution inside an Illinois cloud, as developed from FSSP data.

(no night operations when 45 percent of all rain occurs), and the findings from several years of agricultural impact studies (Hollinger and Changnon, 1973) led to the conclusion that further experimentation involving other seeding approaches needed to be considered (Changnon and Shealy, 1994).

OTHER FORMS OF MODIFICATION

The first weather modification experiment in Illinois began in 1960 and involved attempts to alter the atmosphere's electric field and the space charge in small convective clouds. Using concepts developed by Vonnegut and Moore who desired a flatlands testing site for a field experiment, the Arthur D. Little firm funded in 1960 the start of a multi-year experiment in central Illinois. Survey scientists strung thin wires on poles (TV masts) over 8 miles in a geometric configuration during 1960. In 1961-1962 this was increased to wires strung alongside 28 miles of roads and railroad lines in east-central Illinois, forming a grid of "charged wires" on which a high negative or positive voltage could be applied (Semonin et al., 1962a). Moving dust particles in the atmosphere presumably became charged with ions on the line and thus carried the charge aloft. NSF grants funded field experiments in 1961 and 1962 that involved two aircraft: a C-45 aircraft (obtained by the University of Illinois for this project) and the Tri-Pacer that had been instrumented for the aerosol flights in prior years. The aircraft measured the atmospheric space charge on the fair weather potential gradient (Semonin et al., 1962b) and the electrical charge of small cumulus clouds (Bradley and Semonin, 1967). Radar measurements of the echoes in the area were made with the TPS-10 radar; six all-sky dome cameras in the area photographed the clouds, and ten electric field mills measured the electric field.

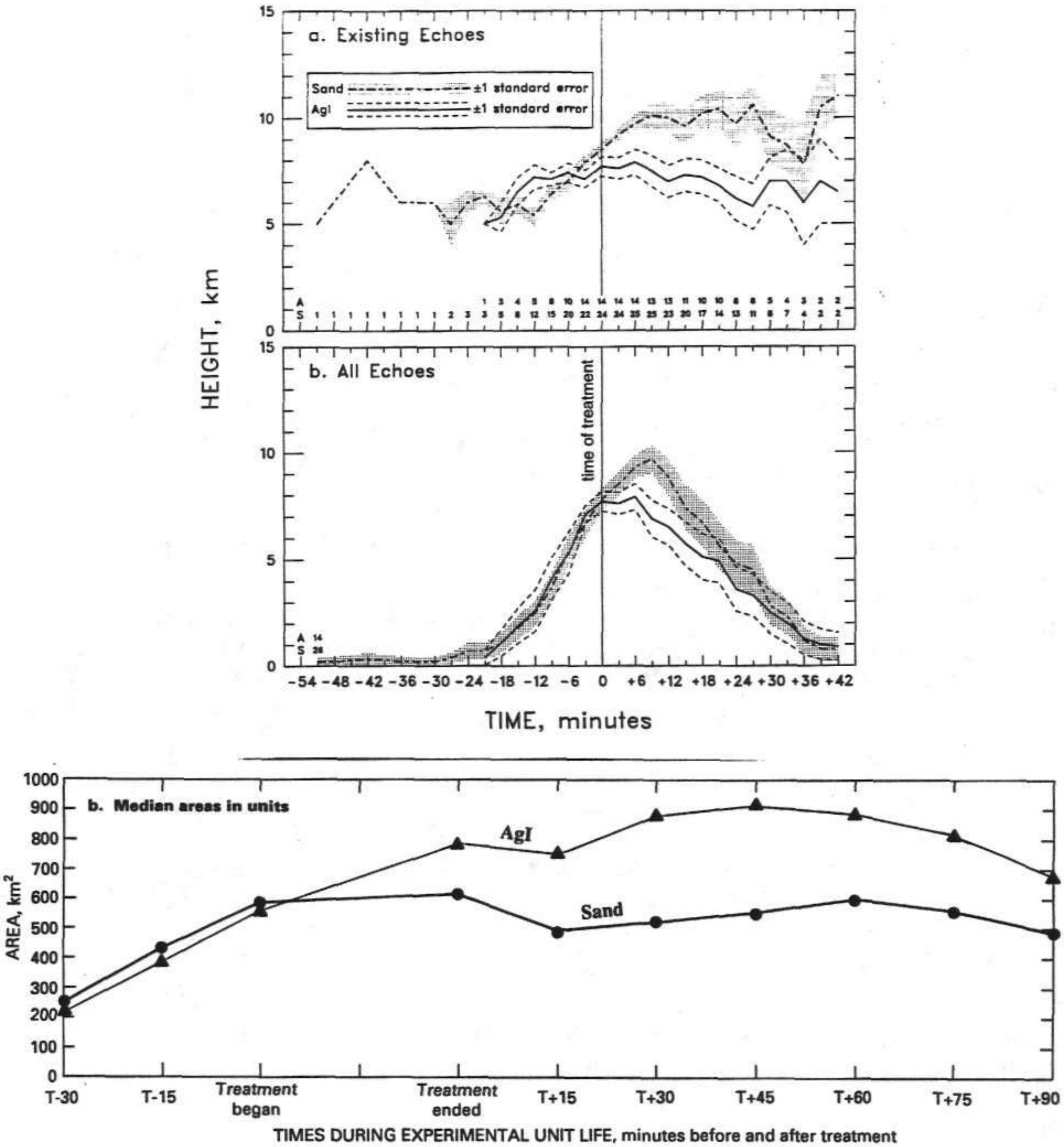


Figure 6-6. These two illustrations are from the data collected during PACE 1989 field experiment. The upper two graphs show the temporal changes in mean echo heights (as defined by the 10-dBZ contour) for the group of echoes seeded (AgI, solid line) and the group of echoes not seeded (sand, dash line). There are two classes: all echoes, and only echoes that were existing when seeding passes began. The results show the sand (placebo) treated clouds grew taller than the AgI-treated clouds, an outcome contrary to the seeding hypothesis expectations. The lower graph compares the median values of rain areas for the AgI- and sand-treated cloud units with time. These results indicate that the seeded (Agl) storms grew larger than the non-treated cloud systems after seeding, as expected from the seeding hypothesis. Thus, the echo growth and echo area results were in conflict.

One of the project's problems was that the Arthur D. Little and NSF funding for 1960-1962 did not include sufficient amounts for study of the data. Finally at the end of 1962 some funds were obtained, but they were inadequate and the research lagged. Bradley and Semonin (1969) summarized the experimentation showing that 16 percent of the clouds investigated and located downwind of the charged wires had been electrified (see Chapter 8 which describes how this work led to a cloud physics research program). A Water Survey scientist (Ken Beard) participated in studies involving use of large volume water sprays to dissipate warm fog (Keller et al., 1986).

PROGRAMMATIC ISSUES AND GOVERNMENT POLICIES

By 1975 the Water Survey's endeavors in weather modification had become sizable, quite diverse, and also heavily dependent on federal funding support. This situation led to studies in two directions: 1) assessments of the broad issues of weather modification research, and 2) assessments and involvement in government policies relating to weather modification.

Interest in the broader aspects of weather modification led to reviews of various forms of weather modification and the research needs (Changnon et al., 1975c). Results from the 1971-1975 METROMEX effort were used to define lessons relevant to cloud seeding, including the fact that urban-related rain enhancement was most successful during highly convective rain systems (Semonin and Changnon, 1975). Changnon (1975f) examined the future national potential for weather modification and the efforts necessary to achieve development and wide application. A comprehensive assessment of the hail suppression field clarified the issues (Changnon, 1977c). Changnon (1979c) reviewed the history of varied weather modification efforts at the Water Survey, and massive literature searches produced major bibliographies about predictor variables (Westcott, 1979) and about design and evaluation findings (Hsu and Changnon, 1981). A study of the historical use of hail camions to suppress hail in Europe illustrated lessons detrimentally affecting the development of the current field of weather modification (Changnon and Ivens, 1981).

Interest and concern over federal and state policies relating to weather modification was first addressed in 1974 as a result of a series of seemingly questionable decisions by several federal agencies about handling the field in 1972 (Changnon, 1973b). Related state governmental activities in 1974 concerned the development of a weather modification control law in Illinois (Ackermann et al., 1974), and Semonin (1980) assessed the effectiveness of this model law. Changnon argued for a strong national research program in weather modification citing scientific gains and new instrumentation as the new rationale for federal support (Changnon, 1980c). An assessment of the roles of state government in weather modification programs including promotion, funding, research, and regulation was made (Changnon, 1983c). The survival of the Illinois weather modification law during state efforts to sunset regulatory acts was documented (Changnon, 1983d). An historical study of the nation's handling of weather modification research (Changnon and Lambright, 1987) revealed considerable federal mismanagement. A related study of the handling of several controversial weather modification projects identified key problems (Lambright and Changnon, 1990), and drew a critical response (Changnon and Lambright, 1990). In a field faced with declining support, Changnon (1992b) argued for the importance of weather modification research and development as a key endeavor of the atmospheric sciences. Commentary on the federal policies ended as federal interest and support for research ended.

SUMMARY

Accomplishments

The Survey's long-lasting research endeavors in weather modification have achieved most of the original goals. The research has defined, with certain limitations, that seeding approaches to enhance convective rainfall in Illinois are not clearly workable, but there is weak evidence that the experimental and operational cloud seeding in Illinois has increased rainfall under certain circumstances.

A major achievement of the Illinois program has been the development and sustainment of a strong in-state constituency for weather modification research and thus for the entire atmospheric research program of the Water Survey. These endeavors have provided the atmospheric sciences efforts of the Survey with as much positive in-state visibility as any other component of the 50-year program. Interactions with agricultural and water resource interests were a major activity during PEP, a factor leading to strong support for the research from the Illinois Farm Bureau (IFB). These positive interactions helped get IFB support of the model regulatory law promoted by Survey scientists and developed for Illinois by Professor Ray J. Davis of Arizona. The Illinois Weather Modification Advisory Board formed under this 1974 law was led by Changnon from 1975 through 1983, and the board had well-known members from the legal, environmental, and agricultural sectors during its busy years (1975-1981 when eight cloud-seeding projects were in progress. Survey staff were heavily involved in monitoring and assessing the eight projects in Illinois. We worked closely with the local groups in Illinois who organized and raised funds to support these projects.

These activities and the Survey studies that showed how cloud seeding would benefit Illinois agriculture (Chapter 10) were meaningful services to the state. They became key factors in getting in-state support for seeking restoration of the annual funding for PACE and PreCCIP (-$0.5 million per year) from 1982 through 1995. As a result, several Illinois members of Congress worked to restore this funding in the annual budgets of NOAA. On several occasions this constituency was also helpful in influencing state policies favorably affecting the Survey.

It is safe to say that the Survey's research in planned weather modification gained wide national acclaim and recognition for its high quality and expertise, of which there are numerous examples revealed in the foregoing history. For example, the Survey's proposals to NSF for designing and developing a hail suppression experiment, seen as a follow-up to the Colorado experiment (NHRE), were funded over a nine-year period at a cost of $3 million. The Survey was awarded the prestigious and highly competitive $1.1 million contract to perform the design for HIPLEX. Other examples were the numerous invitations to present major review papers at major national and international conferences, a mark of the quality of the Survey staff. The ability to attract more than $15 million in federal support for the weather modification research efforts is also a reflection of their quality and in itself is a major achievement. Since 1975 the Survey has advocated development of a strong, well-balanced federally supported research program dealing with planned weather modification.

Awards

Several Survey scientists became national leaders in weather modification, including the means to design and evaluate experimental and operational weather modification projects, and in the impacts of weather modification (see Chapter 10). Five Water Survey staff (Changnon, Czys, Morgan, Schickedanz, and Semonin) have been asked serve on the AMS weather modification committee, and Changnon and Czys have been elected president of the Weather Modification Association. Changnon was one of 12 members chosen for a national review panel for weather modification conducted during 1976-1978, and he received the 1983 Thunderbird Award by the Weather Modification Association. The final report of the technology assessment of hail suppression, a two-year project (1976-1978) garnered the 1978 Award for Professional Excellence from the American Agricultural Economics Association (see Chapter 10).

Key Projects

There were several important projects beginning with the NSF-funded project to study space charge modification during 1960-1962. The next major project, PEP, was funded by the Bureau of Reclamation and lasted from 1971-1975. Design of HIPLEX (1976-1977) kept a well-trained and devoted staff functioning together and developing me skills needed for the critically important PACE project, which began in 1978 and still continues in 1996. Several other NSF-funded projects supported the nine years of research to develop the design of a potential Illinois-based experiment in hail suppression. Other NSF projects supported the critically acclaimed projects dealing with the evaluation of experimental and operational projects.

Major Pivotal Publications

The 1967 paper on how to address rainfall variability in evaluating weather modification efforts brought national attention to the Survey and its capabilities in the evaluation aspects of modification (Changnon and Huff, 1968). Floyd Huff then wrote a series of important papers on rainfall evaluation for the hydrologic community (1966, 1967d, 1968a). The invited paper for an international conference reviewing the wide range of design and evaluation methods in North America (Changnon, 1973i, 1975c) further established Survey credentials in the national and international arenas.

Semonin and Bradley's (1969) paper on electric charge was a major step in defining the Survey's experimental capabilities. Two other early papers (Changnon 1973b, 1975e) addressed national policies and the handling of weather modification research, setting the stage for speaking on national policy issues. Paul Schickedanz wrote several important papers addressing the use of statistical techniques in design and evaluation, which established him as a national leader (Schickedanz and Changnon, 1970; Schickedanz, 1977a, 1977b). A paper about piggybacking scientific research on operational cloud seeding projects (Gabriel et al., 1981) won wide acclaim and helped launch several years of Survey research in this area. Bernice Ackerman made a major contribution in her comprehensive assessment of the characteristics of Illinois clouds, including a key summary (Ackerman, 1986). The final results of the 1989 seeding experiments in Illinois resulted in a very significant report revealing the dynamic cloud-seeding approach did not produce the anticipated results (Czys et al., 1993).

Extremely important documents for Illinois were the seven reports describing the cloud-seeding projects in Illinois during 1976-1981 and evaluating whether rain had been changed (Changnon and Towery 1976, 1977; Changnon et al., 1979f; Changnon and Hsu, 1979, 1980, 1981; Hsu and Changnon, 1981). These reports made the Survey's scientific endeavors highly visible and valuable to the state.

Key Staff

Most of the atmospheric sciences staff who worked at the Water Survey during the 1970s were involved in some form of the weather modification research being conducted at that time (figure 6-9). Long-term key staff members were Richard Semonin, Floyd Huff, and Stanley Changnon, who were deeply involved in this research from the late 1950s until the mid-1980s. Subsequently, Huff and Changnon continued to be involved through 1996. Other staff members were major scientific contributors for eight years or more including Bernice Ackerman (1973-1987), Robert Czys (1984-present), Griffith Morgan (1970-1978), Nancy Westcott (1983-present), and Paul Schickedanz (1967-1978). Professor Ruben Gabriel of the University of Rochester has worked with Survey scientists since 1977 and has contributed significantly to the Survey's program. Chin-Fei Hsu also made major contributions to the evaluation endeavors, as did Neil Towery.

Figure 6-7. On the opposite page are photographs relating to the Water Survey's program in planned weather modification research. The upper left show Bob Czys (foreground) readying his notes for a cloud-seeding flight in PACE July 1986 experiment. The upper right shows Chief Arthur Buswell in 1954 who took an interest in weather modification and decided to launch the Survey's weather research group in 1947 and sustain it until he retired in 1956.

The left middle is Ron Grosh who is seen tuning a radiosonde recorder. The right middle photo is of the 1986 PACE crew including (l. to r.) Jim Wood (pilot) and Tom Henderson (aircraft director) both of Atmospherics Inc., Gene Mueller (CHILL radar head), Bob Czys (director of the PACE operations), Bob Scott (chief forecaster), Pat Kennedy (radar operator), Bill Woodley (in front, meterological consultant), Dave Brunkow (behind Woodley, radar engineer), Stan Kidder (satellite data system), Nancy Westcott (radar operations supervisor), Stan Changnon (PACE director), Harry Ochs (nowcasting system), and Floyd Huff (seeding officer).

The bottom photograph shows the two meteorological aircraft used during the PACE 1986 field experiment, both parked at the University of Illinois Airport.





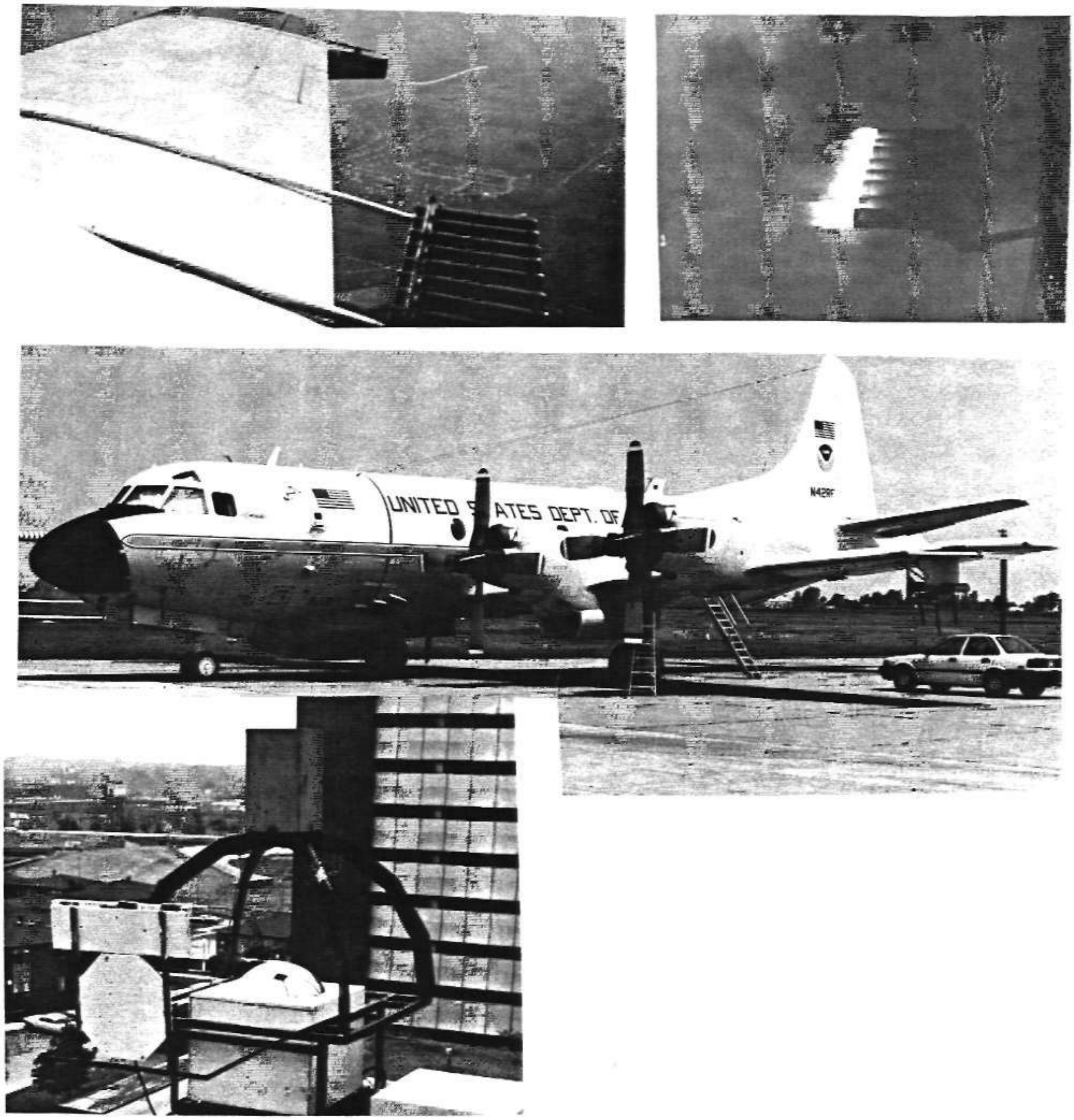


*Figure 6-8. The seeding of clouds to make rain and the release of tracers to help follow in-cloud air motions and rain development were often done with seeding flares attached to an aircraft's wing. **Upper left** shows a rack of flares just behind the wing. When the aircraft was located in the cloud's updraft at cloud base, the flares were ignited **(upper right)** to burn and release the chemicals. **Middle** is NOAA 's P-3 meteorological aircraft filled with the latest sensors including airborne radars, at the University of Illinois Airport in 1977. The aircraft was brought to Illinois in two different summers, as part of PACE, to collect data on in-cloud conditions. **Lower left** is one of the Survey's various all-sky cameras used to collect cloud photographs. The camera was housed inverted in the box above the dome and was sequenced to take a photograph of the ball every few minutes, providing a continuous record of cloud types, cloud development, and cloud movement. These were used in several field projects including METROMEX and PACE.*

Chapter 7

INADVERTENT WEATHER MODIFICATION AND CLIMATE CHANGE

Stanley A. Changnon

INTRODUCTION

Research dealing with inadvertent weather modification developed as a result of external stimuli rather than internal planning. The first effort came after inquiries from Chicago authorities about precipitation over Lake Michigan, which led to a 1960 study of the unique precipitation data from a water-intake crib located in the lake. The study concluded that there was more precipitation over the central city as a result of urban and lake influences (Changnon, 1961a). This was followed by an invitation from leading climatologist Helmut Landsberg to present a paper at a national conference on urban pollution and its effects on the weather. The invited paper was to assess possible urban effects on the rainfall distribution across the Champaign-Urbana area using data from the dense Boneyard raingage network (Changnon, 1962d). Another Water Survey paper presented discussed observed industrial influences on clouds and rainfall (Stout, 1962). Although these limited early studies set the stage for a program in inadvertent (urban) weather modification, no organized research in this area ensued. Climate change research was the result of direct programmatic planning during the 1970s.

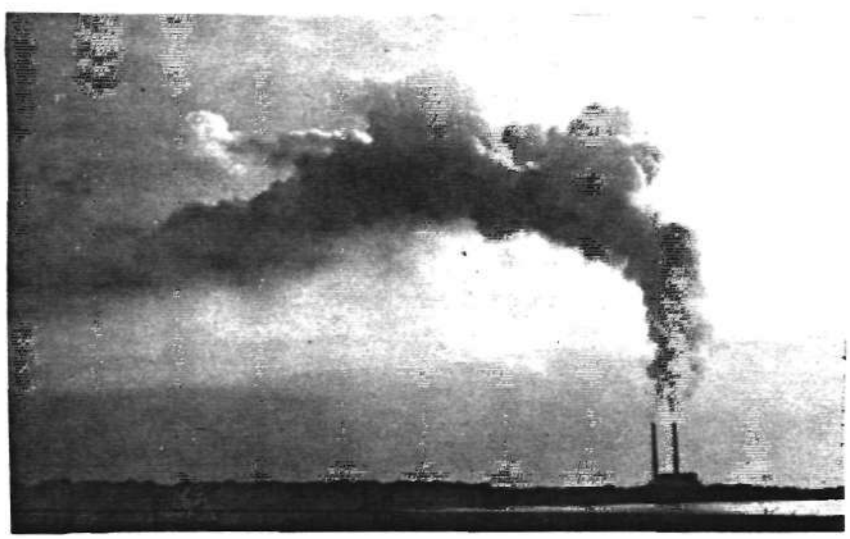


Figure 7-1. This photograph taken near Alton, IL, in July 1971 shows convective clouds growing from the plume of the huge power plant at Portage du Sioux.

Back in 1965 Changnon and Huff initiated a federally funded project examining the influences of Lake Michigan on precipitation. As part of that study, an anomalous increase in rainfall and thunderstorms was found in the historical data at La Porte, a weather station in northwestern Indiana. Increases in summer rain and storminess over time coincided with the growth of pollutants from the Chicago-Gary area 18 miles upwind of La Porte, which led to an analysis of the causes and a paper, "The La Porte Anomaly, Fact or Fiction?" (Changnon 1968c). It gained wide national attention in the news media and in scientific circles because it was the first U.S. study to show the dramatic potential for human-induced effects on rainfall and storminess (earlier European studies had found moderate increases in precipitation in large cities). Articles about the unique La Porte findings appeared in the *Saturday Review* (April 6, 1968, "The Home-brewed Thunderstorms of La Porte, Indiana"), in *Scientific American* (April 1968, "Factory-Made Rain"), and in *News Focus* (April 19, 1968, "Industrial Pollution Can Alter Climate"). Figure 7-2 illustrates the issue as presented in one national magazine.

The La Porte findings also created a major scientific controversy over whether such changes were possible or even if the La Porte data were valid (Holzman and Thom, 1970; Changnon, 1970b; Changnon, 1971g and 1971h; Holzman, 1971). Other scientists became embroiled in the issue and investigated the growth of local area tree rings and streamflow, concluding that an anomalous increase in precipitation coincided with the La Porte records and the growth of the Chicago metropolitan area (Hidore, 1971; Ashby and Fritts, 1972). Anxious to further investigate the urban influences, Huff and Changnon (1969) analyzed daily rainfall data at Chicago and St. Louis and found strong evidence of localized increases in heavy rains downwind of both cities. Changnon was invited to present a review paper about urban effects on clouds and precipitation at an international conference sponsored by the World Meteorological Organization (Changnon, 1970c).

By 1970, the subject of inadvertent modification of rainfall was receiving wide national attention and offered major opportunities for exploiting the Survey's pioneering research accomplishments. With the blessings of Chief Ackermann, Changnon, Huff, and Semonin planned a major field experiment to thoroughly study the issue, including how a city affects cloud and rain processes, and how much and exactly where the rainfall was altered (Changnon et al., 1971a). It is important to appreciate that the types of research associated with inadvertent weather modification and planned modification shared many similarities so that staff expertise could be applied to each of these rapidly expanding program areas. *Great growth occurred in the Atmospheric Sciences Section during the 1970-1975 period and involved new staff to meet needs related to major new projects such as METROMEX, PEP, and NHRE (see Chapter 6).*

Section Head Changnon and Semonin worked to get other scientific groups involved in the big urban field program they envisioned as necessary to assemble the equipment and expertise to tackle such a sizable and complex atmospheric issue. *Consequently, a major new program area addressing inadvertent modification of clouds and rainfall (and storms) was initiated in 1970.* The new field and analysis project was named the Metropolitan Meteorological Experiment (METROMEX) and was slated to take place at St. Louis during the 1971-1975 period. This massive undertaking involved more than 100 scientists from five scientific

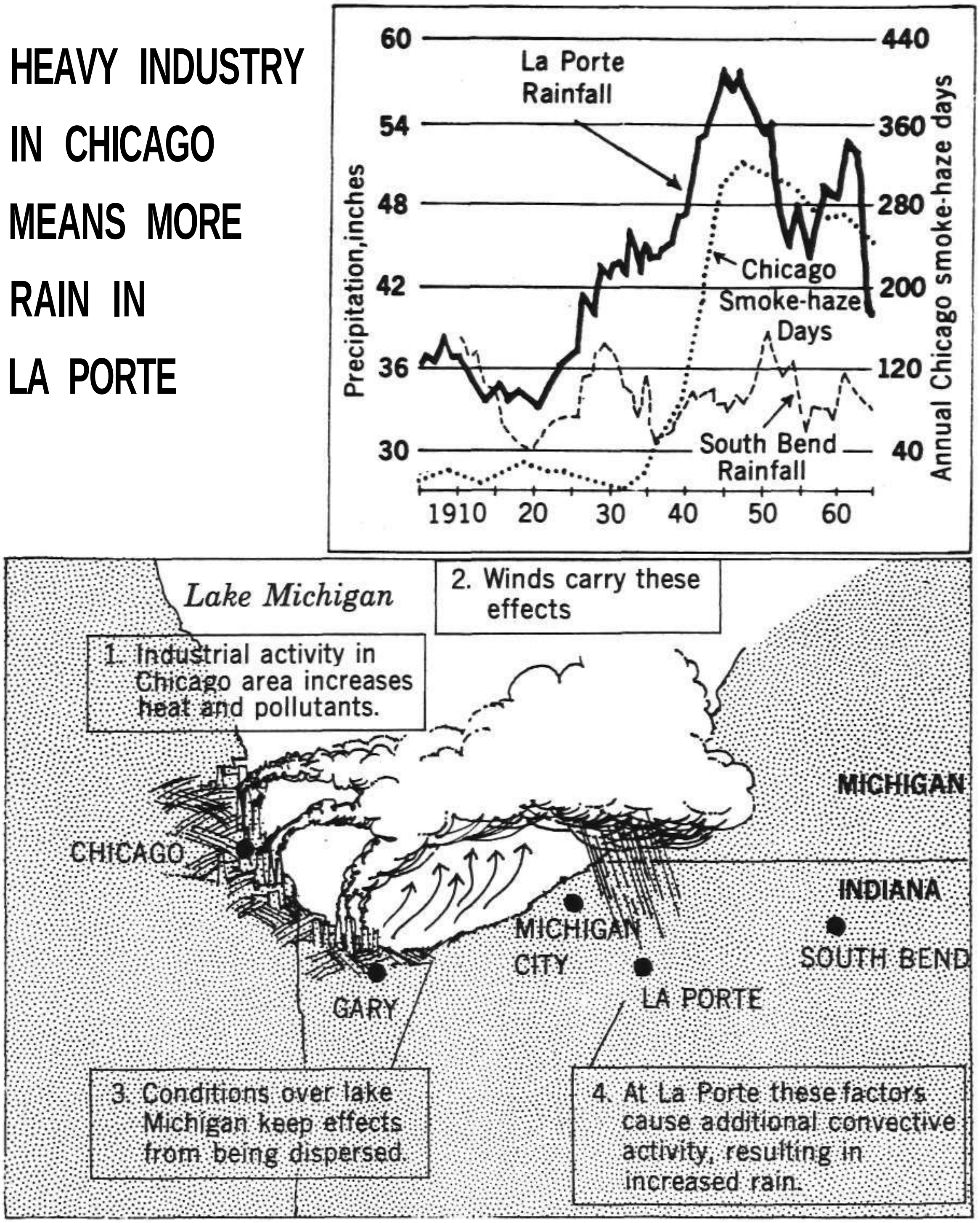


Figure 7-2. The La Porte weather anomaly illustrated in graphical and map form, as depicted in News Focus issue of April 19, 1968. Similar diagrams and reports appeared in many national magazines and journals.

groups and a vast array of equipment, including 225 raingages and hail pads, three radars, and four weather aircraft (fig. 7-3). Grants to the Water Survey for METROMEX exceeded $8 million making it the largest and costliest field project ever conducted by Survey scientists. Allied research concerning the socioeconomic and environmental impacts of inadvertent weather modification and localized climate change were also pursued (see Chapter 10).

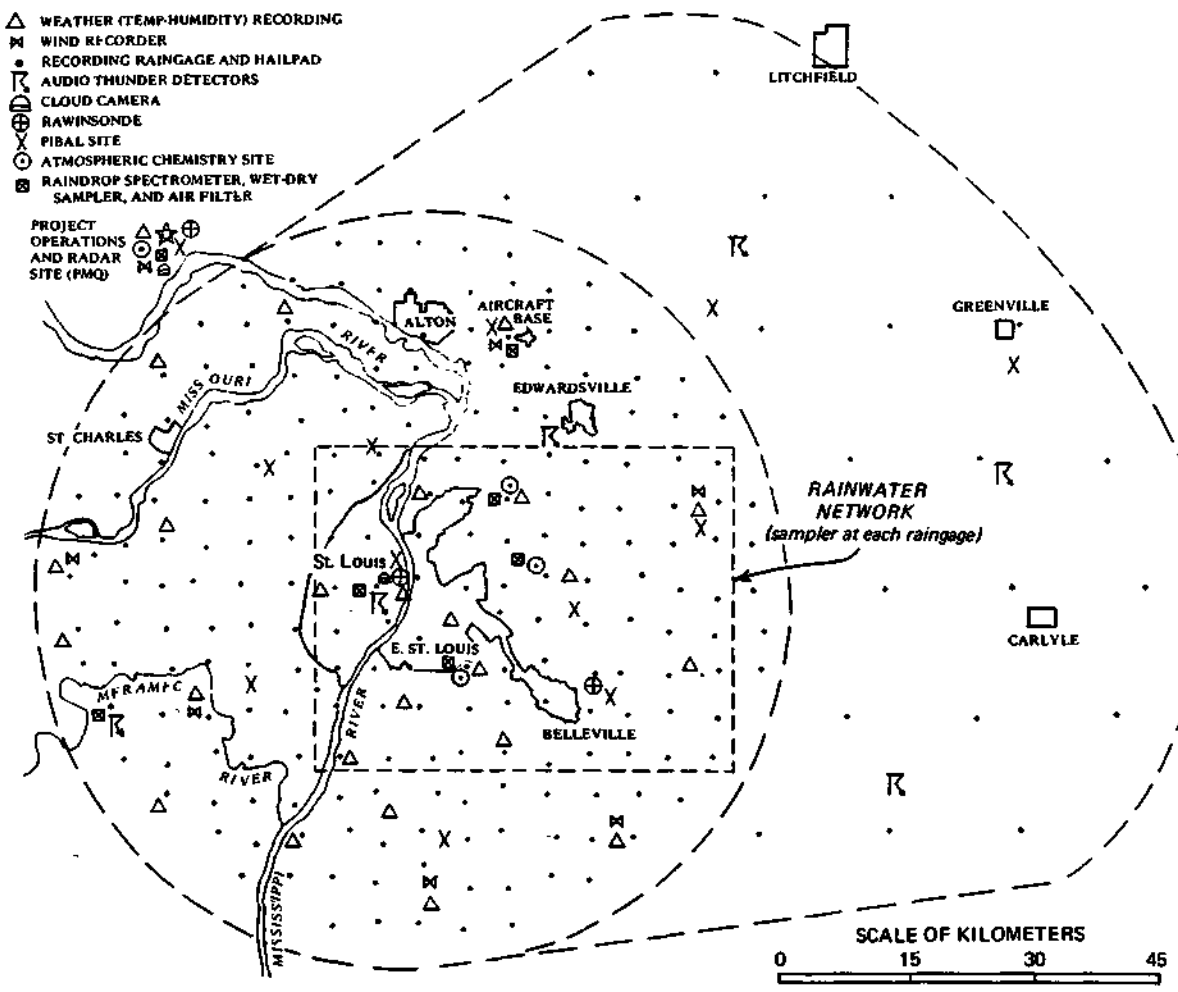


Figure 7-3. The large dense network of weather sensors installed in the St. Louis area by the Water Survey as part of the massive METROMEX field effort during 1971-1975. The Survey's field headquarters were at Pere Marquette State Park located northwest of St. Louis.

Concern and inquiries received about the type and potential magnitude of effects of waste heat and the addition of large volumes of moisture to the atmosphere from large cooling towers and cooling lakes prompted research into these effects from 1971 to 1980. These modeling efforts and field studies were conducted under the leadership of Floyd Huff and John Vogel.

Climatological studies of inadvertent weather modification continued under a series of National Science Foundation (NSF) grants awarded to Water Survey scientists during the 1970s and early 1980s. For example, historical records of several U.S. cities were gathered, and studies made of temperature, precipitation, cloud, and storm conditions in and around these cities, especially Chicago and St. Louis. Detectable changes were found in rain and storms at the larger cities (Huff and Changnon, 1973). Other studies of cloud records in the Midwest indicated a growth in cloud cover since the 1950s. A study of this done during 1978-1980 suggested that cirrus clouds created by jet contrails were a primary cause (Changnon, 1981b and 1981c). A series of investigations resulted based on NSF grants and as part of the PreCCIP program funded by the National Oceanic and Atmospheric Administration (NOAA) from 1989 to present (fig. 7-4).

Two scientists (Bill Lowry and Stan Changnon) began assessing inadvertent climate change during the 1970s well before climate change had become a household word. In the 1970s, some well-known atmospheric scientists at other institutions claimed that the widespread release of particulates from combustion would shield the earth from incoming solar radiation and

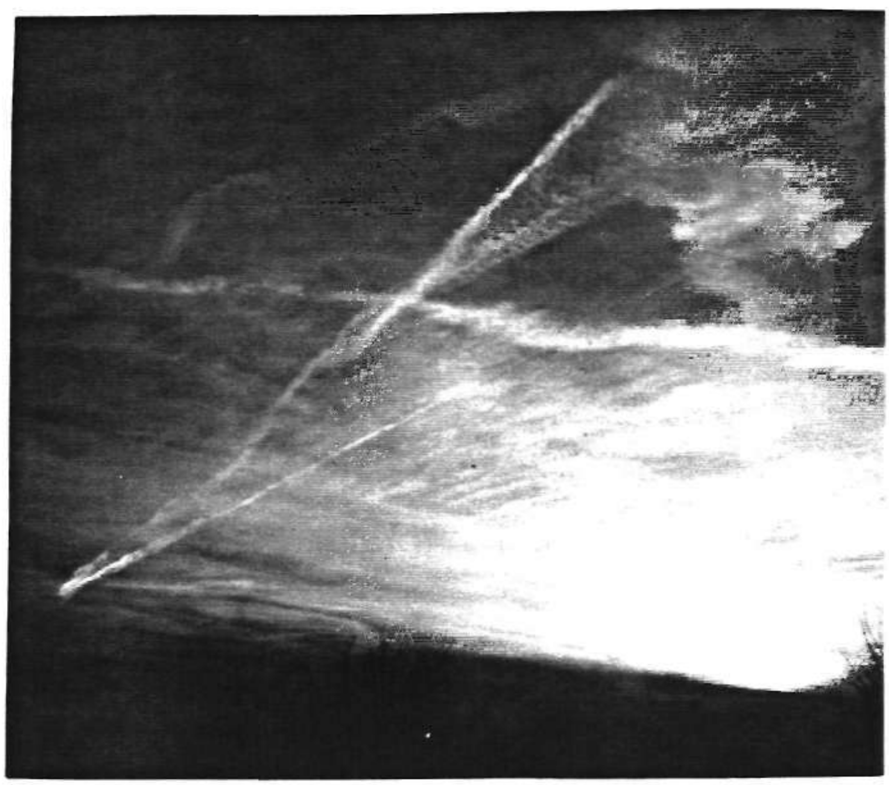


Figure 7-4. A typical example of many contrails often present over central Illinois seen on an October 1984. Survey studies of such spreading contrails and the false cirrus clouds they create has found they have altered the cloud cover over Illinois and radiative budget.

lead to global cooling, but by 1980, thinking shifted to a belief that the release of carbon dioxide and other trace gases would enhance the global greenhouse effect and in turn lead to global warming, known commonly as climate change[1]. In keeping with the philosophy of former Chief Buswell, Survey scientists in 1971 began to assess climate change, seen as a future major atmospheric issue facing Illinois (Changnon, 1973f; Lowry, 1972). As a member of the newly formed State Water Plan Task Force in 1980, Chief Changnon advanced the climate change issue, and the Task Force identified it as one of 11 major issues facing the state's future water resources. The challenge of this new atmospheric issue was clear, and Changnon employed new staff climatologists, who became extensively involved in climate change research during the 1980s. This included a strong focus on the impacts of a changed climate (Chapter 10).

The evolution of the Survey's research directed toward inadvertent weather modification and climate change is partially illustrated by the number of Survey publications (table 7-1). After early studies during 1960-1962, there were four years with no publications on these topics. Studies resumed as a result of the La Porte anomaly, which is reflected by five papers in 1968-1970. The evolution of METROMEX with parallel studies of cooling tower effects and continuing climatic investigations produced a major increase in publications during the 1970s (fig. 7-5). Research concerning contrail-induced clouds and climate change were the topic of several publications during the 1980s and 1990s.

Chief Semonin asked Stan Changnon to develop and head the Illinois Global Climate Change Program at the Survey in 1990. This interdisciplinary program has resulted in a program planning document and the preparation of eight state reports about climate change published in the 1992-1994 period.

This program area relates to investigations of how human-induced changes in land use or in emissions to the atmosphere act to change the atmosphere and alter weather conditions, which leads to changes in the climate on small (local) to large (global) scales. Assessment of the 143 publications in the field (excluding those devoted to the impacts of inadvertent weather modification or climate change, which are described in Chapter 10) revealed five major themes of investigation.

First and longest lasting area of study are the *climatic investigations of urban weather and climate modification,* work that began in 1960 for which research is still in progress (fig. 7-5). A related theme has been the *field studies of urban effects, which* embraced the massive efforts in METROMEX from 1970-1976 and four years of ensuing analyses, and the Chicago Area Project of 1977-1980 and ensuing analyses of the data generated. The third theme has involved *studies of effects on weather and climate conditions of emissions of pollutants and heat*

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[1] Climate change refers to regional or larger scale (hemispheric or global) changes in climatic conditions due to human influences (emission of particulates and gases) on the atmosphere. The atmospheric effects of cooling tower effluents, urban areas, and industrial emissions have been labeled as "inadvertent weather modification" because of their smaller scale and greater attention to the physical processes involved. Nevertheless, However, they too relate to climate change due to human activities. Changes produced by humans affect the atmosphere and weather conditions. These changes may persist to change the climate, largely as a result of land use changes and/or emissions of various pollutants including excessively large releases of moisture.

Table 7-1. Number of Publications Related to Inadvertent Weather Modification and Climate Change Written by Water Survey Scientists. (Numbers do not Include Impacts from these Atmospheric Changes, See Chapter 10).

		Reports		
Year	*Papers*	*State series*	*Contract*	*Total*
1961-1963	3	0	0	3
1964-1967	0	0	0	0
1968-1970	5	0	0	5
1971-1973	18	2	7	27
1974-1976	22	2	2	26
1977-1979	16	3	2	21
1980-1982	9	0	3	12
1983-1985	7	0	5	12
1986-1988	7	0	0	7
1989-1991	9	4	0	13
1992-1994	8	8	1	17

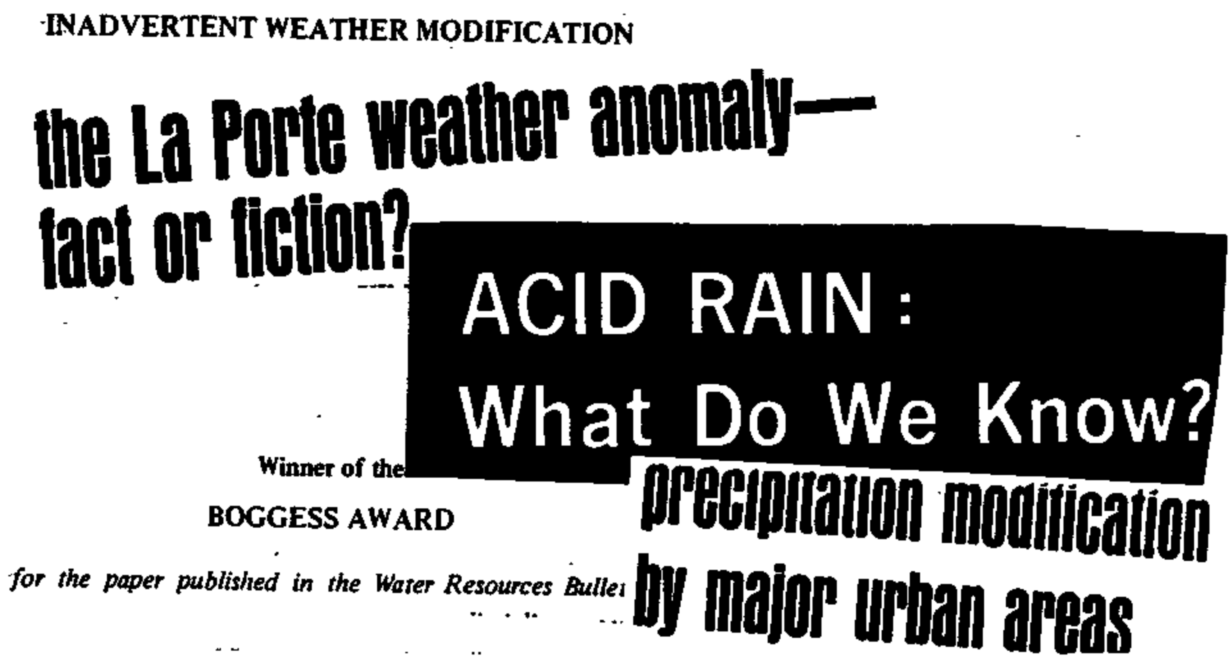

Figure 7-5. Titles of selected Water Survey publications illustrating the research in inadvertent weather modification, acid rain, and climate change.

and moisture emitted into the atmosphere. These studies have been wide-ranging, including effects due to industrial emissions, heat and moisture from cooling towers and lakes, shifts in surface radiation and the moisture budget due to large-scale irrigation, and clouds created by jet contrails.

The fourth theme, *climate change,* embraced investigations to detect change through historical trend analyses, to discern scientific views of whether the climate was changing, to estimate the kinds of future climate conditions using analogs and scenarios, and to calculate possible changes in severe weather conditions. Figure 7-6 illustrates various characteristics of the Illinois climate that vary with time including shifts in variability, trends in the average condition, and changes in the magnitude of extremes. As noted above, considerable work has been devoted to the impacts of possible future climate changes, and this research is described in Chapter 10, which deals with impacts.

The major national position of the Survey as a leader in the field of inadvertent weather modification beginning in 1970 brought calls for broad assessments of the findings, often with a focus on research needs. These endeavors concerning *assessing the state of the science and research needs in inadvertent weather modification* became a fifth theme, a series of efforts that greatly enhanced the Survey's national reputation as a center of atmospheric research.

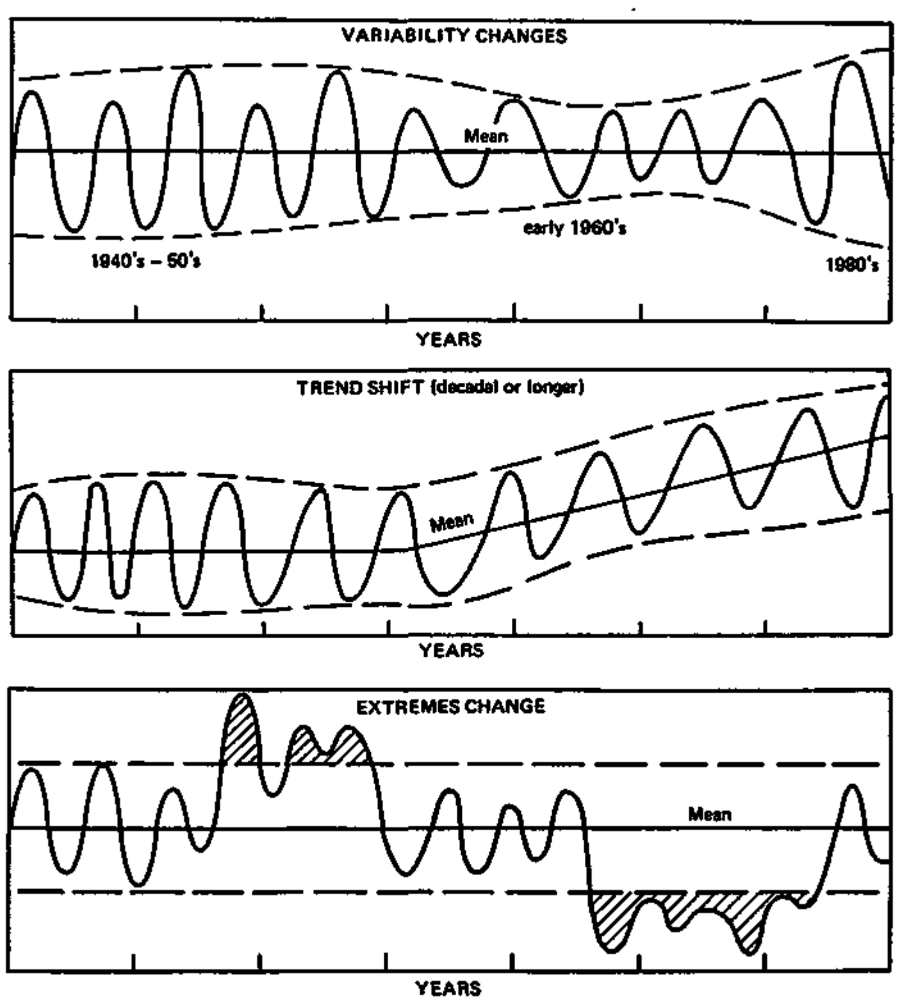

Figure 7-6. Graphs depicting various temporal fluctuations that can occur in Illinois' climate conditions.

URBAN MODIFICATION: CLIMATOLOGICAL STUDIES

The Water Survey's entry into the area of inadvertent weather modification was based on studies of historical data. Exploration of precipitation, temperature, and storm data discerned changes over time and spatial differences in and around cities. Chicago and La Porte were early study areas (Changnon, 1961a, 1968c). Changnon was invited by the World Meteorological Organization to present a review paper describing various findings about urban effects on precipitation at an international conference (Changnon, 1968g). This effort led to an assessment of urban and industrial influences on the atmosphere and rainfall (Changnon, 1969f). Then Huff and Changnon, with a grant from NSF, studied the conditions around eight U.S. cities. They found anomalous increases at the six larger cities with related increases in thunderstorms and hail (Huff and Changnon, 1972; Changnon, 1972d, 1973c).

The development of METROMEX called for an extensive climatological investigation of the historical data for the St. Louis area. This study's results strongly suggested sizable urban-related changes in summer rainfall and heavy rains, as shown in figure 10-8 (Huff and Changnon, 1972a, 1973). The effects detected in thunderstorm and hail frequencies were also found to be sizable (Changnon, 1972e). Beebe and Morgan (1972) used historical synoptic weather data to help explain conditions when urban influences were most effective in altering rain conditions, and Grosh and Semonin (1973) examined wind and moisture field data on occasions when thunderstorms developed over St. Louis.

Urban rain changes detected in the eight-city study were analyzed to determine their implications for urban hydrologic concerns (Changnon, 1973d). Changnon and Detwiller (1976) expanded on this issue with an investigation of long-term (100-year) trends in heavy seasonal and annual rain events at Paris, St. Louis, and Chicago, each showing upward trends with time. A critical evaluation was made of a published assessment of the climates of three cities (Changnon, 1976f). The effects on storm rainfall at Midwestern cities were shown to be sizable (Huff, 1977b), and localized increases in storm rainfall at Chicago were found to create numerous cases of localized urban flooding (Changnon, 1980d).

In 1977, Survey scientists re-examining the La Porte anomaly found that the Weather Service's move of the raingage in 1969 (at the height of the controversy) had altered the record and "eliminated" the anomaly (Changnon, 1977h). Huff and Vogel (1978b) made a detailed investigation to sort out the topographic influences on precipitation from those due to urban effects at St. Louis. Changnon (19801) revisited the La Porte anomaly in a third study that found the anomalous higher rainfall downwind of Chicago appeared at a weather station near La Porte. The influence of St. Louis on visibility in surrounding areas was defined in a study of past data (Changnon, 1982c). Subsequent studies analyzed historical data and METROMEX data to determine the presence of urban influences in the fall, winter, and spring (Huff and Changnon, 1986). Studies of urban influences on lightning activity using historical lightning data at 16 Midwestern cities show increases over and downwind of 13 cities (Westcott, 1995).

URBAN MODIFICATION: FIELD STUDIES

Urban climatological studies conducted by the Water Survey since 1960 were helpful in showing the presence of anomalies due to urban influences, but the controversies over the La Porte anomaly revealed these findings were not capable of providing irrefutable scientific proof of an urban influence, particularly the urban factors causing atmospheric changes that translate into more clouds, rainfall, and thunderstorms (Changnon, 1971b). Urban-related factors that could influence the rain process included the well known urban-rural differences in temperatures due to reflective differences of their surfaces and heat emitted by in-city combustion of fuels, the fact that a large city represents a physical obstacle to wind flow, the emission of various particulates, and a changed moisture budget in the city. Two major field projects were conducted: METROMEX from 1971 to 1975, and the Chicago Area Program (CAP) from 1976 to 1980.

Metropolitan Meteorological Experiment (METROMEX).

METROMEX set out to unravel the causative mysteries of urban influences on summer rainfall and storms, and also to establish the reality of the local changes. METROMEX was a major scientific endeavor unlike anything the Atmospheric Sciences Group at the Survey had ever undertaken. The project required diverse scientific skills and technical capabilities, a large variety of atmospheric sensors, thousands of measurements, and extensive external funding.

To improve its staff capabilities for METROMEX and other on-going weather modification studies (PACE and NHRE), the Survey employed several senior scientists during the early 1970s, including Bernice Ackerman, Bob Beebe, Donald Gatz, Griffith Morgan, and John Vogel. The need for skills and instrument capabilities beyond existing Survey capabilities was also partially addressed by involving scientists from the University of Chicago, the University of Wyoming, Battelle Northwest Laboratory, and Stanford Research Institute, which brought scientists and students, instrumented vehicles, aircraft, lidars, and radars to St. Louis. The Water Survey brought numerous surface weather instruments including 225 recording raingages, 225 hail pads, 24 weather stations, 12 wind recording sites, and 7 thunderstorm sensors all installed in a 50-mile radius circle centered on St. Louis (fig. 7-3). In addition, 2 weather radars, 12 pibal sites, and a rainwater chemistry sampling network with 49 sites was installed and operated during 1971-1975. The Survey also needed field headquarters that were provided by the Illinois Department of Conservation at a former air defense radar site in Pere Marquette State Park. There a dormitory for 15 students was constructed along with facilities for installing and operating radars and radiosonde equipment (fig. 7-7).

Federal funding for Water Survey endeavors came from the National Science Foundation and the Department of Energy in the form of annual grants totaling $1.2 million. In all, the Water Survey received $8.6 million for the 1971-1975 field activities and preliminary analyses, and for ensuing research during 1976-1980. The state contributions in the form of staff and facilities amounted to $1.7 million. Major detailed reports of the annual progress were submitt-

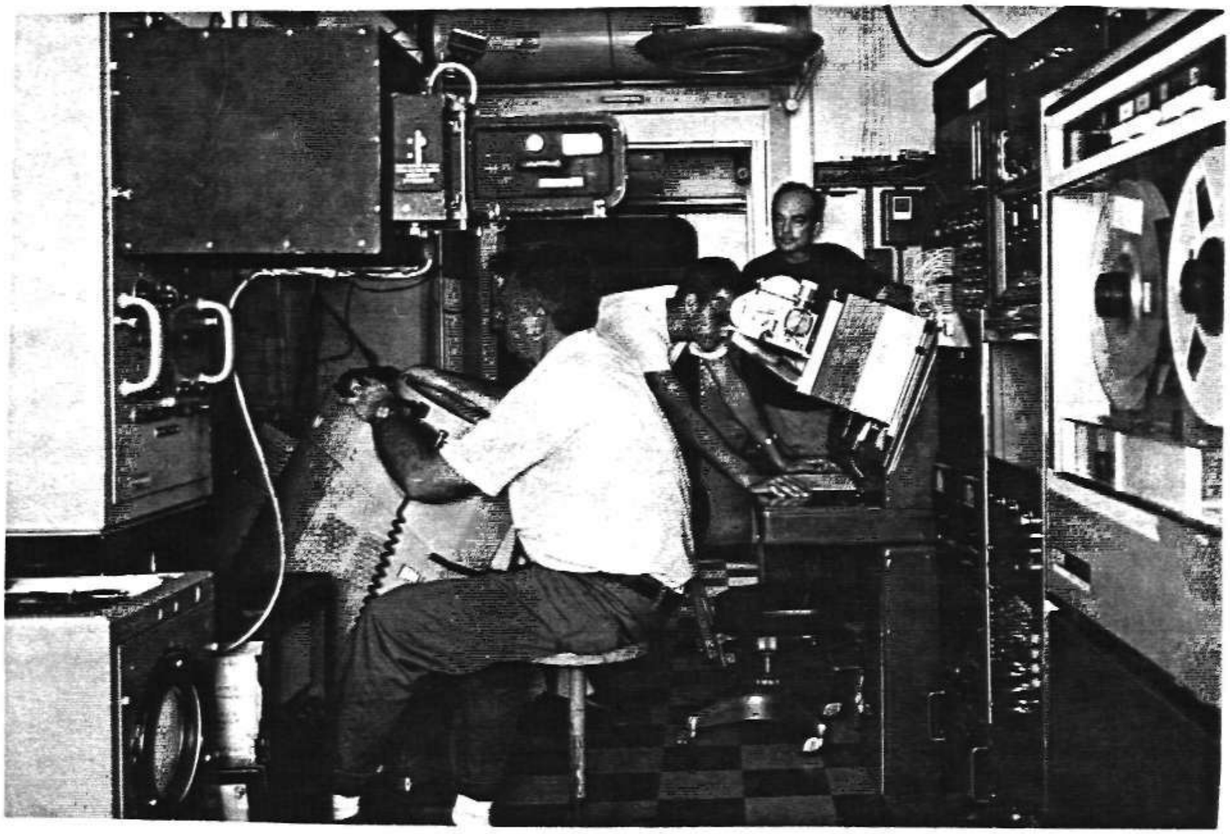

Figure 7-7. The Survey maintained extensive field facilities in the St. Louis area during METROMEX, and here is the operational center for the two Survey radars located at Pere Marquette State Park. Don Staggs who was seniot engineer for the project is on the left, Ron Grosh in the middle, and Doug Jones on the far right.

ed to NSF (Changnon 1972d, 1973j, 1974a; Changnon et al., 1976f), and to AEC (Semonin, 1972, 1973, 1974, and 1975).

Multi-agency funding of various parts of METROMEX also caused the federal agencies to insist that a senior scientist be responsible for overseeing the project, and that a final integrative report be prepared. William Lowry (1973, 1974) was hired in 1972 as program leader, and Changnon became head during 1974-1975. To fulfill the other obligation, senior project leaders Changnon, Semonin, Roscoe Braham, August Auer, and Jake Hales wrote a final report, assembling all the findings in a single document. It was published as a monograph of the American Meteorological Society (Changnon et al., 1981a).

METROMEX operations focused on summer (June-August) when the climate results showed the city's influence to be greatest (Huff and Changnon, 1972c). All groups brought crews of scientists and students and their equipment for most of the summer. The Water Survey was the major institution involved, with the largest number of staff, students, and equipment in the field. The Survey's surface weather network operations were continued during all months of the 1971-1975 period.

Most staff attention and research efforts during the 1971-1975 period were directed toward conducting the field projects as well as the collection and preliminary analyses of the huge database that was accumulating. Annual reports prepared for the funding agencies documented the progress. These included reports to me National Science Foundation about the surface network and radar findings (Changnon, 1971c, 1972e; Lowry 1973, 1974; Changnon and Huff, 1974), and those to the Atomic Energy Commission-Department of Energy about the rainwater chemistry and scavenging experiments (Semonin, 1971; Semonin and Gatz, 1974; Semonin, 1975; Semonin, 1976c).

In the mid-project year of 1973, a series of interpretative research studies summarized what was being learned and defined what should be done during 1974-1975. These mid-term studies included a comprehensive state report describing the 1971-1972 findings (Huff et al., 1973b), a scientific paper about the initial severe storm findings (Changnon and Huff, 1973a), an update in the *Bulletin* (Semonin and Changnon, 1974b), a review paper in a national journal (Changnon et al., 1974b), and two contract reports, one for NSF (Changnon and Huff, 1973b) and one for DOE (Adam et al., 1973). Gatz (1972) reported on washout ratios for several chemicals including copper and zinc, and then assessed aerosol sources at St. Louis (Gatz, 1974). Other research findings during the project included a detailed case studies of nine rain-producing periods using all data available to help define causative factors (Changnon and Semonin, 1975), operational issues (Cataneo, 1974), wind fields found over St. Louis (Ackerman, 1974a, 1974c), boundary layer characteristics over the city (Ackerman, 1974b), characteristics of surface rain cells (Schickedanz, 1974), modeling of cumulus cloud formations (Ochs, 1975), effects of surface conditions on storm development (Vogel, 1975). and urban effects on heavy rainfall (Huff, 1975a). Gatz (1977a) reviewed the use of chemical tracers for studying precipitation characteristics, and he used a factor analysis to identify the aerosol sources in the St. Louis area (Gatz (1977b).

The METROMEX post field project years (1976-1980) were geared to intensive and integrative analyses of the data collected. Two major state reports were generated: Bulletin 62 discussed the weather anomalies and impacts of these anomalies (Changnon et al., 1977a), and Bulletin 63 discussed the causes of the urban weather anomalies (Ackerman et al., 1977).

Numerous other publications were issued describing findings from various parts of the METROMEX puzzle. A hypothesis was developed to explain how the urban factors acted to enhance rainfall (Changnon et al., 1976a). This was based on several findings relating to thermal and aerosol anomalies found at St. Louis (Auer and Changnon, 1977), the urban influence on the microphysical characteristics in the urban clouds (Ochs and Semonin, 1976, 1977), and the urban effects on radar echo development and growth (Huff, 1976c) including first echoes (Ochs and Johnson, 1980). Grosh (1975) used satellite data to measure the urban effect on cloud development. Vogel and Huff (1978) defined synoptic weather conditions present when urban enhancement of rains occurred (often strong cold fronts). Figure 7-8 illustrates the patterns of rainfall from squall lines, including the values when the squall lines were sorted into direction of movement categories to determine if increases occurred in the down-city locations.

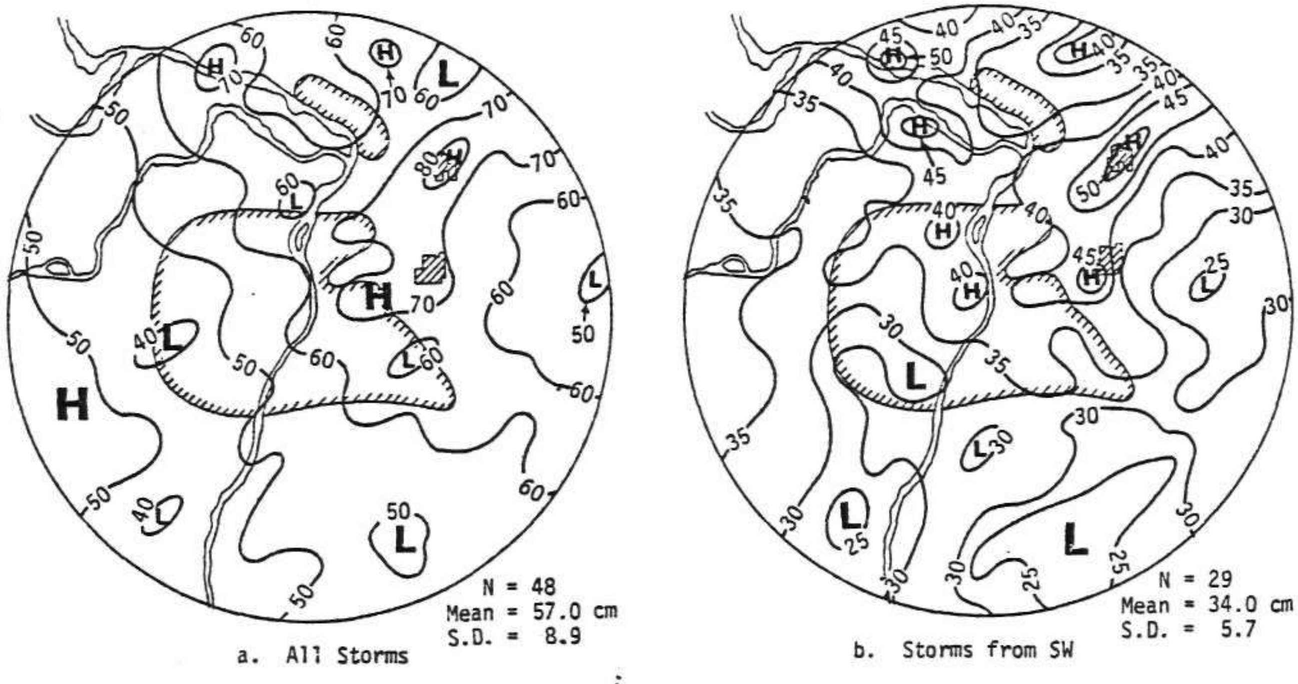

Figure 7-8. Rainfall patterns (rain in centimeters) from squall line storms that occurred at St. Louis during 1971-1975. One isohyetal map (left) is based on all storms, and the other based on storms that moved from the southwest. This shows a rain peak (>50cm) downwind (northeast) of St. Louis.

Changnon (1992c) combined the satellite, echo, cloud camera, and raincell findings from METROMEX to develop a model of how the urban influences acted to create daytime clouds and enhance rainfall. Research supported by DOE after 1975 considered the scavenging efficiency of convective storms over St. Louis (Semonin, 1975; Semonin et al., 1977), and analyzed the variability of pH of found in 22 rainstorms at St. Louis (Semonin, 1976a and b). Factor analysis was used to interpret the role of urban aerosols in altering rainfall (Semonin et al., 1978).

Ackerman (1977a) reported the characteristics of the vertical fluxes, and Ackerman and Hildebrand (1978) reported the planetary boundary layer characteristics over the St. Louis area. Westcott (1989) analyzed mesoscale wind fields over the St. Louis area, and Achtemeier (1980) investigated the relationship of the structure of the boundary layer to the precipitation anomalies.

The influence of St.Louis on the atmosphere leading to changes in rainfall included a study of effects on short-term rain rates (Huff and Vogel, 1977a), an examination of the effect on heavy rain events (Huff, 1977c), delineation of the urban rainfall anomaly (Huff and Vogel,

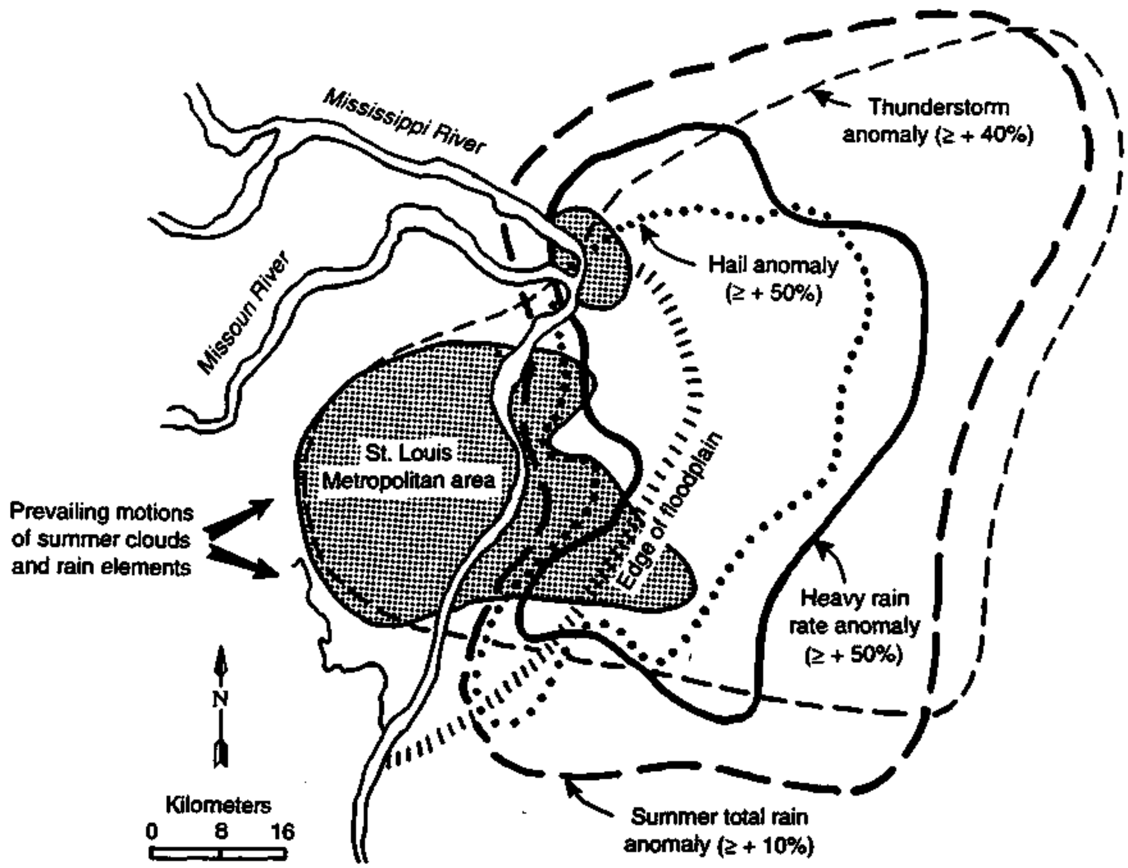

Figure 7-9. The urban-induced rainfall and storm anomalies at St. Louis, as defined by the METROMEX.

1978b), and an investigation of the urban rain cells (Schickedanz et al., 1977). Figure 7-9 presents the various precipitation-related anomalies that were defined during METROMEX. The various changes caused by the city to severe local storms were delineated in Changnon (1977i, 1978e). An important article in *Science* presented findings that established the reality of the urban influences on rainfall, proven by effectively rotating the city, depending on steering winds, so that one could examine the downwind rain patterns (Changnon, 1979d). The final major interpretation of all METROMEX findings was done by several of the principal scientists involved and presented in a book (Changnon et al., 1981a).

Several years later, two of the questions unanswered by the METROMEX analyses of 1971-1981 were finally addressed. One concerned the potential for urban influences on precipitation during the other seasons, and minor increases were found in fall and spring rainfall when convective storms occurred (Changnon et al., 1987d, 1991b). The other study analyzed an apparent rainfall anomaly found in the nocturnal rainfall, an unexpected event and one ignored during the 1971-1975 field work. Analysis of the night storms during 1971-1975 showed that about 20 percent were enhanced by the city (Changnon and Huff, 1986). Kidder and Wu (1987) used satellite data to examine the effect of the St. Louis heat island on snow cover, finding that the city had a strong influence leading to reduced snow cover.

Chicago Area Program

As the METROMEX field effort was winding down in 1975, Survey leaders began the design of a follow-up field effort at Chicago known as the Chicago Area Project or CAP (Changnon and Semonin, 1978). CAP had two objectives: 1) to sort out urban and lake effects on summer precipitation, and 2) to define the hydrometorological applications of storm rainfall data for design purposes and for operation of the Chicago water diversion system (Changnon and Huff, 1976; Huff and Changnon 1978). The CAP research devoted to the hydrometeorological applications is described in Chapter 4. Both Survey objectives were to be served by a large dense raingage-hail pad network (300 sites spread over northeastern Illinois and northwestern Indiana) and the Survey's CHILL and HOT radar systems. As at St. Louis, scientists from other institutions came to make studies of lake storms (Roscoe Braham of the University of Chicago) using the Survey's CHILL radar, and to study development of severe storms, a project involving Survey staff and facilities and those of the University of Chicago (Changnon, 1979a).

Potential urban and lake influences on precipitation at Chicago were assessed and compared with those at St. Louis (Changnon et al., 1979b). Case studies based on radar and raingage data showed how urban and lake influences interacted to develop convective cells over the city (Changnon, 1980g). Changnon et al. (1982b) defined urban-lake rainfall differences using radar data. Ackerman and Hildebrand (1983) assessed urban effects on the urban boundary layer, and Ackerman (1985) defined the Chicago heat island and its temporal fluctuations. Urban-rural differences in humidity in the Chicago area were established (Ackerman, 1987). Changnon (1984i) summarized the final interpretation of the findings about the extent of urban and lake influences on summer rainfall at Chicago, showing a lesser increase in summer rain at Chicago than at St. Louis, a condition resulting from stabilizing lake effects that counteract the de-stabilizing influences of the urban area.

EMISSIONS OF POLLUTANTS AND MOISTURE

During the 1961-1995 period, Survey scientists pursued research involving the atmospheric effects of emissions of pollutants, heat, and moisture from a variety of sources. The potential for atmospheric effects from isolated industrial sources including power plants was one of three areas investigated. Stout (1962) accumulated visual evidence of effects of emissions on cloud growth. The potential influence of emissions from a large steel plant affecting clouds and rainfall was debated (Changnon, 1971d). However, much of the research on concentrated emissions from point (or small) sources concentrated on cooling towers (wet and dry) and cooling lakes used by large power plants. Huff et al. (1971) estimated the possible effects of large cooling towers at a power plant alongside Lake Michigan. The research needs relating to the effects of large volumes of waste heat from towers were defined at a special conference (SWS, 1971) with the help of an NSF grant. Huff (1972a) assessed the potential effects of cooling tower effluent on precipitation. A two-phase project funded by NSF beginning in 1973 assessed the atmospheric effects from large cooling lakes (Huff and Vogel, 1973), and the initial results from climatic studies showed effects on local icing conditions, fog, and clouds (Vogel and Huff, 1974). Effects on fogs were emphasized (Vogel and Huff, 1975), and the synoptic weather conditions favorable for steam fog development were studied (Vogel and Huff, 1978). The research was summarized in a final report (Vogel and Huff, 1981).

Another area of research concerned whether large scale irrigation affected the atmosphere sufficiently to create rainfall. Schickedanz received an NSF grant to investigate this possibility using historical data on irrigation and climate conditions in the High Plains where irrigation became a major activity after World War II. This study found strong indications that the irrigation had increased warm season rainfall over and well beyond the irrigate regions (Schickedanz, 1976). The implications for water resources management were assessed and presented at an international conference (Schickedanz and Ackermann, 1977). Subsequent studies showed how the moisture and localized circulation changes generated clouds and enhanced rainfall (Barnston and Schickedanz, 1981).

Routine climatological research in progress during 1978 detected secular changes in cloud cover in Illinois, with increased cloudy days apparent from the late 1950s until the present. This led to a study funded by NSF of the possible effects of contrails generated by jet aircraft crossing the Midwest. The results strongly suggested a regional and temporal change in cloud cover that was caused by jet contrails (Changnon et al., 1980f). The potential effects on surface weather were also assessed and suggested a moderation of temperatures had occurred from the added cloudiness (Changnon, 1981c). Further investigations examined shifts in various cloud types and used Air Force records of contrails to further confirm the role of contrails in enhancing cirrus (Wendland and Semonin, 1982). Continued research dealt with the use of satellite data to assess the spreading contrails and cloud coverage (DeGrand, et al., 1990). Subsequent research (Travis, 1994; Travis and Changnon, 1994) examined the climatic implications of the false cirrus on radiation and regional climate conditions and found that the radiative properties of contrail cirrus differ from those of natural cirrus and lead to a net cooling effect.

CLIMATE CHANGE

Climate change caused by human influences on the atmosphere is the fourth area of research. Lowry (1972) issued the Survey's first paper on this topic. Review of the research since then reveals that climate change endeavors at the Survey fell into three general categories: 1) assessment of past trends in various weather conditions as an indicator of future fluctuations, 2) efforts to assess and define whether change is occurring, and 3) the development of climate scenarios for future possible conditions. A considerable amount of the Survey's climate change research focused on the possible impacts (see Chapter 10), but this section treats the research dealing just with the atmospheric-oriented studies of climate. Figure 7-10 presents titles of selected Water Survey publications relating to climate change.

Historical trend studies have concentrated on past fluctuations in precipitation and severe weather and related events. However, the first paper addressing trends in long-term records focused on the air and soil temperature data at Urbana, showing an up trend of 1°F in air temperatures due to the local heat island (Changnon, 1964e). Another study (Changnon, 19730 led to a long series of NSF-funded projects dealing with historical fluctuations in thunderstorms. These NSF sponsored studies addressed the secular trends in thunderstorm frequencies (Changnon, 1977e). Trends were assessed for data from the United States and North America (Changnon and Hsu, 1983, 1984), for various sub regions in the United States (Changnon, 1985e), and for the globe (Changnon and Hsu, 1984a, 1984b). Fluctuations in North America have generally agreed with those found in hemispheric temperature, being upwards from 1900 to 1940, then downwards till 1980, and then upwards again (Changnon, 1989g). The temporal behavior of weather catastrophes across the United States was investigated by region and revealed a major increase in the 1980s (Changnon and Changnon, 1993e). Attention was given to moderation of Midwestern temperatures (less difference between the maximum and minimum values since the 1950s (Changnon, 1974b), and to temperature fluctuations in Illinois since 1901 (Changnon, 1985f). Changnon (1984d) also assessed the temporal behavior of all weather conditions in Illinois between 1901 and 1980. Changnon (1986h, 1987h) assessed the changing influence of air pollution on visibility in the central United States and found it to be decreasing with time.

The concept that climate change could alter rainfall and produce heavier rains has also been extensively studied using historical data for Illinois. Changnon (1983b) examined the increasing frequency of 2-inch rains since 1940 as an explanation for increases in flooding. Huff and Changnon (1987a) examined fluctuations in design rainfall frequencies in Illinois, and Changnon (1989a) addressed the changes in precipitation conditions and related alterations in water resources. Changnon and Huff (1991) examined the historical fluctuations in heavy rainfall frequencies found to be increasing with time. Changnon and Kunkel (1993, 1995) also studied the influence of shifts in rainfall on flooding in the Midwest as part of a project funded by the U.S. Geological Survey.

A key question about climate change concerns *detection of the change, an issue addressed by* several Water Survey studies. Changnon (1975b) discussed the potential start of a climate change and assessed the possible limiting implications for agriculture. Lamb (1981) raised the question of whether weather patterns were changing. Changnon (1984b) made an assessment of the behavior of the Illinois climate conditions over the past 100 years, as a guide to detecting unusual shifts. Changnon (1982h) sampled the views of Midwestern scientists in a delphi experiment, learning that few thought the change had begun. Ten years later, a similar delphi experiment revealed that a majority of atmospheric scientists believed a change was developing (Changnon et al., 1992a). Changnon (1991a) described existing knowledge about climate change. A series of public information brochures describing climate change and the greenhouse effect were prepared in 1992 (SWS, 1992a, 1992b, 1992c) as part of the Global Climate Change Program. Croley et al. (1995) conducted a study of the effects of four different climatic regimes on the hydrologic cycle of the Great Lakes, and they found that the climate of the southern High Plains (warm and dry), when transposed to the Great Lakes, resulted in a sizable lowering of lake levels and major alterations in the interannual variability of the lowered levels.

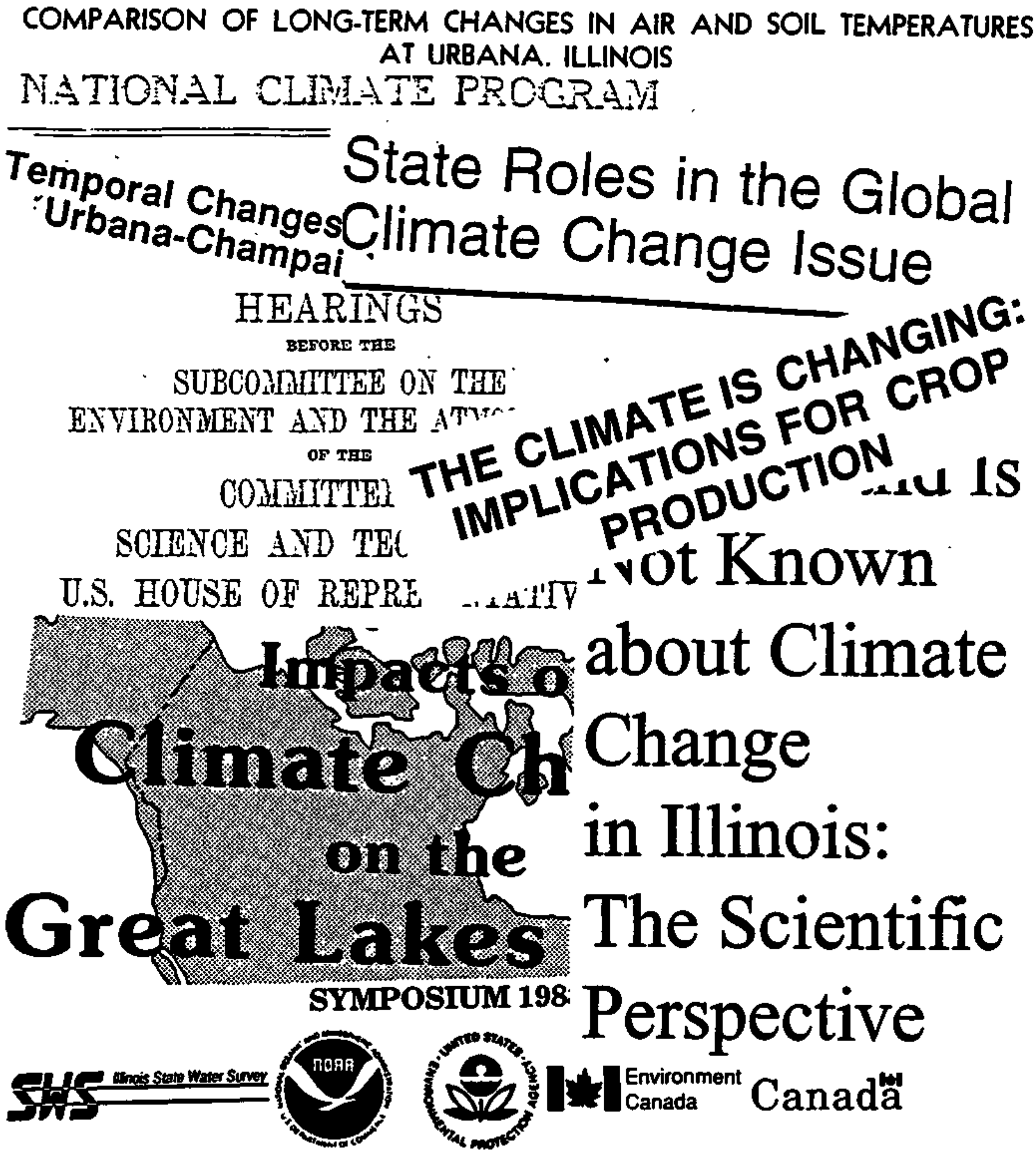

Figure 7-10. Survey scientists have a long history of investigating climate change including its potential impacts on Illinois and their major policy implications. This diagram shows the headlines from selected Water Survey publications dealing with the climate change issue.

Attention also has been directed to the *development of climate scenarios*, empirically-derived estimates of future climate conditions. Lamb (1987) considered the use of regional scenarios in impact research. Quinn and Changnon (1988) created climate scenarios for the Great Lakes basin as a means to estimate possible future changes in lake levels. Changnon (1991b) analyzed various scientific approaches for developing climate scenarios were analyzed in response to an invitation for an assessment of that subject. Possible future climate conditions in Illinois were assessed by Changnon and Wendland (1993).

SCIENTIFIC ISSUES AND RESEARCH NEEDS

By 1970 the Water Survey became a national leader in inadvertent weather modification and this prestigious position led to assessments of the research status and research needs in the field, and in some instances, these assessments were invited by various scientific groups. This fourth area of activity began with an assessment of the importance of inadvertent weather modification research (Lowry, 1972), and an assessment of the research was made at a national conference (Changnon, 1974c). Changnon (1976) reviewed these findings, and those related to the impacts of inadvertent changes. Changnon (1977g) reviewed the inadvertent weather modification research in Illinois at a conference for hydrologists. Changnon and Semonin (1980) prepared a special national review of the progress in the field of weather and climate modification. Changnon (1979e) prepared a special paper illustrating the implications of inadvertent climate changes for design values used by the engineering community.

Development of the climate change issue in the 1970s led to an assessment of climate change research. The first study to assess the possible effect of a changed climate on food production, resulted from an invitation to address this issue at a food policy conference in Springfield (Changnon, 1975i). Then, Changnon (1987d) assessed on-going research relating to climate change, water resources, and government policies. An ensuing study focused on the implications of climate change in Illinois and the need for Illinois to be aware of the issue (Changnon and Lamb, 1990). A 1992 study assessed the findings from METROMEX and other urban studies in terms of the lessons they taught about how to deal with climate change (Changnon, 1992d). A major plan for a climate change research program at the Water Survey was developed (Changnon, 1991f) along with a plan for a major research program dealing with climate change on the Great Lakes basin (Changnon, 1992f). Involvement on the Illinois Task Force for Global Climate Change called for a major assessment of the scientific aspects of climate change as it relates to the Midwest and Illinois (Changnon and Wendland, 1993). This Task Force activity also led to an invited paper for a Midwestern conference addressing the issue of climate change, and the paper addressed the issue of adapting to climate change and research needed for this adaption to occur (Changnon, 1994a).

SUMMARY

Accomplishments

The discovery of the La Porte precipitation anomaly was the first major scientific evidence that a large urban area created significant changes in precipitation and storms over the urban area and many miles beyond. This discovery focused public and scientific attention on the Water Survey's atmospheric research program. Ensuing research on the subject brought the Water Survey national and international recognition for its expertise and pioneering research into inadvertent weather and climate modification.

The development and successful management of METROMEX, the Survey's all-time largest field project, was a major achievement in logistics and scientific findings. The project met its scientific goals, greatly enlarged the staff, and added to the scope and quality of the Survey's research program. Valuable new instruments such as the HOT radar were also acquired. The ten years of research into waste heat and moisture released into the atmosphere from point sources defined the effects of cooling towers and lakes on weather conditions. The National Science Foundation featured the METROMEX project in its Summer 1974 newsletter *Mosaic.*

Survey leaders formulated the concept of the Illinois Task Force on Global Climate Change and helped get it established in 1992 with Changnon serving as science advisor, 1992-present. Earlier in 1980, the Illinois Water Plan Task Force formally accepted Chief Changnon's concept that climate change was one of the 11 major issues facing the state and its water resources, an action that helped launch a considerable effort in climate change research and services. For example, the Survey was asked to join with the National Climate Program Office in developing and co-hosting an international conference in 1989 calling for the assessment of climate change on the Great Lakes. Chief Semonin formed the Illinois Global Climate Change Program in 1991 which has fostered research and provided widespread information about the oft controversial issue.

The work in inadvertent weather modification and climate change represents two key aspects of the Water Survey: early attention and planning with respect to emerging issues critical to Illinois, and the provision of information as a result of the research and expertise developed by getting an "early start".

Awards

The pioneering work in inadvertent weather modification led to numerous invitations to present broad assessments about inadvertent weather modification and what future research should be pursued. The review paper, "Inadvertent Weather Modification," published in the *Water Resources Review* (Changnon, 1976b) won the AWRA's annual Boggess Award as the best paper of the year. The quality of the METROMEX final report led to its selection by the American Meteorological Society for publication as one of their prestigious monographs.

Key Projects

METROMEX, supported by sizable grants from NSF and AEC/ERDA/DOE, lasted for ten years, involved most of the Atmospheric Sciences Section's staff and instrumentation, and was the single largest project the Section had ever conducted. The Chicago Area Project was also a sizable effort. Numerous NSF grants from 1970-1983 supported a continuous series of projects dealing with climatic investigations of various types of inadvertent weather modification.

Pivotal Publications

The paper about the La Porte anomaly (Changnon, 1968c) qualifies as a significant contribution along with the METROMEX monograph (Changnon et al., 1981f). Changnon (1973) provided a broad assessment of how humans had changed weather globally and elevated the Water Survey to a level of importance in the field. A paper about climate change and Illinois (Changnon and Lamb, 1989) created widespread awareness of the issue in Illinois, and an early paper on effects of cooling towers (Huff et al, 1971) helped launch ten years of research into this area.

Key Staff

It was not difficult to identify key staff who contributed significantly to the inadvertent weather and climate change research, both through obtaining funding as Principal Investigators and for writing numerous important publications. Counted among these important contributors were Bernice Ackerman, Stanley Changnon, Donald Gatz, Floyd Huff, Peter Lamb, Richard Semonin, Paul Schickedanz, and John Vogel.

Many other staff members made major contributions to the data collection, the research, and to the very difficult field projects, including Ken Kunkel, Nancy Westcott, Neil Towery, Donald Staggs, David Brunkow, John Adam, Robert Cataneo, Mark Gardner, Harry Ochs, Wayne Wendland, and Douglas Jones. Those who contributed to the database development and data processing included Marvin Clevenger and Marian Busch. Several technicians including Joe Coons and Eberhard Brieschke.

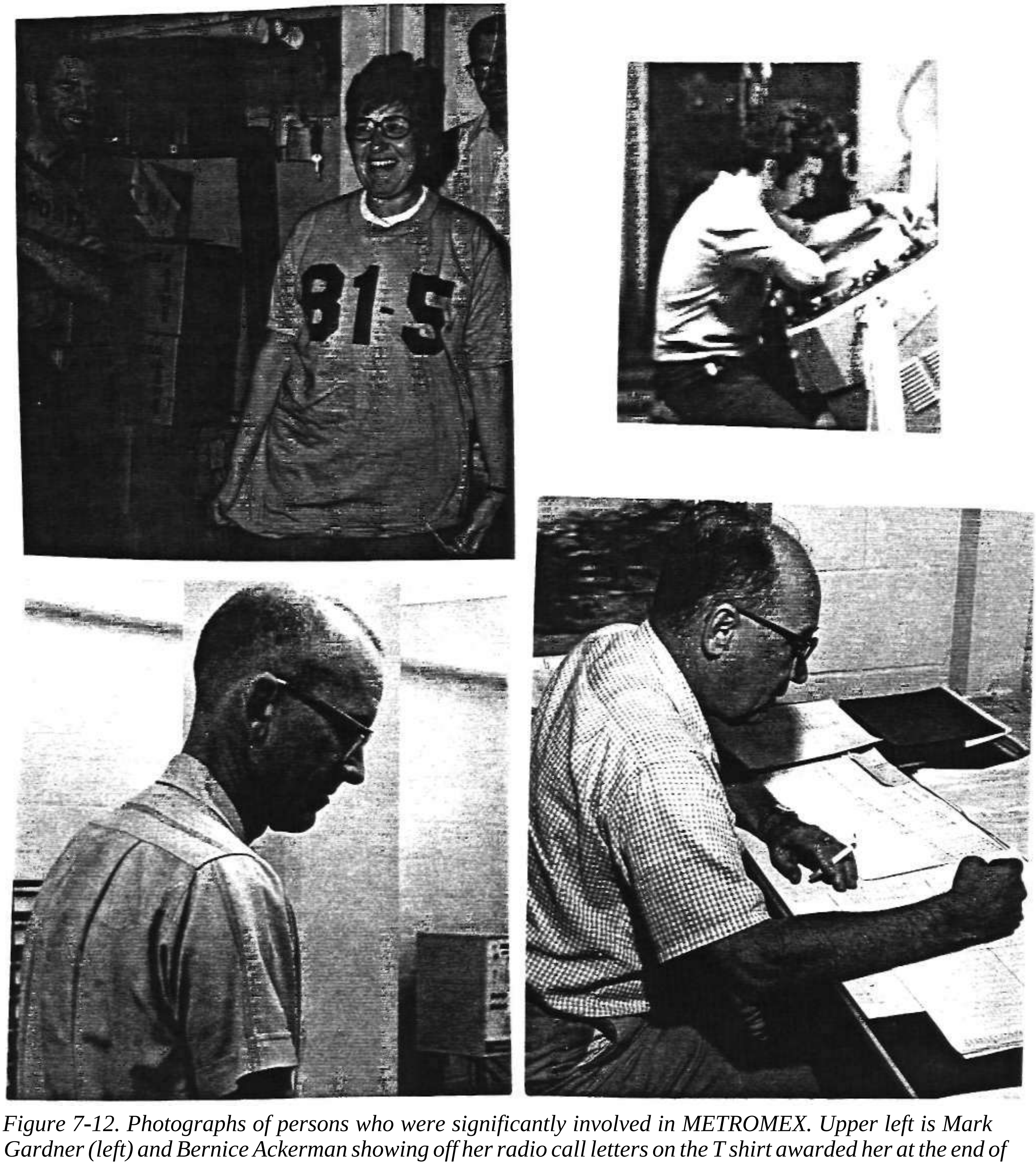

Figure 7-12. Photographs of persons who were significantly involved in METROMEX. Upper left is Mark Gardner (left) and Bernice Ackerman showing off her radio call letters on the T shirt awarded her at the end of METROMEX. Upper right shows Bob Cataneo, one of chief forecasters, analyzing echoes on the HOT radar scope. Lower left is Marvin Clevenger who handled the complex database developed for METROMEX, and who served from the beginning of the Survey's data management efforts in the late 1950s. Lower right is Elmer Schlessman, a quality analyst who handled the many tough assignments given him by Huff and John Vogel.

Chapter 8

CLOUD AND PRECIPITATION FORMATION

Stanley A. Changnon

INTRODUCTION

In the mid-1950s, Survey meteorologists who had been concentrating on describing the characteristics of precipitation and how to better measure it started to investigate the surface factors and weather conditions that affected clouds and the formation of precipitation. Explanations for what was being observed were needed to confirm the reality of the statistical descriptions. Atmospheric phenomena that were ultimately investigated embraced conditions extending across many scales, ranging from sub-micron particles in clouds to cold fronts covering hundreds of miles. Some studies focused on the internal "microphysics" of clouds addressing issues such as how small cloud droplets interact and grow. Others focused on the "cloud scale" assessing how individual clouds develop and how their rain volumes grow and propagate themselves. Studies at the mesoscale addressed the atmospheric conditions that produce conditions suitable for cloud and rain development. These "causative" studies have been central to the group's mission, which was focused on *describing and understanding the precipitation part of the hydrologic cycle.*

The traditional branches of the atmospheric sciences encompassed by this program area are known as cloud physics and dynamics, precipitation physics, mesoscale meteorology, and forecasting. A considerable portion of this research has been more fundamental or *basic research* rather than the more directly applied research that includes most of the efforts of the Meteorology Group since 1947. Much of the research addressing cloud and precipitation formation was funded with grants from federal agencies and little input of state resources. Many grants were awards from the National Science Foundation (NSF) and were based on proposals incorporating the ideas and expertise of individual Survey scientists. Significant portions of the cloud and mesoscale research also relied on funding from large Survey projects focused on applications in air pollution, weather modification, or urban-caused climate modification. These endeavors were more applied and directed to addressing needs-to-know of these projects.

It was a difficult process to identify research that belonged strictly in the "formative" process category, as opposed to the research that belonged in other program areas such as "precipitation measurements" (see Chapter 3). There were numerous studies from 1953 onwards that were central to the cloud-rain formation study area and overlapped another program area. For example, Ken Beard's studies of raindrop behavior (1983) were in the cloud physics realm, but they were also relevant to the radar-rainfall applications, a part of the precipitation measurements program. In such instances, the research and its relevance is described in both program areas.

Initiation of the studies involving the microphysics of clouds began in 1960. Richard Semonin, who had the charge to lead the Survey's "cloud physics" endeavors, interacted with University of Illinois staff in the Electrical Engineering Department to begin laboratory studies addressing effects of electrical charges on cloud drops and their coalescence (Semonin and Plumlee, 1963). This research was relevant to the weather modification program Semonin was pursuing at the time (see Chapter 6). These early endeavors in the laboratory led to continuing efforts and the development of a cloud physics laboratory under Semonin's leadership. He and those who followed (John Adam, Bob Cataneo, Ken Beard, Harry Ochs, and Bob Czys) have developed the world's finest Cloud Physics Laboratory, and much of the work since 1960 has been funded by a series of NSF grants. The laboratory facilities are particularly suite for addressing a wide number of problems.

The "cloud scale" endeavors began earlier, in 1952, as a result of the Cloud Physics Project funded during 1952-1954 by the University of Chicago. The Chicago Meteorological Group had an assortment of equipment and provided the Survey some new instruments (three radars, panoramic cloud cameras, electric field mills in a dense network, and various air-sampling devices). These were installed and operated by Survey staff in and around Champaign-Urbana. Data collection, in support of the University of Chicago's ambitious Cloud Physics project at the Survey, addressed three topics: 1) atmospheric electric fields and their relationship to convective cloud electrification and rain development, 2) the relationship between the development of cumulus clouds and rain cells within them, and 3) the chemistry of the atmosphere. Survey scientists were able to pursue some research deriving comparisons of the growth of the tops of congestus clouds and their initial radar echoes (Changnon and Bigler, 1955), and the chemical content of rainwater from samples collected during 1953-1954 (Larsen et al., 1956).

Semonin and Don Staggs, as the first step in a Survey-designed effort to understand cloud physics and rainfall development, launched a cloud-oriented field project west of Champaign during 1956. Equipment installed included all-sky dome cameras, anemometers, soil thermometers, a series of home-made evaporation pans, and raingages. The data from this project were never analyzed because the Weather Bureau State Climatologist Al Joos complained to Chief Ackermann about the inadequacy of the evaporation pans. In 1957-1958 Semonin shifted attention to the role of atmospheric salts in the production of Midwestern precipitation (Semonin and McCready, 1960). Sampling aloft was done with a nuclei sampler mounted on a Tri-Pacer aircraft (fig. 8-1).

As noted in Chapter 3, Water Survey radar operations during the 1950s focused on rainfall measurements, but certain studies also investigated echo-cell behavior and growth (Wilk, 1961), the merging of rain cells (Changnon, 1976c; Westcott, 1984), and the behavior of lines of cells (Changnon and Huff, 1962). These studies were often motivated by projects attempting

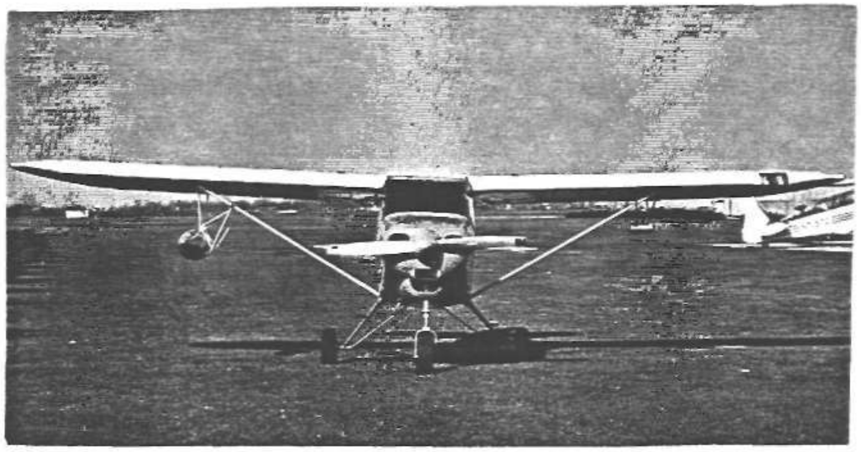

Figure 8-1. The first aircraft used by the Water Survey to study clouds. This Tri-Pacer was used in the late 1950s-early 1960s to collect data on aerosols with an emphasis on salt nuclei in the atmosphere. The air sampler pod built by Survey scientists is under one wing (left) and a meteograph is suspended below the other wing.

to understand the effects of cloud seeding or the detection and forecasting of storm elements. Surface descriptions of cloud-scale entities were also defined, including rain cells (Schickedanz, 1974), convective raincells (Changnon, 1981a), hailstreaks (Changnon, 1970d), and hailstripes (Morgan, 1976). Ochs (1975) modeled urban clouds to compare with observed values (fig. 8-2), and Changnon (1969a) developed models of surface hail falls.

The mesoscale research also has an interesting history. Mesoscale meteorology was a relatively new field in the early 1950s, being addressed to improve short-range forecasting and getting an emerging scientific foundation from the exciting findings of the famed Thunderstorm Project. This national project was designed and conducted by University of Chicago scientists in Ohio and then Florida during the 1947-1950 period (the Cloud Physics Project of 1951-1954 was their logical major follow-up project and one the Water Survey was involved in). Mesoscale research was recognized as holding the key to future major improvements in short-

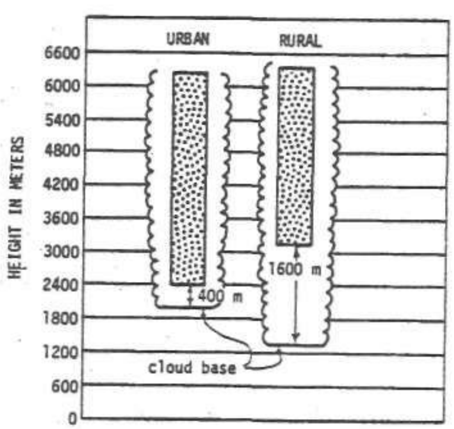

Figure *8-2. Average bases and tops of urban and rural first echoes and clouds (bases only) based on METROMEX data. Values predicted using cloud models agreed with these actual values.*

term weather forecasting, and certain federal agencies recognized this as a promising new area of research and launched research projects. One such project funded by the Signal Corps was obtained by the Water Survey, and staff were hired and worked on the project during 1955-1958 (Blackmer et al., 1958). However, the project's conclusion was not followed by further studies, and the new staff disbanded. The ensuing mesoscale investigations were devoted to explaining cell and multi-storm behavior (Feteris, 1966), to conceptual or numerical modeling (Ceselski, 1975), or to developing improvements in fixed-area rain forecasting (Ackerman, 1982). Much of this research was driven by needs of the Survey's larger field-research programs (PEP, METROMEX, and PACE). The analytical approaches employed have included case studies, analyses of voluminous atmospheric data in numerical or conceptual models, and empirical/statistical studies of synoptic weather conditions.

Major memes of cloud research followed the scale of me phenomena. They include those at the *microscale* (microphysics of clouds and rain), the *cloud scale, and the mesoscale.* Table 8-1 shows the number of publications in the cloud-precipitation formation program. This research has been very productive, generating 128 papers in 40 years. There have been only two reports published in the State series and 19 grant-contract reports. This publication profile reflects that most of this research was supported through grants and very little by state funds. The cloud microphysical research, including the development of a major Cloud Physics Laboratory, has been heavily supported through NSF grants since 1960. The extensive production of papers during the late 1970s to mid-1980s was the result of research by Ken Beard and Harry Ochs (fig. 8-3), plus the mesoscale efforts of Gary Achtemeier and Bernice Ackerman. Cloud-scale research by Ackerman and Nancy Westcott, coupled with cloud physics research by Beard, Ochs, and Czys, sustained the high level of papers published since the mid-1980s.

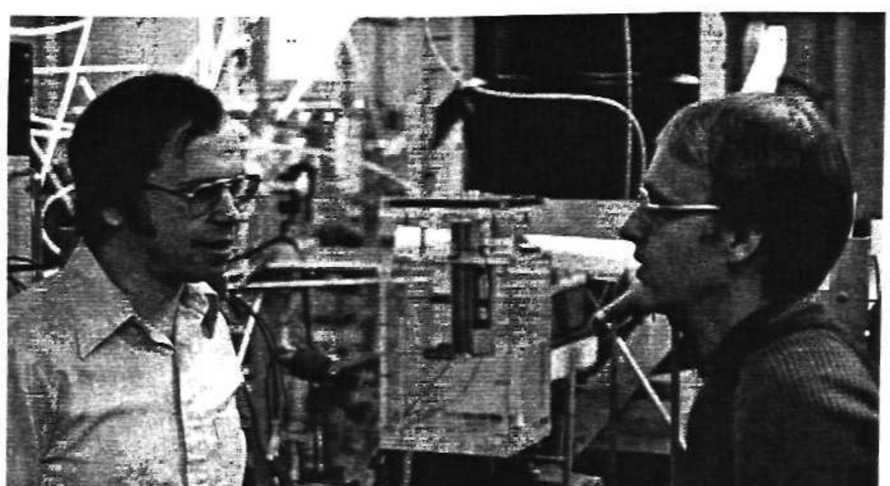

Figure 8-3. Two leaders of the Survey's cloud physics research since 1975 were Harry Ochs (left) and Ken Beard seen in the Survey's Cloud Physics Laboratory which their grants helped instrument.

MICROSCALE PHYSICS

Research dealing with the microphysics of clouds evolved from the Meteorology Section's involvement in the aerosol sampling field research in the late 1950s, and from the famed "hot wire" project aimed at altering the atmospheric charge of small cumulus clouds (see Chapter 6). Understanding the electrical behavior of cloud droplets and how altering their charge changed

Table 8-1. Number of Publications Addressing Cloud Physics, Cloud-scale Studies, and Mesoscale Investigations at the Water Survey.

		Reports		
Year	*Papers*	*State series*	*Contract*	*Total*
1954-1956	1	0	0	1
1957-1959	1	0	3	4
1960-1962	0	0	2	2
1963-1965	7	0	2	9
1966-1968	6	0	4	10
1969-1971	6	0	0	6
1972-1974	6	0	0	6
1975-1977	14	0	0	14
1978-1980	13	0	2	15
1981-1983	25	0	4	29
1984-1986	12	1	0	13
1987-1989	17	1	0	18
1990-1992	12	0	2	14
1993-1995	8	0	0	8

the in-cloud behavior and interactions of cloud droplets to lead to precipitation became the issue that initiated the start of the cloud physics endeavors at the Survey.

Dick Semonin, who directed the hot wire project, began working with graduate students and staff of the University of Illinois Electrical Engineering Department in 1961. Together they established the Charged Particle Research Laboratory in 1963. This joint effort with the Electrical Engineering Department continued until new laboratory facilities in the addition to the Water Survey building became available in 1965. Semonin moved his group into the state-of-the-science laboratory and the Charged Particle Research laboratory remained in the EE Department. From 1962 through 1970, the research entailed use of numerical calculations of droplet behavior, laboratory measurements, aircraft and surface field measurements, and the development of instruments required for laboratory experiments and on aircraft. The objective of most of these NSF-and ARPA-supported efforts was to study and define the collision and coalescence of cloud droplets with and without the influence of electrical charges.

Initial results were based on calculations of the collision efficiencies of uncharged droplets both in and not in electrical fields (Lindblad and Semonin, 1963). This work was done in conjunction with the decade's first laboratory experiments that focused on the coalescence of two colliding curved water surfaces under controlled conditions (Lindblad, 1964). Schneider et al. (1965) described the laboratory apparatus being developed for these coalescence and collision experiments. Lindblad and Schneider (1965) defined the method for producing a uniform stream of droplets and for single droplets desired in the experiments. Plumlee and Semonin (1965) developed a mathematical model for defining the effects of forces acting on two spherical droplets, including the electrical forces, and for calculating the collision efficiencies between pairs of droplets in the 5 to 70 micron size range. Semonin and Plumlee (1966) calculated the collision efficiencies for charged small droplets colliding with larger uncharged droplets, a subject of considerable relevance to the electrification of clouds. Figure 8-4 shows two colliding droplets (suspended on hypodermic needles) as photographed at 14,000 frames per second. This early laboratory research faced the major problem of controlled droplet generation in an undisturbed environment, a theme that carried through the microphysical research from then until present.

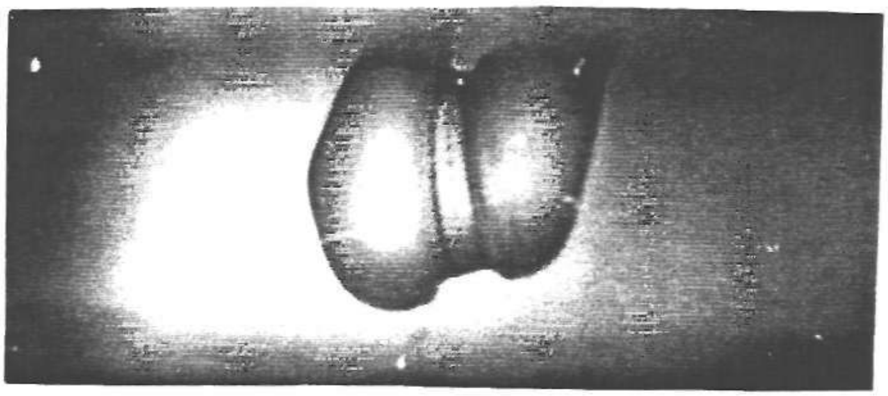

Figure 8-4. A photographic example from the Survey's high-speed camera (14,000 frames per second) developed in the 1960s to capture the interaction when two cloud droplets collided, as shown here.

The Cloud Physics Program also became involved in atmospheric sampling of electric fields and other atmospheric conditions using devices mounted on a C-45 aircraft leased from the University of Illinois during 1962-1966. The plane was equipped with then-standard meteorological sensing instruments (but instruments still in their infancy compared to those of the 1990s). A large device was developed (fig. 8-5) for high volumetric sampling aloft of precipitation particles from clouds (Bradley and Martin, 1967). Semonin (1966) reported on the measurements of giant chloride particles from filter-paper samples taken on aircraft flights between Illinois and the Gulf of Mexico during the 1960s, an activity designed to sample the potential role of chlorides (from ocean salts) in the development of Midwestern rainfall. The chloride particle sizes and their numbers were found not to relate to air mass conditions nor to the incidence of Midwestern precipitation. Semonin (1972) revisited the chloride issue and compared filter samples of chlorides measured in Hawaii and modeled their removal efficiency. The Survey's cloud physics aircraft program had become ambitious, and for a while, a full-time pilot (Bill Bullock) was even employed. Wayne Bradley first worked on the 1962 hot wire flights, and for a while the Survey employed both the TriPacer and C-45 aircraft in cloud flights. The ensuing research revealed that certain atmospheric processes were influencing the measurements of the condensation nuclei counter and Semonin and Hayes (1968) investigated these.

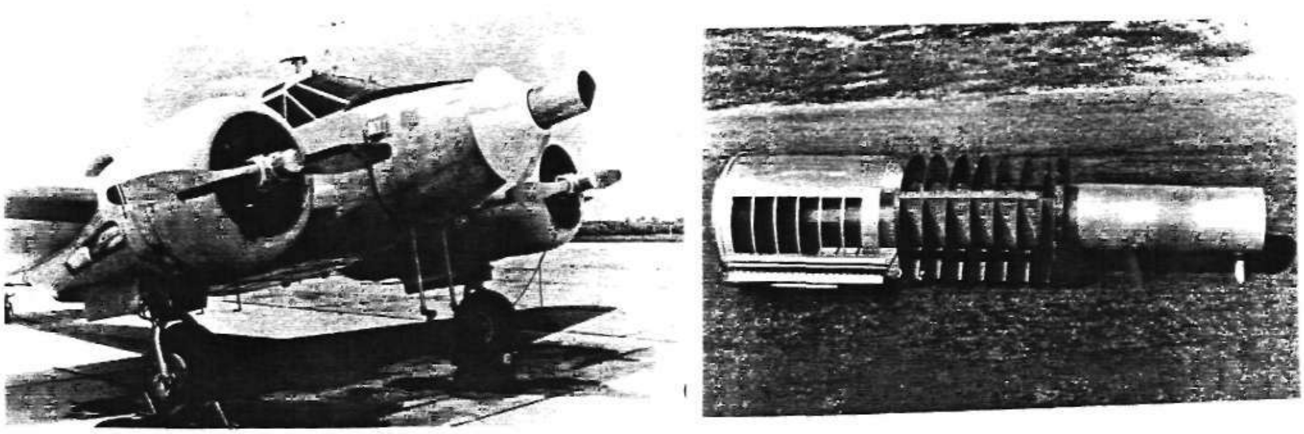

Figure 8-5. The C-45 aircraft used in many cloud flights during the 1960s. The device (right) was mounted on the nose and used to collect cloud water samples. The sampler was designed and built by Survey scientists.

Work to develop a hologram for measuring small droplets and their Rayleigh resolution began in 1966, leading to a series of papers about the calculations, the instrument's development, and the limited results for measuring the di-electric of a glass sphere (Stigliani, et.al, 1967, and Stigliani, 1969) (fig. 8-6). Work on droplet interactions also continued, and Cataneo and Semonin (1969) reported on their calculations of droplet velocity-distance profiles for different sized droplets. John Adam (1970) compared results of his theoretical and experimental (lab) results, which showed that the instability of a stream of droplets could be reduced by charging the droplets. Adam et al. (1971) developed a simple droplet generator for the laboratory experiments and defined its capability to generate a well-controlled pair of droplets *(this generator set the stage for much future research).* Cataneo et al. (1971) performed a related empirical study of the distance between falling droplets and the influence of the wake effect of the lower droplet. The actual process of producing droplet pairs of equal and unequal sizes was developed (Cataneo and Semonin, 1971).

The drop generation technology developed by Adam, Cataneo, and Semonin led to the sustainment of the Cloud Physics Laboratory into the 1970s. The technique of exciting capillary waves on a liquid jet to produce a stream of uniformly shaped drops, in conjunction with a computer control system (developed later by Beard, Ochs, and Czys) so as to manipulate individual drops in both time and space *to produce isolated collisions between dissimilar-sized drops in free fall,* gave the Cloud Physics Laboratory a capability that no other laboratory possesses. These advances since the late 1960s gave Survey scientists an enormous advantage in that precipitation production could be studied under various laboratory conditions that closely resembled those in clouds.

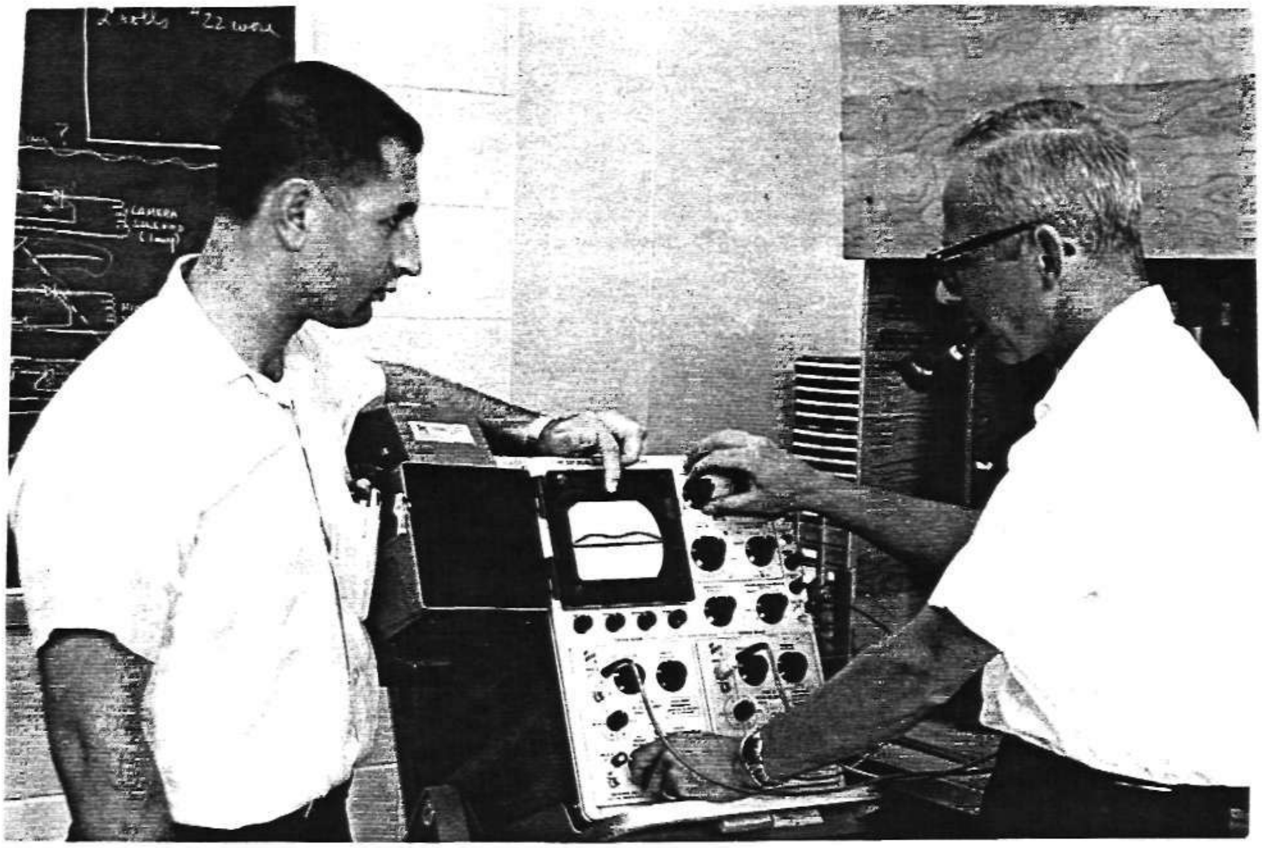

Figure 8-6. Two cloud physicists, Dan Stigliani (left) and Dick Semonin, discuss their cloud physics research and the development of a hologram for measuring small droplets developed during the late 1960s.

By 1971, major findings from the laboratory and numerical analyses had provided guidance for how electrical fields might affect the coalescence and collision of cloud droplets, and the principal scientists involved (Semonin, Adam, and Cataneo) shifted their attention to the demands of METROMEX. This laboratory research, coupled with the needs of METROMEX, provided the basis for and push into cloud modeling, a tool used in the METROMEX assessment of how urban influences altered clouds, and Ochs (1976) described the microphysical computations used in "urban" and rural clouds. Ochs trained in electrical engineering had been employed in 1972 to develop numerical cloud modeling for METROMEX (see Chapter 7) and PEP (see Chapter 6).

Griffith Morgan joined the staff in 1971, and Bernice Ackerman joined in 1972. Both became major contributors to the cloud and precipitation formation studies. Morgan (1972) performed a theoretical analysis of precipitation particle trajectories in clouds necessary for the growth of large hailstones. Ackerman (1974d) analyzed the partitioning of liquid water near the freezing level based on PEP and METROMEX aircraft data collected in 1973. In 1976 Cataneo and Semonin compared the collision efficiencies reported in a recent study with their earlier results from 1970.

A new senior scientist capable of leading the Survey's microphysical research and sustaining the Survey's Cloud Physics Laboratory was needed by 1975 when Adam left. The employment of Ken Beard, who was at UCLA in 1976, fulfilled this need (fig. 8-6). He began studies using both theoretical calculations and laboratory facilities to assess drop behavior and interactions. His first NSF grant was "to assess collision and coalescence of cloud drops," and his first paper concerned drop behavior and distortion (Beard, 1977a). A method was devised to adjust the terminal velocity of falling drops so as to estimate their sea level velocities (Beard, 1977b). Ackerman and NOAA scientists flew a National Oceanic and Atmospheric Administration (NOAA) P-3 aircraft through Illinois clouds during a two-week period in 1977. The ensuing study compared the microstructures of Illinois clouds with those of Florida clouds (Sax et al., 1978). Meanwhile, Ochs was mixing cloud microphysics and numerical modeling. He developed a numerical scheme for computing microphysical properties of drops including condensation, collection, and breakup (Ochs and Yao, 1978a), and then tested their computations with a model (Ochs and Yao, 1978b).

Beard and Ochs, each with different expertise, combined their talents to become a research team and obtained their first grant from NSF in 1978 to investigate the phoretic mechanisms for removal of sub-micron particles in clouds, another study requiring further development of specialized lab equipment. These experiments provided measurements of the efficiency of collections of cloud droplets (Beard et al., 1979). Beard further assessed the effects of altitude and electrical forces on the terminal velocity of hydrometeors, and Ackerman (1980) examined the dependence of internal cloud variables on external atmospheric conditions.

Since 1980, the cloud physics research program of the Water Survey continued to involve laboratory measurements, modeling, theoretical research, and field measurements often in conjunction with major projects such as PACE, the Hawaiian Rainband Project (HaRP)>, the Cloud and Precipitation/Electrification Project (CaPE), and the STORM Fronts Experiment Systems Test (STORM FEST) conducted in central Illinois using Water Survey facilities (HOT radar) in 1990. Several studies focused on the interaction between cloud physics and dynamics, with investigations addressing four areas: ice formation in Midwestern clouds, warm cloud precipitation physics, raindrop shapes, and raindrop coalescence.

Beard (1980) assessed the effects of electrical forces on the terminal velocity of hydrometeors. Leong (1981) studied the morphology of aerosols generated from the evaporation of droplets and, in turn, the capture of particles by evaporating cloud drops (Leong and Ochs, 1982). Their ensuing studies addressed collisions between aerosol particles and small evaporating raindrops (Leong et al., 1985). Johnson (1982a) reported on his study of the role of giant aerosols in the development of warm rains, and also assessed the melting rates of graupel and frozen raindrops (Johnson, 1982b). Further studies assessed spatial variations in cloud base temperatures. (Johnson, 1982c). Accretion of cloud drops by precipitation sized drops was analyzed (Ochs and Beard, 1982), as was the collection efficiencies of cloud drops (Beard and Ochs, 1983). Johnson (1982d) also addressed raindrop multiplication due to the breakup of drops. Collection efficiencies leading to accretion of drops was the subject of another laboratory investigation (Ochs and Beard, 1984), as were the collection and coalescence efficiencies for accretion (Beard and Ochs, 1984). The effects of coalescence on the formation of precipitation (Ochs and Beard, 1985) was an important paper summarizing results from several past studies. Coalescence efficiencies for small precipitation drops were derived from more laboratory experiments (Ochs et al., 1985). Beard and Heymsfield (1988) measured adjustments to ascertain the terminal velocity of ice crystals and graupel. Czys (1989) developed a method to visualize cloud droplet spectra.

Jameson and Beard (1982) measured the axial ratios of raindrops as part of several studies with applications in radar-rainfall measurements. Other studies concerned raindrop distortion (Beard et al., 1982) and raindrop oscillations (Beard, 1982), with subsequent studies addressing how collisions affect drop oscillations (Beard et al, 1983). Johnson (1980) assessed cloud drop concentrations, and Johnson and Jameson (1982) assessed the behavior of melting ice particles as they fall into air warmer than freezing. Beard and Jameson (1983) defined canting of raindrops, plus raindrop axial ratios and backscatter ratios using a numerical model (Beard and Johnson, 1984; Beard, 1984). Beard and Chuang (1987) developed a new model for defining the equilibrium shape of raindrops, and further defined the electrostatic shape of drops (Beard et.al., 1989; Chung and Beard, 1990). Beard et al. (1989) measured the oscillations of small raindrops. Laboratory measurements of small raindrop distortions included oscillation frequencies, axial ratios, and fall behavior (Beard et al., 1991a, 1991b), and field studies were made of the oscillations in small raindrops (Beard and Tokay, 1991).

Past findings about the reactions of raindrops to electrical charges were summarized (Ochs, 1987), and the charging mechanisms in clouds and thunderstorms were assessed in an invited review paper (Beard and Ochs, 1986). Czys and Ochs (1988a) measured the influence of electrical charges on coalescence of free-falling drops and then assessed the behavior of charged raindrops (Czys and Ochs, 1988b). The effect of aircraft acceleration flows on the orientation of hydrometeors was also explored (Beard, 1983).

Czys' cloud physics research was the basis for several experiments involving other sized drops, but over time his work became focused on applications in understanding weather modification, which led to studies of the ice initiation by collisions of drops in warm-based clouds (Czys, 1989). Several new hypotheses have been developed regarding the origin of ice in Midwestern clouds, and these were tested experimentally, theoretically, and with observations. Laboratory studies were initiated to determine whether collisions between raindrops cause freezing, and if the complete evaporation of cloud droplets can result in nuclei conducive to freezing. Studies of the freezing of water and water drops will help improve forecasting of precipitation, identifying regions of icing dangerous to aircraft and mitigating damage from freezing rainstorms. A technique for objectively classifying droplets and graupel from aircraft records was devised, greatly aiding future data analysis (Czys and Petersen, 1992).

Song pursued a series of studies of supercooled clouds. Initially, he used laboratory measurements to investigate the growth of crystals in supercooled clouds (Song, 1992a) and, in turn, the aerosol scavenging occurring in supercooled clouds (Song, 1992b). Further studies examined ice in these cold clouds (Song, 1994a, 1994b), the effects of chemical mixtures on stratospheric clouds (Song, 1994), and the effects of volcanic aerosols on global cloud radiation (Song, 1995). Williams et al., (1992) investigated the chemical composition of cloud condensation nuclei (see Chapter 9).

CLOUD SCALE RESEARCH

Existing between cloud microphysics and the three-dimensional mesoscale environment are clouds and precipitation cells, both of which came under extensive study over several decades. These investigations were often motivated by efforts to understand and explain the dynamic influences of urban areas and of seeding materials on convective clouds. Included were measurements of these entities aloft and at the surface. Many studies involved investigations of storm entities producing severe weather (hail, lightning, and heavy rains). Data came from several sources including radar, satellites, dense networks of rain and hail sensors, and special field investigations.

The Water Survey's first paper addressing cloud-scale research was a study of relationships of the heights of convective clouds and their echoes, as detected by 3-cm radar and all-sky cameras (Changnon and Bigler, 1955). After that effort, no research in this area occurred for nearly a decade. A field study of severe hailstorms in 1963 led to a cell-scale study of two intersecting hailstorms (Changnon, 1964d). Participation in a field project in Hawaii led to a study of the characteristics of cells that produced warm rain (Semonin et al., 1968).

Several field investigations of hailstorms during 1960-1967 were done for the hail insurance industry. These provided sufficient data to develop the first surface model of hail shafts and their relationship to rain cells (Changnon, 1969a). NSF-funded grants for hail research in Illinois began in 1967 and led to a radar-based study of the characteristics of echo cores associated with hailstorms (Towery and Changnon, 1970). Changnon (1970a) used the large volume of data on surface hail falls to identify "hailstreaks", the surface path of a single cloud volume of hail (see fig. 3-11). Typical hailstreaks were found to be 4.5 miles long and 0.4 mile wide. Much large hailstreaks across the Survey networks in southern Illinois during a major storm became the subject of a special study (Changnon, 1970d). Some other exceptionally large hailstreaks were defined in a dense hail network during a very severe storm outbreak in May 1969 (Changnon and Wilson, 1971). Morgan (1976) discovered a feature within many hailstreaks caused by strong winds and labelled them as "hailstripes". The many cell and surface hail conditions were summarized in a review paper on the *Scales of Hail* (Changnon, 1977). Grosh (1977) defined the relationship between echo tops and the incidence of severe storm conditions. The morphology of isolated rain cells, radar echoes, and lightning were also assessed (Grosh, 1978).

Numerical modeling of convective clouds and their regional environment began in 1972 (Ceselski, 1973, 1974). Modeling of clouds to ascertain urban influences began in 1973 (Ochs, 1974), and were tested with cloud and echo initiation data from urban cases (Ochs, 1975). Cloud modeling results from METROMEX cases were useful in explaining first echo development and to examine the possible role of giant nuclei from city sources on echo development (Ochs and Semonin, 1979). Ochs and Johnson (1981) examined the urban influences on the development of first echoes, finding then distinctly different than first echoes in nearby rural area clouds. Changnon (1976c) analyzed the behavior of 702 echoes in and around St. Louis and found that urban-area cells typically were taller and there were more mergers between cells over and near St. Louis. Schickedanz (1974) developed the concept and objective definition of surface raincells, the surface path of rainfall from a single convective element. Later Schickedanz et al. (1977) analyzed the five-year METROMEX network data and defined 2,890 raincells, which were used to develop a statistical model. Subsequently, isolated convective rain cells measured in several Survey networks (fig. 8-7) were analyzed to derive

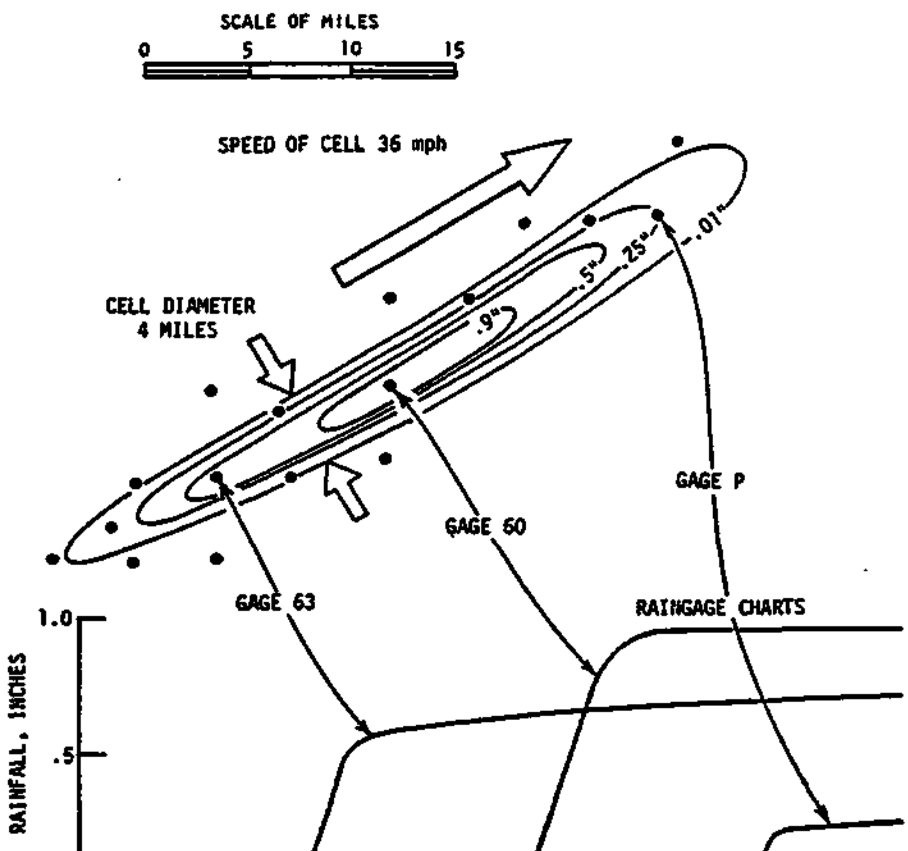

Figure 8-7. The depiction of a raincell, as defined during a June 1965 rain period on the little Egypt Network in southern Illinois, showing its isohyetal pattern, speed, and rain rate traces at selected raingages.

their average characteristics, showing average dimensions of 16 miles long and 5 miles wide (Changnon, 1981a). Grosh (1977) analyzed satellite data of convective clouds at St. Louis to define cloud characteristics and frequencies over and beyond the city.

Considerable cloud-scale research was driven by the specific needs of the Survey's weather modification research. Semonin (1977) analyzed historical sounding data using a one-dimensional model to assess weather modification potential for Illinois clouds (fig. 8-8). Later, Ackerman and Sun (1985) compared cloud-echo predictions of two one-dimensional models for their applicability to weather modification operations and evaluation. In a pivotal summary paper, Ackerman and Westcott (1986) made a comprehensive review of many studies to identify the key findings about the characteristics of Midwestern clouds.

The structure of radar echoes based on CHILL radar data taken in Colorado were used to develop and compare the characteristics of nonseeded and seeded hailstorms (Mueller and

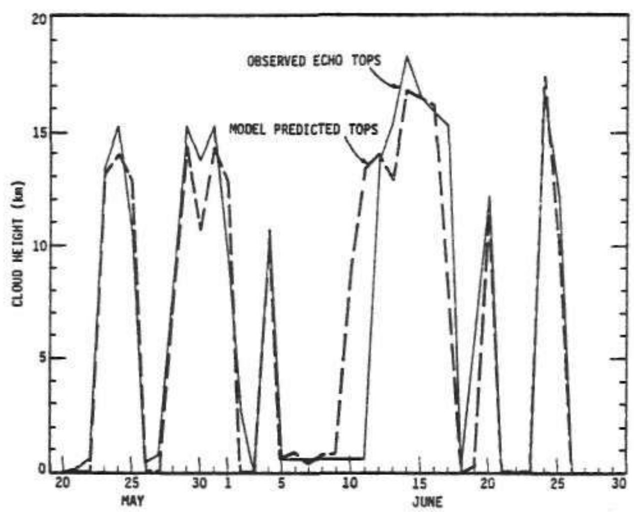

Figure 8-8. Comparison of the cloud tops, as predicted by a numerical model for echo tops in central Illinois, and those actually measured on a series days in May and June 1978.

Changnon, 1974). Huff (1987) summarized characteristics of individual radar echoes measured in Illinois projects were summarized for applications to weather modification project need. Westcott and Ackerman (1985) reviewed the characteristics of convective storms for applications in weather modification research. Westcott (1989) compared the echo characteristics of seeded and nonseeded cells from a 1986 field experiment; Czys (1991) analyzed the structure of updrafts in cumulus clouds suitable for seeding trials; and Czys et al. (1993) analyzed the echo core responses from dynamic seeding trials. Figure 8-9 defines the updraft properties measured during the 1988 cloud penetrations.

Some studies investigated multi-cellular groups of convective clouds. Results from METROMEX suggested that merging of cell entities often led to increased rainfall. Ackerman and Greenman (1978) performed a case study of one such cloud mass. Ackerman (1980) analyzed the relatioship between various cloud features and external (environmental) conditions.

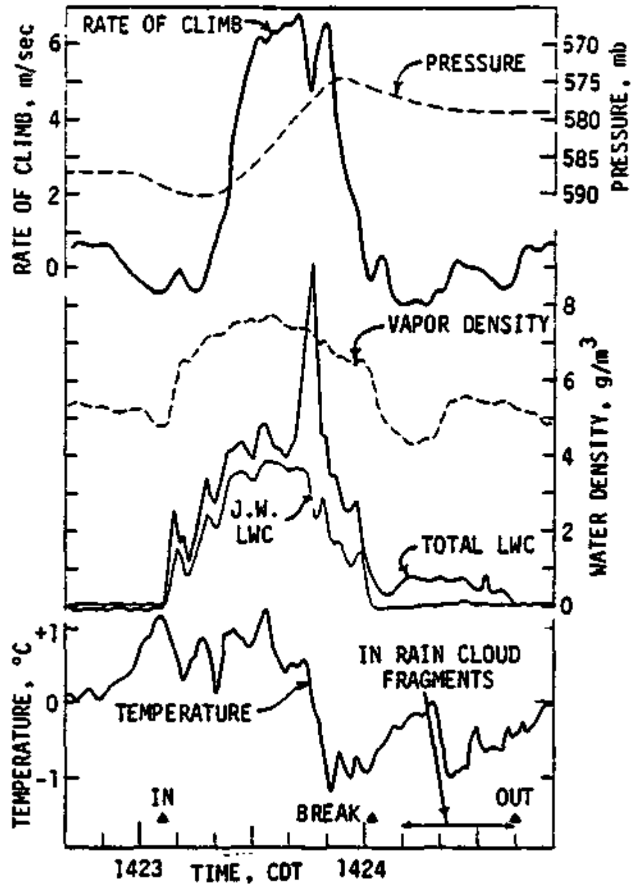

Figure 8-9. Water Survey cloud flights during the 1970s and 1980s collected data on various in-cloud characteristics. Here is a graph of cloud data taken inside a cumulus congestus during 1988.

Westcott (1988) studied local conditions influencing the growth of single thunderstorms. Westcott (1984) assessed what was known about the dynamic effects of merging on cloud growth and rainfall showing sizable increases in echo intensity and area following mergers (fig. 8-10). Ackerman and Westcott (1984) assessed the morphology of merged clouds. A case of cell developments and mergers in a thunderstorm case were investigated using doppler data for airflow measurements (Westcott, 1989), and Westcott (1989) analyzed the properties of first echoes that led to multi-celled rainfall entities, and also the bridging and subsequent growth of aggregating echo cores (Westcott, 1991). Spatial relations between rain cells, hailshafts, and cloud-to-ground lightning were defined for several storm cases in an attempt to explain their dynamic relationships aloft in thunderstorms (Changnon, 1993f). Westcott (1994) assessed the development of merged cloud entities and the effect on new cloud development.

MESOSCALE INVESTIGATIONS

Mesoscale research during 1955-1958 (Blackmer et al., 1958) initially involved efforts to define the mesoscale dimensions of various weather conditions (wind, temperature, and

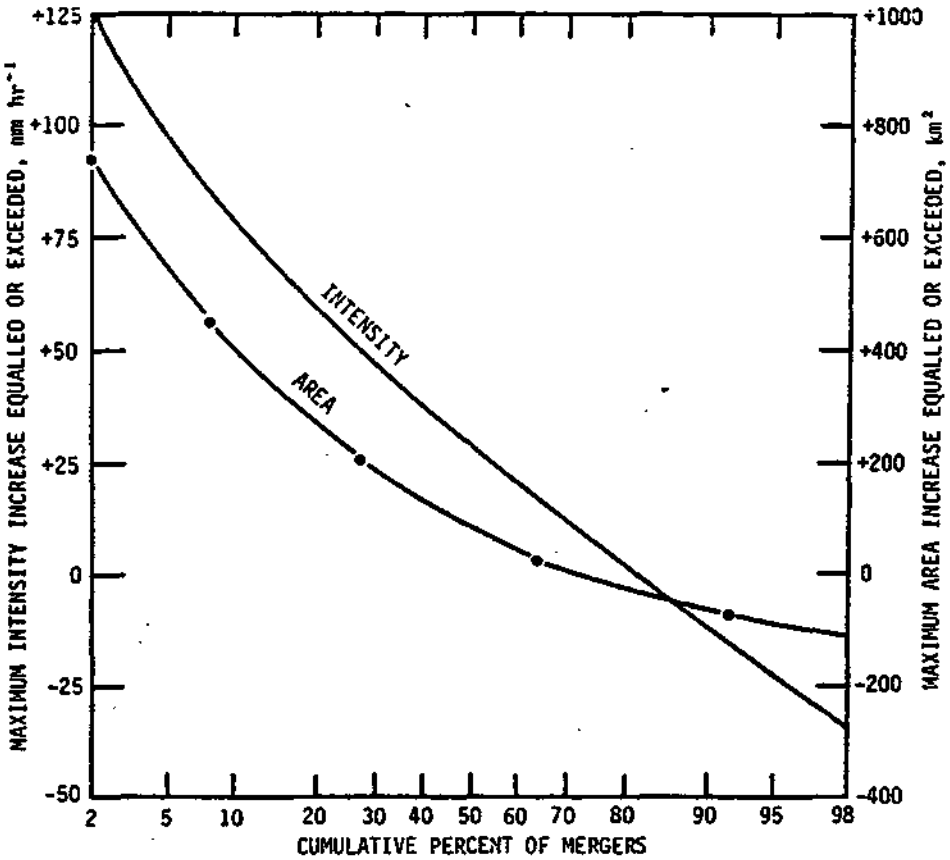

Figure 8-10. A primary finding from numerous Survey cloud-echo studies was that the merging of two clouds led to increased rainfall. This graph, based on the study of 1,040 cell mergers at St. Louis, shows the frequency distribution of the increase in rain intensity and rain area following mergers of radar cells.

moisture fields) to improve short-range forecasts of rain, objectives of many of the Survey's subsequent mesoscale studies. On the same initial Signal Corps contract, Ted Fujita who just had arrived at the University of Chicago was hired to perform a detailed mesoanalysis of squall line situation using data from the 1947 Thunderstorm Project in Ohio (Fujita, 1958). He sought to develop and illustrate methods for mesoanalysis for which he would later become famous. Changnon and Huff (1959) analyzed the mesoscale behavior of organized lines of precipitation, as defined by Survey radars for Air Force supported project. Huff and Shipp (1968a) defined the mesoscale variability of convective rainfall elements in the Midwest, and Bradley (1968) used sounding data to define the relationship between fair weather electric fields and the incidence of rainfall, finding no useful predictive relationship. As part of an NSF grant, Peter Feteris (1968) used detailed mesoscale weather data collected in Holland for a statistically based analysis of how atmospheric conditions related to the behavior of showers and thunderstorms.

On a broader scale, Ceselski (1973) numerically modeled vertical motions and Midwestern convection and precipitation for PEP applications. Changnon (197le) assessed the mesoscale weather features created by the Great Lakes, such as lake breezes, and their effects on temperatures, precipitation, winds, and other conditions. Extensive studies of the low-level mesoscale wind field in the St. Louis area, and the influence of the urban area on the winds fields and the planetary boundary layer resulted in several publications (Ackerman, 1974a, 1974b, 1977b). Under Bernice Ackerman's leadership, further studies of wind fields and precipitation development occurred in the late 1970s.

Many studies were directed at improving short-range rainfall and storm forecasting with applications to the planned and inadvertent weather modification projects (PEP, METROMEX, PACE, and CAP). Achtemeier and Morgan (1975) tackled the thunderstorm forecasting problem, as did Vogel (1975) using surface variables. Grosh (1975) explored a radar-thermodynamic approach for forecasting regional occurrences of hail. As part of an NSF project, Achtemeier (1975) tested the variational method as a forecast tool. This study also included the development of a thunderstorm forecast method using "four-dimensional evaluation of mesoscale stability" (Achtemeier, 1976). Subsequent forecasting research concerned variational initialization of storm cyclogenesis (Achtemeier, 1978). Chin-Fei Hsu, a meteorological statistician, used regression analyses of forecast variables for convective precipitation amounts (Hsu, 1980) and later investigated synoptic variables as covariates in rainfall forecasts (Hsu, 1981).

Beginning in 1977 a series of investigations of rainfall prediction used surface and near surface wind fields. Bernice Ackerman was awarded $700,000 by NSF in 1978 to pursue a three-year project to define the effects of low-level convergence on the development of convective rainfall. The VIN (Virginia-IUinois-NOAA) project included scientists from other institutions and featured a summer field project in central Illinois involving the CHILL radar and a dense weather network. Its goal was to improve rainfall forecasts (Ackerman et al., 1982, 1983). Vogel (1983) reported on the capability of sub-cloud layer kinematics to predict convective rainfall, and in the wind field studies the surface signatures of dry gust front were measured (Scott, 1983). Achtemeier (1983) used objective techniques in a test of predicting rains in the St. Louis area with low-level wind fields. Ackerman (1988) analyzed the influence of the boundary layer on the development of a mesoscale rainstorm. A nowcasting system was successfully developed for use in PACE (Ochs and Kidder, 1986).

Some forecast analyses addressed problems other than rain forecasting, largely as a result of sources of available funding on other projects. Achtemeier (1984) assessed forecasts of the mesoscale wind fields for applications in forest fire management. Achtemeier and Scott (1985) assessed weather forecasting for pest movements, and Peppier (1991) analyzed pest movement in the boundary layer using wind and radar data. Czys and Scott (1992), as part of the PACE research, developed techniques to forecast the occurrence of convective rain clouds, maximum cloud top heights, and the suitability of the atmosphere for dynamic seeding.

Achtemeier (1986) continued fundamental studies focusing on objective analyses of boundary conditions in models, and use of other statistical techniques for improving objective analyses (Achtemeier, 1987). He also addressed techniques for improving boundary layer models (Achtemeier, 1991). Peppier (1984) assessed the truncation errors in estimates of geostrophic winds and relative vorticity, and then examined the relationships of static stability indices with thermodynamic parameters (Peppier, 1988).

Several studies of mesoscale phenomena were pursued as pan of a NASA-sponsored project. Kidder and Achtemeier (1986) examined biases in the use of satellite data for detecting mesoscale patterns in day and night surface temperatures, and followed with a satellite case study of a cyclonic system (Achtemeier et al., 1987). Kidder and Wu (1987) used satellite data to develop surface temperature fields over varying snow covers at St. Louis. Chance (1986) tackled the problem of using satellite data to help in developing 3-dimensional wind fields, and Achtemeier (1986) assessed the modification of a variational objective analysis model for the lower troposphere and tested the spatial resolution and accuracy of satellite data.

The most recent research have again addressed effects of the Great Lakes on mesoscale conditions. Kristovich (1993) analyzed the average circulation in rolls found in the boundary layer near Lake Michigan during lake-effect storms, and further analyzed the mesoscale structure of wind field in lake storms (Kristovich, 1993). Cloud bands appearing over the Great Lakes were also studied (Kristovich and Steve, 1995).

SUMMARY

Major Achievements

A notable achievement has been a long-running strong research program in cloud microphysics, nationally and internationally recognized for its accomplishments in fundamental cloud droplet and raindrop research. Associated with this strong program has been the development of a state-of-the-art Cloud Physics Laboratory considered one of the best in the world. The success of this program is further reflected in the fact that most of the resources for staff and facilities have come through a series of grants from the National Science Foundation. The group also established the Midwest Association for Cloud and Aerosol Research that promotes cooperative research between numerous cloud scientists mostly at Midwestern institutions. The research has also involved the education and training of more than 15 graduate students.

As a result of this research effort, Water Survey scientists have been able to define, in considerable detail, the three-dimensional characteristics of Midwestern convective clouds and their rainfall cores including factors leading to rain initiation and growth as well as the influences of merging of cloud and rain elements, and the resulting effects on rainfall and hail. Important weather phenomena including raincells, hailstreaks, and hailstripes were discovered and the Survey scientists were among the first to model their characteristics.

Forecasting methods were developed and found useful in short-term forecasting convective rainfall incidence and amounts over discrete areas, including those where field operations were conducted, a major objective of the mesoscale research at the Survey. Advances in fundamental mesoscale research techniques were also achieved. The capability to forecast convective rainfall by analyses of the low-level convergence was defined.

The foremost achievement of the studies concerning cloud and precipitation formation and development is that they have answered the "needs-to-know" associated with the applied studies in planned and inadvertent weather modification for the benefit of Illinois.

Pivotal Publications

Much of the microphysical research evolved from the development of a reliable drop generator (Adam et al., 1971). Cloud physics research focusing on urban influences was critically important. Findings about the microphysical properties of urban and rural clouds (Ochs, 1976), and those explaining the different form of first echo development over the city - and the role of giant nuclei were pivotal in defining urban influences on the growth of clouds and rain over a large city. The invited assessment of cloud and precipitation research findings was a major recognition of the leadership role the Water Survey scientists provided (Beard, 1987). Work on surface hail measurements developed the first model of a hailstorm (Changnon, 1969a), and the definition of "hailstreaks" was a discovery that helped define hail formation. Westcott's research on clouds and their mergers has defined the importance of these dynamic influences and how they occur (Westcott, 1984, 1994). Ackerman and Westcott (1986) assembled an outstanding paper assessing what was known about all facets of Midwestern clouds that has been used as a guide in many projects in and outside the Water Survey.

Key Projects

The long running number of 29 NSF grants that have supported the microphysical research and developed the cloud physics laboratory, worth more than $2 million, is an amazing achievement. The NSF grants for the VIN project totaling $700,000 over three years were also significant. The METROMEX NSF grants, leading to definitive studies of rain cells, the behavior of radar echoes, and modeling, were significant in solving much of the urban rainfall puzzle. The NSF grants for hail research during 1967-1976 ($955,000) were pivotal in getting at hailstorm processes. Finally, the PACE-PreCCIP grants from NOAA since 1978 have provided major support for cloud and echo studies that advanced our knowledge at all scales, the microphysical to mesoscale.

Major Staff

The key staff, as defined by their publications and service as principal investigators (and hence able to attract funds for research in this program area, have been identified and classed by their roles in the three theme areas. Those most prominent in microphysical research were Dick Semonin, Ken Beard, Harry Ochs, Bob Czys, John Adams, David Johnson, and Bob Cataneo.

Major contributors in the cloud-scale investigations have included Griff Morgan, Bernice Ackerman, Nancy Westcott, Harry Ochs, and Stan Changnon.

The principal contributors in the mesoscale area were Bernice Ackerman, Gary

Achtemeier, John Vogel, and Peter Feteris.

Others who have made major scientific contributions are Floyd Huff, Peter Hildebrand, Paul Schickedanz, David Johnson, David Kristovich, Bob Scott, and Nahui Song.

Figure 8-11. Photographs of several staff who contributed to the cloud and mesoscale research efforts of the Survey. Top left is the 1967 hail research project staff (l. to r.) Don Staggs, Joe Coons, Pam Collins, Harold Danforth, Ira Pfeffer, Susan Ting, Karen Stepper, Ron Rinehart, Edna Anderson, Neil Towery, John Pearson, Christine Hagen, and Paul Schickedanz (John Hornaday and Stan Changnon were absent). Top right shows Bernice Ackerman talking to Dave Brunkow during VIN. The lower left is Wayne Bradley who was involved in cloud physics research; lower center is Peter Feteris who pursued mesoscale studies; and lower right is Ed Silha who worked as a radar engineer at the Survey for several years.

Chapter 9

ATMOSPHERIC CHEMISTRY

Floyd A. Huff

INTRODUCTION

The atmospheric chemistry program began in the early 1950s with a two-year rainwater sampling project. The program grew over time to become one of the Survey's major research endeavors. This chapter describes the evolution of the program from the 1950s to the 1990s.

During the 1960s the Atmospheric Sciences Group began a project to study radioactive fallout in rainfall. The Survey's major activities in atmospheric chemistry shifted in the late 1960s from studies of radioactive fallout to an investigation of chemical tracers for analyzing atmospheric precipitation movements, work done during the late 1960s and early 1970s. Dry fallout studies also became part of the atmospheric chemistry research in the early 1970s. The acid rain problem began drawing major attention in the scientific community (and the media) during the 1970s, and interest in precipitation chemistry continued into the 1980s.

THE 1950s AND 1960s

The earliest contact with atmospheric chemistry in the Meteorology Section occurred in 1952-1954 in conjunction with a contract with the University of Chicago. Under this contract, the Survey was to operate radar and other meteorological equipment at the Survey's Meteorological Laboratory to collect data for a cloud physics project (see Chapter 8). One part of this operation the Survey scientists under Stan Changnon's direction used special equipment furnished by the University of Chicago to collect data on the frequency and sizes of atmospheric particles. Chicago cloud physicists then analyzed these data to determine whether sodium chloride particulates serve as possible hygroscopic nuclei in the atmosphere. Rainwater samples were also collected in 75 rain events as part of the project. The Survey's Chemistry Section analyzed the samples, and Larsen and Hettick (1956) summarized the results showing that sulfate concentrations in rainwater decrease with increased rainfall rates (fig. 9-1).

Another similar project aimed at understanding how to modify the weather had an atmospheric chemistry component. It began during 1957-1958 and involved the sampling of airborne particulates in the Midwest, a project under Dick Semonin's direction (see Chapter 6).

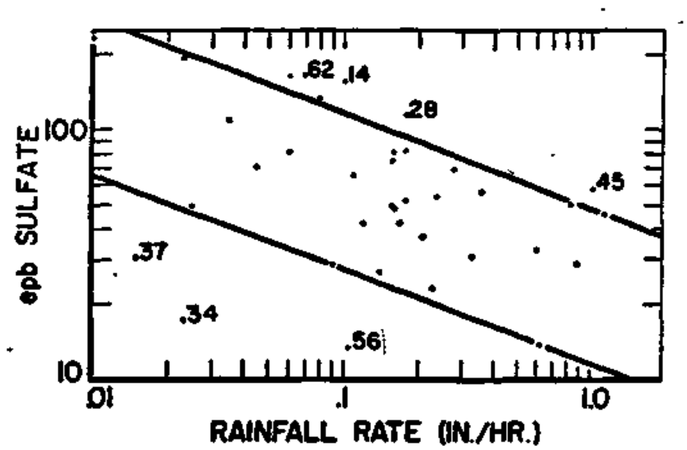

Figure 9-1. The relationship between rain rate and sulfate concentration, showing a decrease in concentration with higher rates. These findings were from rain samples taken in 1952-1954.

This project included a chemically-specific spot analysis of each filter sample with particular emphasis on sodium, chloride, and sulfate. In 1960, precipitation samples were collected and analyzed at the Survey's chemical laboratories. The research program was expanded in 1962 when Glenn Stout negotiated a 12-month contract with the Fallout Studies Branch of the Atomic Energy Commission (AEC) to conduct research on the rainout of radioactivity. Convective storm studies were to be the primary emphasis of the research. Again, Water Survey facilities (radar and raingage networks) and knowledge of their use contributed to the awarding of this contract. There waas also considerable concern about fallout in precipitation from the Soviet nuclear tests in fall 1961. Similar to what occurred with weather modification a decade earlier, deposition of fallout from the tests and potential consequences became a "pet" topic of the media (and others) and resulted in the usual exaggerations about the dangers. Consequently, both the government and the public were clamoring for a thorough AEC evaluation of the problem. This resulted in several scientific studies funded by the Fallout Branch, of which one was awarded to the Survey.

Floyd Huff, who had a degree in chemical engineering, was appointed as the project's principal investigator and assumed supervision of the collection and analysis of both chemical and meteorological data. Ken Wilk supervised radar operations, which were an important part of the study. Stout procured temporary but necessary laboratory facilities to conduct chemical analyses of the radioactive fallout from University of Illinois professor Ben Ewing of the Sanitary Engineering Department. Later, space was obtained in the Survey's Chemistry Section to carry out the analyses.

Rena Gans, who had a degree in chemistry, was hired to perform the analyses. Dr. Frank Sollo of the Survey's Chemistry Section was very helpful in assisting with the design of the chemical analysis program. Dick Boyd, the Survey's weather observer and an excellent mechanic, was named chief technician on the project. With the facilities available, it was possible to perform chemical analysis of gross beta (total fallout), but not of individual isotopes. A contract was therefore negotiated with Isotopes, Inc., of Westwood, New Jersey, to analyze selected isotopes.

This project marked the official entry of the Meteorology Section into atmospheric chemistry, another new program that eventually developed into one of the major programs of the Atmospheric Sciences Section. No one imagined when the First Annual Report (Huff and Stout, 1963) was submitted to the AEC in 1963 that 15 additional annual reports would eventually be submitted under contract AEC(11-1)-1199.

Radioactive Rainout Project (1962-1967)

This initial project in atmospheric chemistry continued for five years (1962-1967) until radioactivity levels became too small to be of major interest to AEC, and the research objectives shifted. The project employed a combination of recording raingages, rainwater samplers, radar observations, radiochemical analyses, and synoptic weather data to investigate and define the time and space distribution characteristics of radioactive rainout in storm rainfall, with respect to the concentration and deposition of radioactive material at ground level.

In the first year, only total storm samples of rainwater were obtained. Analysis revealed that it was imperative to develop an automatic rainwater sampler that would make it possible to obtain sequential samples throughout a storm event, and thereby determine the time distribution characteristics of the storm rainout. A sequential sampler designed to function without electric power at remote sites was also developed mainly through the efforts of Dick Boyd and Ron Tibbets. Multiple streamwater samples were also obtained in conjunction with the project during selected storms from two small basins (Kaskaskia and Boneyard) in the Champaign-Urbana region, and these were used to investigate the potential effects of radioactive rainout on surface water quality. By 1964, project scientists had completed a spatial analysis of the rainout in. convective rains (Huff and Stout, 1964). Huff (1965) presented further radioactive analyses based on the network data. The findings from the four years of data collection on radioactivity in rainfall were summarized showing sizable spatial variability (Stout and Huff, 1967). Huff and Stout (1967) also described the relationships between two radioactive isotopes found in the rainfall.

Starting in 1965, air samples were also collected at several sampling points for correlation with the precipitation samples. Wayne Bradley performed initial work on evaluating radioactive tritium as a possible atmospheric tracer, and Peter Feteris became involved in determining the feasibility of isentropic trajectory analysis for tracing radioactive air. Then spatial measurements of radon concentrations were initiated (Bradley and Feteris, 1966). Bradley also investigated the relation between radioactive rainout and radioactive concentrations in the ambient air by using a specially designed and locally constructed precipitation collector for the aircraft used to collect samples, as shown in figure 8-5 (Bradley and Martin, 1967). At the end of 1967, the original radioactive rainout studies had answered their objectives and were terminated, and attention focused on the tracer studies (Huff et al., 1967).

The five-year field study and subsequent data analyses provided much needed information on the mesoscale time and space distribution characteristics of radioactive rainout and the relationship between the rainout and various precipitation parameters and synoptic weather conditions. One finding of major interest was that the storm profiles of rainout in convective precipitation could be grouped into four major and three minor types (Huff, 1965), with the major types accounting for 90 percent of the cases. The most frequent type occurred 45 percent of the time, and the heaviest rainout occurred most frequently at the leading edge of the storm being sampled (fig. 9-2).

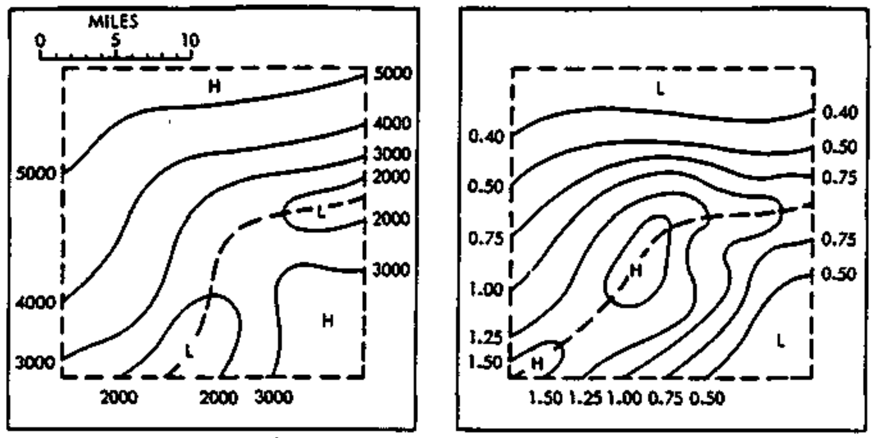

Figure 9-2. The pattern of beta concentration (picocuries/liter) on the left and rainfall (inches) on the right for the rain storm of July 1, 1963, on the East Central Illinois raingage network.

In addition to the AEC contract reports and research reports, papers were presented at several scientific meetings and several research papers were published describing various phases of the project and analytical findings. A total of six publications resulted from the rainout studies: three were published in professional journals (Huff and Stout, 1964; Huff, 1965; Huff and Stout, 1965), two in symposium proceedings, and a chapter in a book published by the AEC Fallout Studies Branch.

Major contributors to the radioactive rainout project included Glenn Stout (director), Floyd Huff (principal investigator), Kenneth Wilk and Douglas Jones (radar meteorologists), Rena Gans (chemical analyst), and Dick Boyd and Ronald Tibbets (technicians). Others who joined the staff in the later stages of the project and included Peter Feteris, Wayne Bradley, and John Wilson (meteorological analysts). Huff decreased his involvement in the project at the end of 1965, and left the program entirely at the end of 1967 to devote full time to hydrometeorological research. Richard Semonin became the project's Principal Investigator in 1969 as the project shifted its focus to non-radioactive washout and rainout processes.

Chemical Tracer Project and Related Studies (1966-1970)

A project to evaluate the use of chemical tracers for tracking atmospheric movements of cloud and precipitation entities was initiated in 1965. Several aircraft flights were made during 1966 to measure the vertical distribution of tritium in the atmosphere. Nuclear blasts injected this radioactive isotope of hydrogen into the stratosphere where it combined with oxygen to form a tagged water molecule, a potentially useful tracer for certain types of meteorological studies.

A second study undertaken in 1966 involved the feasibility of using isentropic trajectory analysis to trace radioactive air with respect to precipitation systems. If successful, the method could prove useful in determining these mechanisms and atmospheric conditions maximizing radioactive rainout and fallout. A third study began in 1966 and involved the determination of radon concentrations in the lower troposphere by aerial sampling. The purpose of the study was to determine the feasibility of relating these concentrations to various meteorological occurrences.

These studies were continued during 1967 and 1968 and they produced useful information about chemical tracers and their applicability in meteorology. Findings were summarized in the annual reports and in research reports submitted to AEC (Huff et al., 1967; Wilson and Bradley, 1968).

A related project initiated in 1969 under Semonin's direction was the Illinois Tracer Experiment (Project ITREX) to investigate the scavenging characteristics of convective storms. This cooperative project sponsored by AEC involved the Water Survey, the University of Michigan, and Argonne National Laboratory. It included the placement of a unique chemical tracer into a prescribed part of convective clouds and subsequent analysis of the tracer contained in storm rainwater samples from 196 recording raingages in a 1600-square-mile area of the central Illinois raingage network. In addition to the field experiment, laboratory studies of the scavenging efficiency of raindrops were conducted. Only one field experiment was carried out in 1969 due to various problems, particulalry the the lack of convective systems. However, during the spring 1970, six convective storms were inoculated with indium, lithium, or both tracers by pyrotechnic devices carried aloft on an aircraft flying over a 400-square-mile subnetwork of the Central Illinois Network (Semonin, 1970).

Indium analyses were carried out at the University of Michigan which had the required laboratory equipment was available. Chemical analyses of lithium, sodium, potassium, and magnesium were conducted in the Survey's Chemistry Section, and other analyses were done at Argonne National Laboratory. As scheduled, ITREX field experiments were terminated after 1970, but data analyses continued for two more years (Semonin, 1971). These analyses yielded necessary information pertaining to the application of chemical tracers for tracking surface fallout from convective rainstorms, which was then applied in the next phase of the tracer studies carried out as part of METROMEX research in St. Louis in the 1971-1975 period.

THE 1970s

In 1969, Dick Semonin led the AEC-sponsored research in atmospheric chemistry, and the Survey's atmospheric chemistry program entered a period of substantial growth as AEC became involved in other aspects of atmospheric chemistry, which resulted in increased funding for the Survey's project. This also brought research funding from other sources, and the success of the Survey's program received greater national recognition. Don Gatz joined the staff in 1972 and he was the first true atmospheric chemist on the staff. He had been involved in Project ITREX at Argonne. Major endeavors of the continuing atmospheric chemistry program are now briefly summarized in the ensuing text. The first of these involved expanding research in the application of chemical tracers in meteorology.

Chemical Tracer Studies Associated with METROMEX (1971-1975)

In 1971, the ITREX field experiments were transferred from central Illinois to the St. Louis area where tracer experiments became an integral part of Project METROMEX, which was designed to determine the effects of urban areas on the precipitation processes (see Chapter 7). In conjunction with METROMEX, unique chemical tracers (lithium and indium) were released into the updrafts of convective clouds in selected storms to obtain insight into the scavenging mechanism of the treated clouds. The University of Michigan group under Nelson Dingle elected to discontinue its participation in the field research, but the Battelle Northwest Laboratories at Hanford, Washington, joined METROMEX.

A rainwater chemistry network was installed over a 700-square-mile area within the 2000-square-mile METROMEX raingage network (see fig. 7-3). Chemical samplers consisted of approximately 80 single-sample collectors plus several sequential samplers and other special collectors located at strategic positions. Convective clouds were inoculated with tracers using METROMEX project aircraft. However, ground release of tracers also occurred as part of the field experiments to simulate emissions from sources such as automobiles and small industrial plants. Some experiments even determined the natural background of tracers in both wet and dry deposition. Figure 9-3 shows the patterns of lithium (solid lines) and rainfall (dashed lines) from a tracer release by aircraft into the base of a thunderstorm on August 11, 1972.

Analyses were performed in the atmospheric chemistry laboratory which had been established at the Survey to handle the large numbers of chemical analyses that had to be performed in conjunction with the growing field program (Rattonetti, 1974). For example, the Annual Report to AEC of April 1974, indicated that the 1973 field effort produced 1,513 total rain samples from 81 sites, 450 sequential rain samples from three locations, 266 wet/dry samples from eight sites, 270 air filter samples from seven sites, 81 Anderson impactor samples from three locations, 14 water samples from aircraft cloud sampling, and nine air filter samples from aircraft (Semonin, 1974). Figure 9-4 shows the wet/dry sampler devised and built by Survey scientists.

Schicht and Huff (1975) made a two-year study of the effect of precipitation scavenging of airborne and surface pollutants on surface and groundwater quality in urban areas. The study used two small basins near St. Louis: one subject to urban effects and the other was not.

Chemical analyses of the precipitation chemistry samples from METROMEX were conducted at the Survey's analytical chemistry laboratory under the direction of Mark Peden. A large number of dry deposition samples were collected in addition to rainwater samples. For example, Peden reported in the Survey's Board Report of April 1975 that a total of 2,000 dry deposition and rainwater samples were processed in the laboratory during the previous year.

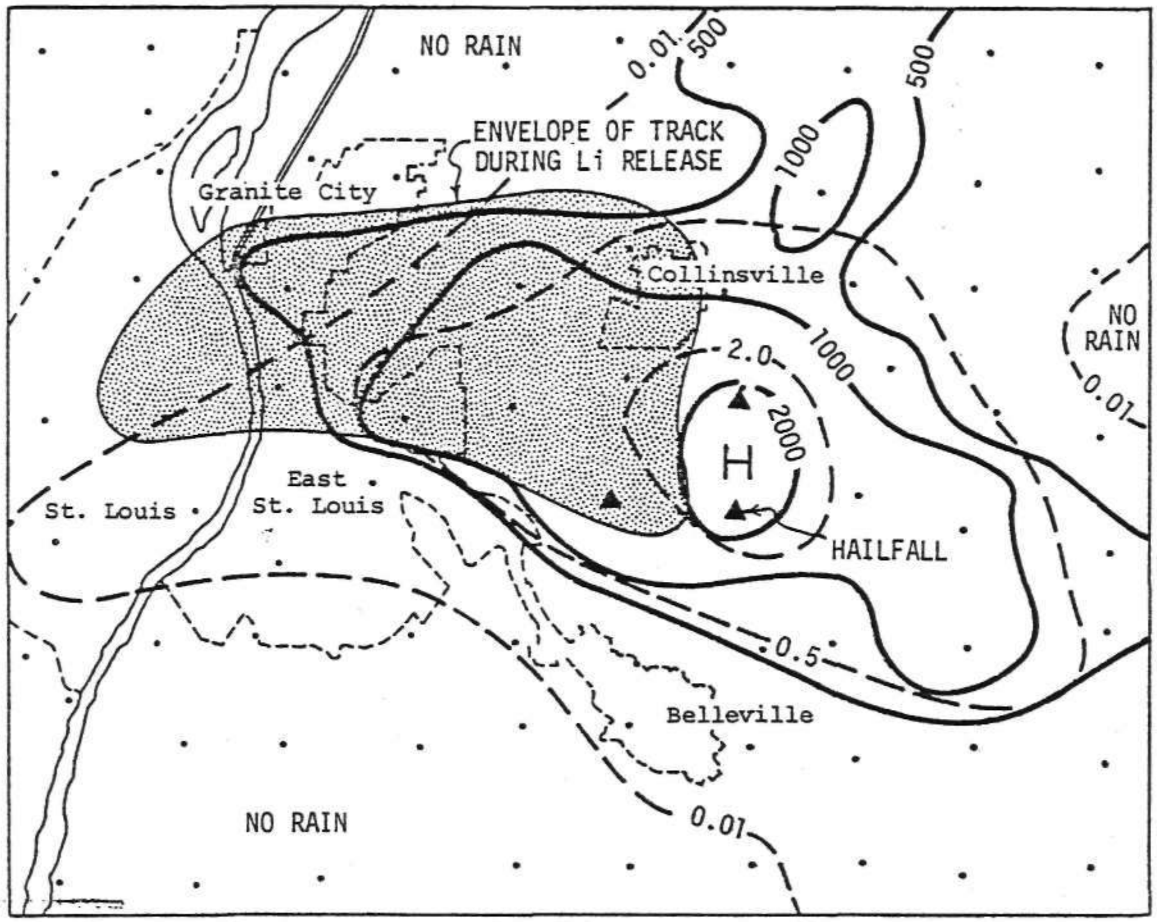

Figure 9-3. Pattern of lithium found in rainwater samples from an aircraft tracer release (stipled area) in clouds over and east of St. Louis on August 11, 1972. The rainfall (in.) is in dashed lines and places where hail fell.

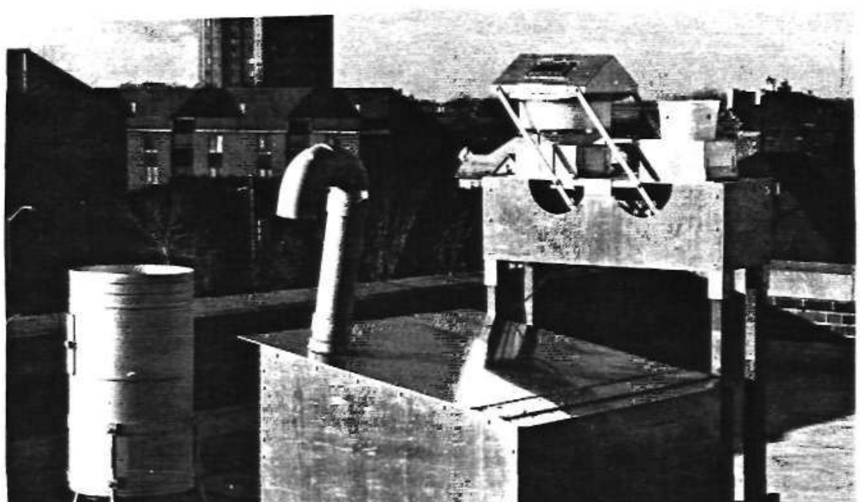

Figure 9-4. A raingage, an air sampler, and a wet-dry sampler on the roof of the Survey's building on campus in 1979. The cover over one part (left) of the wet-dry sampler had a rain-sensor which when rain occurred activated the motor, moving the cover over the dry sampler, allowing rain to fall in the collector to the left.

The purpose of this extensive chemical sampling in conjunction with METROMEX was stated in the Survey's 1975 Annual Report, "Through the interpretation and correlation of all the various types of data, a complete picture of the total removal of materials from the atmosphere to the earth's surface can be determined." The report further stated that the analyses were a prerequisite to the determination of St. Louis (or other large urban/industrial areas) as a source of pollutant materials to downwind regions, and made it possible to determine the city's contribution to regional environmental quality. Results of the METROMEX tracer and dry deposition studies were discussed in detail in the Annual Reports to AEC and in research reports to AEC, the funding agency (Semonin, 1972; Adam et al., 1973; Semonin and Gatz, 1974; Semonin, 1975).

The METROMEX research results also began to appear in the scientific literature during and after METROMEX ended. Gatz (1972) assessed the washout ratios of metals in the St. Louis urban area and in surrounding rural areas, which was followed by a paper estimating the aerosol source coefficients and elemental emissions at St. Louis (Gatz, 1974). Two technique

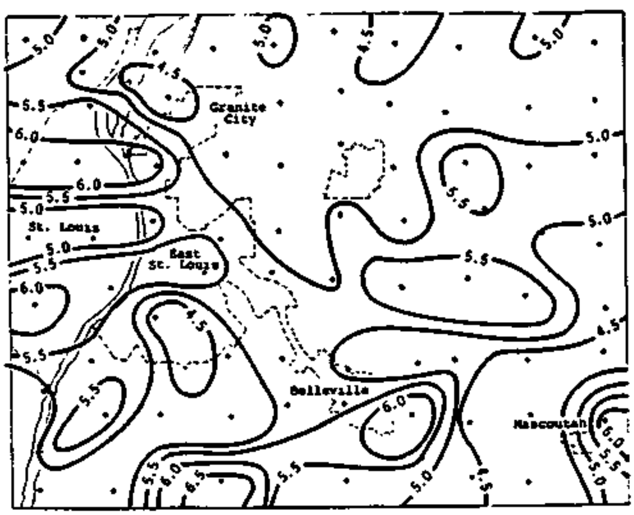

Figure 9-5. The mean pH values in the St. Louis area based on 14 rain events during 1972, showing considerable spatial variability.

papers were published: one describing a new method for estimating source coefficients of pollutants (Gatz, 1975c), and the other the use of scavenging ratios to estimate wet deposition (Gatz, 1975d). Semonin (1976) analyzed the pH found in convective storm rainfall at St. Louis, finding great variability (fig. 9-5). Gatz (1977) reviewed the results of the tracer experiments at St. Louis and elsewhere, and he used a factor analysis technique to identify aerosol sources at St. Louis (Gatz, 1978). Gatz had previously analyzed the sources of urban aerosols at Chicago using a special method (Gatz, 1975a), and had further estimated the deposition of pollutant aerosols into Lake Michigan (Gatz, 1975b). The relationship between the strength of the pollutant sources at St. Louis and the amount of rainfall was investigated (Gatz, 1978) and the results showed that there was no relationship between the aerosols and the urban rain anomaly. Semonin and Stensland (1977) had analyzed individual rain events at St. Louis to detect the effects of the urban pollutants on the local precipitation chemistry. Gatz (1980) summarized many of the project findings about the spatial distribution of chemical constituents found in rainwater. A subsequent post-METROMEX project examined the presence of urban pollutants in the soils in and beyond St. Louis (Gatz et al., 1981)

Laboratory Studies under AEC Contract (11-1)-1199

Laboratory research in atmospheric chemistry under the AEC-supported program began in 1970 with a study that involved the experimental determination of the collection efficiencies of falling drops as a function of their size and electrical charge. Such information is pertinent to understanding the characteristics of convective rainfall with respect to the removal of aerosols by rain processes. Funding allowed the development of an excellent atmospheric chemistry laboratory facility at the Water Survey, and laboratory studies on various aspects of precipitation chemistry continued through the early and middle 1970s (Peden and Skowron, 1978). These studies provided new information on the subject. Results were discussed in detail in the contract reports (Semonin et al., 1977), and summarized in several papers presented at conferences and meetings.

A Change in Direction

In 1977, the Department of Energy (DOE), which administered former contract AEC (11-1)-1199 after the AEC was eliminated in a federal organizational change, was developing new programmatic trends that differed from those relating to tracers. DOE informed the Water Survey that they would no longer support field data collection and laboratory research, but they were still interested in results developed from analyses of past data obtained under the contract. This meant loss of support for operation of the extensive atmospheric chemistry laboratory facilities developed by the Survey during 1971-1977. Sustaining laboratory operations at existing levels would require an estimated $100,000 annually.

However, a new option that could diminish the effects of the DOE action surfaced. In 1976, Semonin was invited to participate in the first international conference on acid rain, and there he presented maps of rain pH from METROMEX. These illustrated the strong natural variability. At the conclusion of this conference, several panels were created to assess the research needs for national acid rain program. Semonin was appointed to the panel on monitoring and analysis, and after several ensduing meetings, the group gathered at the National Academy of Sciences in 1977. A sampling device was chosen for a national network, program names were proposed, and discussions began on selecting a laboratory for the analyses of the rain samples from the soon-to-emerge national network. The name finally chosen for the monitoring and analysis activities was the National Atmospheric Deposition Program (NADP). In addition to seeking locations for the samplers, the panel opened competition for operating a "Central Analytical Laboratory" (CAL). Its efforts would be based on multi-agency funding sent through a coordinator's office at U.S. Department of Agriculture (USDA) to Colorado State University and then to the laboratory operator. The Survey entered the national competition to become the nation's laboratory, and was declared the winner in 1978. As a result, the analytical chemistry program received a strong financial boost with funds becoming available for procuring additional laboratory equipment and personnel to carry out the large analytical operations.

Peden was appointed supervisor of the CAL operations (fig. 9-9). One of the major goals of the NADP project was to provide long-term precipitation chemistry monitoring across the entire United States. In October 1978, there were 11 sites operating in the NADP. By spring 1980, there were 45 sites in operation and growth was continuing. By 1980, the NADP data were already being widely used by the scientific community. For example, data from four sites in Illinois were used to assess the problem of acid precipitation in the state. The NADP data would prove very useful in evaluating the location, intensity, areal extent, and other properties of acid precipitation across the United States (fig. 9-6). By 1981, analytical interpretations of the network data were appearing (Bowersox and Stensland, 1981).

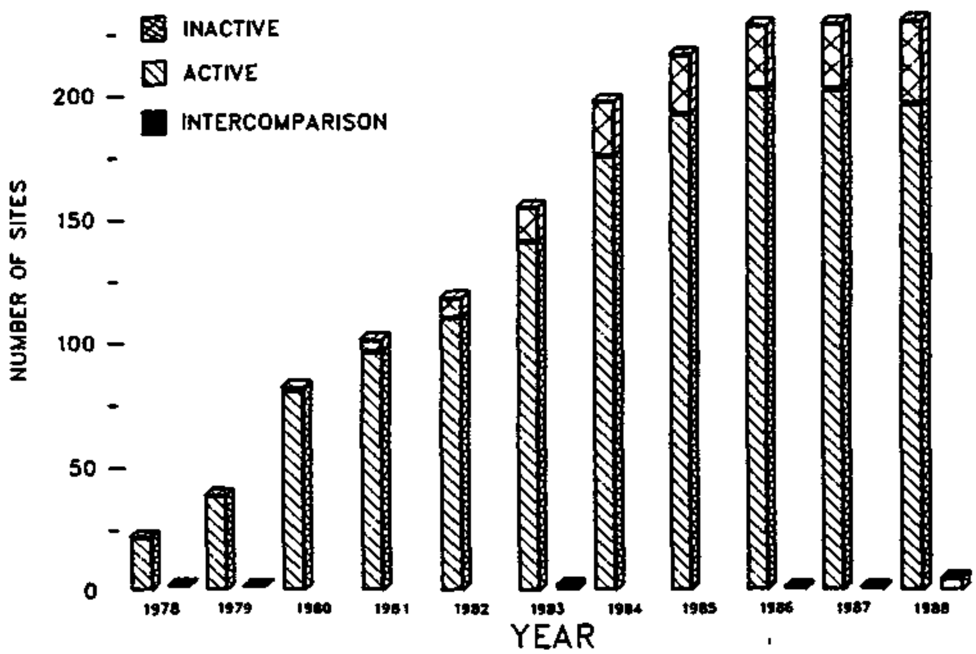

Figure 9-6. The number of NADP/NTN precipitation chemistry sites in the United States between 1978 and 1988. The Survey's laboratory analyzed the samples from all these sites.

An important aspect of operating this nationally visible laboratory was the development and maintenance of quality analytical techniques, an objective that led to several publications reporting on various techniques for sample monitoring, quality assurance in the laboratory, and data validation (Stensland et al., 1983; Peden, 1984; Stensland, 1984; Stensland and Bowersox, 1984a and 1984b; Bowersox, 1984; Gatz and Smith, 1984; Bigelow et al., 1984, Keller and Peden, 1984; Dolske and Gatz, 1985; Bachman and Peden, 1987; Brennan and Peden, 1987; Gatz et al., 1988).

THE 1980s

In 1980, newly appointed Chief Changnon made substantial organizational changes in the Water Survey (see fig. 12-1). As a result, Atmospheric Chemistry became a section with an initial staff of eight people and Donald Gatz as Section Head. At the same time, all the laboratory components of the Water Survey's Atmospheric Sciences and Chemistry Sections were combined into a single group, forming the Analytical Chemistry Laboratory Unit under me direction of Mark Peden.

Relatively rapid growth achieved by me Atmospheric Chemistry Group and the growing importance of atmospheric chemistry in me field of atmospheric sciences were responsible for the establishment of me section. Acid rain had become a "hot" topic and national problem by 1980 within the scientific community, as well as in the media and in government circles. The Atmospheric Chemistry Section was already delving into this problem (Evans et al., 1981), and me research eventually brought the Survey's group recognition as one of the national leaders in this field. The Survey's 1981 Board Report included me results of a study comparing precipitation pH (acidity index) at urban and rural sites among the Survey's major accomplishments of the year. The Survey's 1982 Annual Board Report showed that the Analytical Chemistry Unit had analyzed 18,161 samples, of which 5,800 (32 percent) were for studies involving me Atmospheric Chemistry Section. Bowersox et al., (1982) assessed the sulphur dioxide content in precipitation samples and me relationship with the $S0_2$ content found in near surface air.

Much of the research during the early 1980s was directed toward providing information for assessment of acidic deposition in the United States (DOE Annual Report, September 1984). This effort required extensive data collection and analytical facilities for bom wet (precipitation)

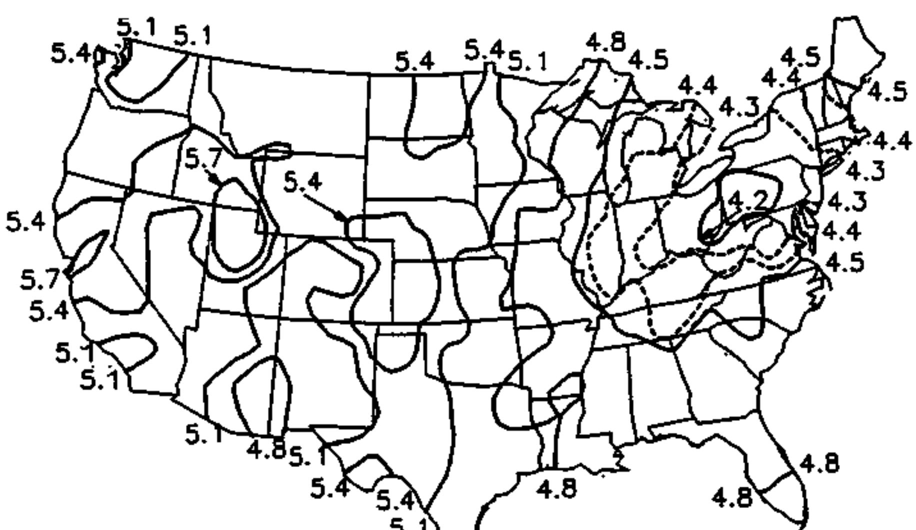

Figure 9-7. Five-year average (1983-1988) of acid rain in United States derived from NADP/NTN data, based on pH analyses conducted by Survey's atmospheric chemistry laboratory. This shows acid rainfall maximizing in the northeastern United States and lowest along the West Coast.

deposition and dry deposition, as well as interpretation and evaluation of the analytical results to provide quantitative estimates of the deposition and its relationship to atmospheric conditions and other factors leading to spatial-temporal variability in the deposition distribution (fig. 9-7). Semonin and Bowersox (1983) wrote a chapter in a book in which they assessed the patterns of various inorganic chemicals deposited in rain falling across North America and found discrete areas in the eastern half of the continent. Stensland and Semonin (1982) made a major analysis of the historic rainwater chemistry data for the United States and concluded that the drought of the 1950s skewed the early data, and that prevailing thinking about rapid upward trends in the pH of rainwater was faulty. This brought on a scientific controversy to which they responded (Stensland and Semonin, 1983a, 1983b). Semonin and Stensland (1984) also reviewed the observational problems affecting accurate determination of acid rain trends. Coincident with the acid rain focus was the study of the emission and deposition of various pollutants in Illinois, including road dust (Gatz et al., 1985). Gatz (1981) assessed rural Illinois sources of airborne calcium. Dolske and Gatz (1984) made comparisons of field measurements, and Gatz (1984) investigated and reported on the sources of rainwater impurities found in Illinois. Another area of study being addressed was the solubility of heavy metals in atmospheric deposition (Gatz et al., 1984)

This continued growth in atmospheric chemistry was illustrated in the Survey's Interim Board Report of April 30, 1984, which listed various research projects conducted under grants and contracts. Total funding for Atmospheric Sciences was in excess of $1.2 million, of which $592,000 was for operation of the CAL in conjunction with the NADP, and $275,000 from DOE for the study of atmospheric pollution scavenging. Other atmospheric chemistry research was funded by NSF, NOAA, USGS, DENR, USDA, and the National Park Service.

Extensive research programs in atmospheric chemistry continued throughout the 1980s and into the 1990s. Survey scientists provided scientific reviews of various aspects of the world of atmospheric chemistry, reflecting on the credibility and competence of the group. Gatz et al. (1986) reviewed the role of alkaline materials in precipitation chemistry, including the sources

Table 9-1. Time Distribution of Research Papers in Atmospheric Chemistry

Period	Journals	Proceedings	Total
1971-1975	6	2	8
1964-1970	3	4	7
1976-1980	8	3	11
1981-1985	16	14	30
1986-1990	5	27	32
1991-1994	6	14	20
Total	44	64	108

of wet and dry deposition. Semonin (1987) made a critical review of a book on trends in acid deposition in the *Bulletin of the American Meteorological Society.* Bowersox et al. (1990) took a broad perspective on the global implications of the findings on pollutants in rain, including acid rain, in the United States, which showed downward trends in calcium, sulfates, and hydrogen ions for 1979-1986. Sisterson et al. (1994) reviewed the spatial and temporal trends of various chemicals found in rainwater across North America.

One measure of the relatively rapid growth of the atmospheric chemistry program is the increase in the number of atmospheric chemistry papers published over time (table 9-1). The publications have been divided into two groups, papers appearing in professional journals (or as part of a book), and papers in the proceedings of conferences and symposiums. The table does not include the numerous annual reports and research reports submitted to funding agencies.

THE EARLY 1990s

Table 9-2, which was abstracted from a 1991 Survey report, summarizes activities of the Atmospheric Chemistry Section during the 1989-1991 period. It also identifies project leaders, topic, funding source, and duration of each of the 23 projects. Don Gatz had long been involved in studies relating to the deposition of pollutants into the Great Lakes (Gatz, 1975a, 1975b), pioneering research that helped lead to funding in the late 1980s for new investigations addressing the atmospheric chemistry of the Great Lakes. Gatz et al. (1989) discussed the lead and cadmium loadings in precipitation falling on the Great Lakes using data from the GLAD Network of 1982-1983. They found amounts less than those from earlier estimates. A sizable

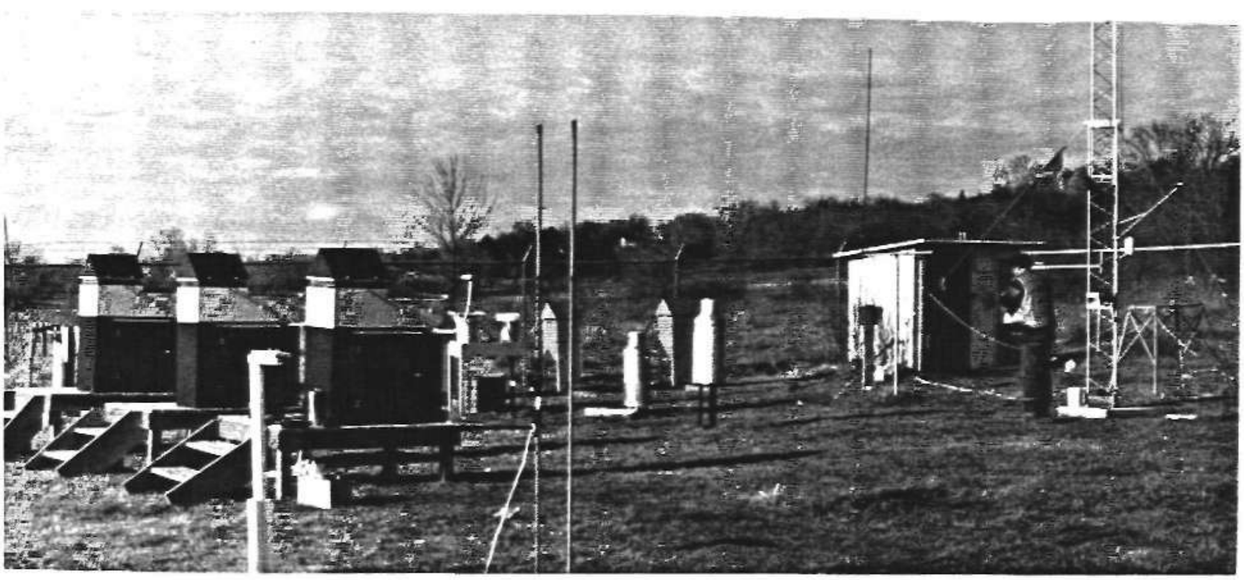

Figure 9-8. The Survey's various air chemistry samplers at Green Bay, WI site. Clyde Sweet, one of the directors of the project to sample air toxics on the Great Lakes area, is near the data shed. The three large box-like instruments on the left are wet-only precipitation collectors (for organic compounds); to their right is a wet-dry sampler; a high-volume sampler (for organic particles and vapor), a data shed, and a tower with instruments to measure winds, temperature, humidity, and solar radiation.

USEPA sponsored project (table 9-2) for study of air toxics deposited in the Great Lakes was initiated with sampling sites installed and operated by Survey scientists and technicians. One of the sampling sites for the air toxics deposition on the Great Lakes project (fig. 9-8) shows Clyde Sweet at the Green Bay, WI location. Sweet et al. (1993) reported on their findings about PCBs deposited into Green Bay.

The projects in Table 9-2 reflect the environmental subjects in which the Survey has had interest and expertise in recent years. Annual support for the atmospheric chemistry research and analysis had expanded to $3.3 million by 1991. Projects 1, 2, and 19 each had annual budgets of about $800,000. Total atmospheric chemistry staff in 1991 included 18 scientists, four technicians, and seven students, which represents considerable growth in a program that started with an initial annual grant of $50,000 in 1962 and a staff of six people. The atmospheric chemistry program had grown so large that when another organizational change in the Water Survey occurred in 1992, the Atmospheric Sciences Section was subdivided into two offices: the Office of Precipitation Quality under Van Bowersox (fig. 9-9) and the Office of Air Quality under Donald Gatz (fig. 9-9).

SUMMARY

Major Achievements

Most major achievements in atmospheric chemistry have developed within three general types of studies: A) *precipitation chemistry* with special emphasis on acid rainfall; B) collection, analyses, and archiving of large amounts *of atmospheric chemistry data* that serve a wide range of scientific needs; and C) *pollutant* sources, emissions, and atmospheric concentrations.

Precipitation Chemistry. Important investigations included trends in atmospheric chemistry and Be and metal solubilities in precipitation. Studies also assessed the role of alkaline dust in acid rain neutralization, development of optimum methods to express mean precipitation acidity, clarification of the effects of acidic precipitation on soils, and the measurement of scavenging ratios of base cations and metals.

Atmospheric Chemistry Data. National and international atmospheric deposition databases were developed. Significant aspects of these projects were the development of quality assurance methods for atmospheric deposition analysis and chemical measurement methods for precipitation.

Pollutants. Among this group were important studies such as estimation of alkaline dust emission fluxes for soils and unpaved roads, measurement of the concentrations of agricultural chemicals in the atmosphere, demonstration of the utility of air pollution source apportionment methods, and the measurement of atmospheric fluxes of toxic pollutants to and from the Great Lakes.

Table 9-2. On-going and Recently Completed Projects in the Atmospheric Chemistry Program

Project Leaders	Topic	Funding Source	Duration
Precipitation Chemistry Studies			
1. Bowersox/Stensland/ Peden	National Acid Rain Laboratory	NOAA, USDA, USGS, NPS, BLM, etc.	15 years (ongoing)
2. Gatz/Sweet	Air Toxics Deposition to the Great Lakes	USEPA	5 years (ongoing)
3. Stensland	Study of Elevation Effects on Wet Deposition in the Rocky Mountains	USFS	~7 years (ongoing)
4. Bowersox	Precipitation Chemistry Interlaboratory Comparison Study	USGS	~10 years (ongoing)
5. Gatz	Evaluation of Urban Precipitation Chemistry Data	NPS	~2 years (ended)
6. Bowersox/Stensland/ Song	Evaluations of Patterns and Trends in NADP/NTN Precipitation Chemistry Data	DOE and ILL-GRF	~15 years (ongoing
7. Bowersox/Stensland	Comparison of Alternative Sampling Methods for NADP/NTN sites	NADP/NTN and ILL-GRF	~4 years (ongoing)
8. Vermette	A Metals Precipitation Chemistry Pilot Network	USGS	~2 years (ended)
9. Peden et al.	Inorganic Chemistry and Acidity Methods Development	NADP/NTN and EPA	~10 years (ongoing)
10. Peden et al.	Trace Metal Methods Development	EPA	~10 years (ended)
Air Quality Studies			
11. Sweet/Vermette	Toxic VOCs and Trace Metals in Air in Illinois Urban Areas	IL-HWRIC	~5 years (ended)
12. Stensland/Dolske/ Bowersox	Long-Term Monitoring of Wet and Dry Deposition at a Rural Illinois Site-Bondville	DOE, EPA, and ILL-GRF	~13 years (ongoing)
13. Vermette	Monitoring of Airborne PCBs and Trace Metals at a Superfund Site	IL-HWRIC	~2 years (ended)
14. Gatz	Analysis of Critical Environmental Trends for Illinois	ILL-ENR	2 years (ongoing)

15. Vermette/Sweet	Measurements of Toxic VOC Sources in Residential Indoor Air	ILL-HWRIC	2 years (ended)
Studies of Sources of Air Pollutants			
16. Stensland et al.	Characterization of Alkaline Aerosol Emissions from Unpaved Roads	NOAA and ILL-GRF	~8 years (ongoing)
17. Williams/Sweet	Atmospheric Emission and Deposition of Agricultural Pesticides	ILL-GRF	~3 years (ongoing)
18. Gatz et al.	Characterization of Atmospheric Emissions from Soil Sources	NSF	6 years (ended)
Cloud Chemistry			
19. Williams	Chemistry of Cloud Condensation Nuclei	DOE	2 years (ongoing)
20. Song/Lamb (Song's Ph.D. work)	Aerosol Scavenging by Ice Crystals in Supercooled Clouds	NSF	~5 years (ended)
Dry Deposition Projects			
21. Gatz/Dolske	Intercomparison of Dry Deposition Measurement Methods	EPA	~3 years (ended)
22. Dolske	Chemical Deposition and Deterioration of Materials at National Park Service Properties	National Park Service	10 years (ongoing)
Aquatic and Terrestrial Effects			
23. Krug	Causes of Lake Acidification	DOE	~5 years (ended)

Additional Studies. Other lesser studies have achieved considerable scientific value. These included the measurement of toxic pollutants concentrations in urban air (mostly Chicago), measurement of the chemical composition of cloud condensation nuclei, clarification the role of air pollutants in ice formation in the stratosphere and upper troposphere, documentation of time trends in air quality and atmospheric deposition in Illinois, and measurement of dry deposition fluxes. Initial research on rainout of radioactivity from the atmosphere established the base for later growth and expansion of atmospheric chemistry at the Water Survey.

Major Projects

Four major project areas have led to the continued growth and recognition of the atmospheric chemistry program at the Water Survey. First, there was the AEC-supported project in the 1960s related to rainout of radioactivity from nuclear tests. This project led to establishment of the first atmospheric chemistry unit in the Survey. The success of this undertaking provided the initial recognition for the Survey in this field, and helped gain support for continuation of the program afterthe radioactive rainout program ended in the late 1960s.

The next major project involved studies associated with the large-scale METROMEX research program on inadvertent weather modification in the early 1970s. These studies provided substantial new information on various aspects of wet and dry fallout under different atmospheric weather conditions. They paved the way for much of the atmospheric research during the late 1970s to early 1990s.

Acid rainfall studies initiated in the early to mid-1970s led to recognition and acknowledged expertise on this very important subject that dominated activities in the atmospheric chemistry field in the 1970s-1990s. Establishment of the Survey's facilities and expertise in acid precipitation promoted substantial financial support in the form of grants and contracts from Federal agencies.

Establishment of an analytical chemistry laboratory for atmospheric chemistry in the early 1970s proved to be a very important addition to the research activities. Successful operation of this laboratory was a key factor in the Survey winning the national competition for operation of a Central Analytical Laboratory with multi-agency funding in conjunction with the National Atmospheric Deposition Program. This operation has provided a large amount of funding for laboratory operations and it also stimulated the award of large amounts of research funds for various studies of atmospheric pollution scavenging.

Key Papers and Reports

Precipitation chemistry studies included major contributions by Stensland and Semonin (1982), Summers et al. (1986), Stensland et al., (1986), Sisterson et al. (1994), Bowersox et al. (1990), and Lynch et al. (1995) that provided new information relative to spatial and time trends in precipitation composition. Gatz and Chu (1986) and Brown et al. (1989) contributed significantly to the knowledge of metal solubility in precipitation. Gatz (1984), Gatz et al.

(1986), and Gillette et al. (1992) contributed to clarification of the role of alkaline dust in acid rain neutralizations. New information regarding optimum methods for expressing mean precipitation acidity was provided by Stensland and Bowersox (1984), Stensland et al. (1993), Gatz and Smith (1994a, 1994b). Contributions for clarifying mechanisms of acidic precipitation effects on soils were made by Krug et al. 1985), Krug (1989), and Krug and Lefohn (1990). An important paper by Gatz (1975c) dealt with the measurement of ratios of base cations and metals.

Atmospheric chemistry studies included reports by Stensland (1984), Sisterson et al. (1990), and Bowersox (1995), all important contributions to the development of national and international databases for atmospheric deposition. Several contributions were made to the development of quality assurance methods for atmospheric deposition and included papers by Peden and Skowron (1978), Bowersox (1984), Stensland and Bowersox (1984), Bigelow et al. (1984), and Gatz et al. (1988). Bachman and Peden (1987) and Brennan and Peden (1987) contributed to the development of chemical measurement methods for precipitation.

The pollutant studies included key papers by Barnard et al. (1986) and Gillette et al. (1992), and provided information on estimation of alkaline dust emission fluxes for soils and unpaved roads. Similarly, Williams et al. (1992) provided important information on the concentration of agricultural chemicals in the atmosphere. Gatz (1975, 1978, and 1984) demonstrated the utility of air pollution source apportionment methods. Sweet et al. (1993), Hoff et al. (1994) and Hornbuckle et al. (1995) provided useful information on the measurement of atmospheric fluxes of toxic pollutants to and from the Great Lakes.

Staff

From 1962 to 1996, the total number of staff involved in one or more projects in some type of atmospheric chemistry endeavor is too large to acknowledge adequately. Individuals who contributed significantly in the early years of the atmospheric chemistry program (1962-1970) included Glenn Stout (Program Director), Floyd Huff (Principal Investigator), Ken Wilk and Doug Jones (radar meteorologists), Rena Gans (chemist), and Dick Boyd and Ron Tibbets (technicians).

During the latter part of this period, Wayne Bradley, John Wilson, Peter Feteris, and Gordon Martin became involved in meteorological studies related to the radioactive rainout problem.

Major changes occurred in the program during the 1970s. Active participants during this period included Dick Semonin (program director), Don Gatz, Mark Peden, Gary Stensland, Van Bowersox, Tony Rattonetti, Bob Cataneo, Jack Adam, Florence McGurk, and Loretta Skowron.

Since 1981, many of the same people (Gatz, Peden, and Stensland) continued to be active in the research and services program. Newcomers included Don Dolske, Allen Williams, Clyde Sweet, Steve Vermette, and Bill Barnard.

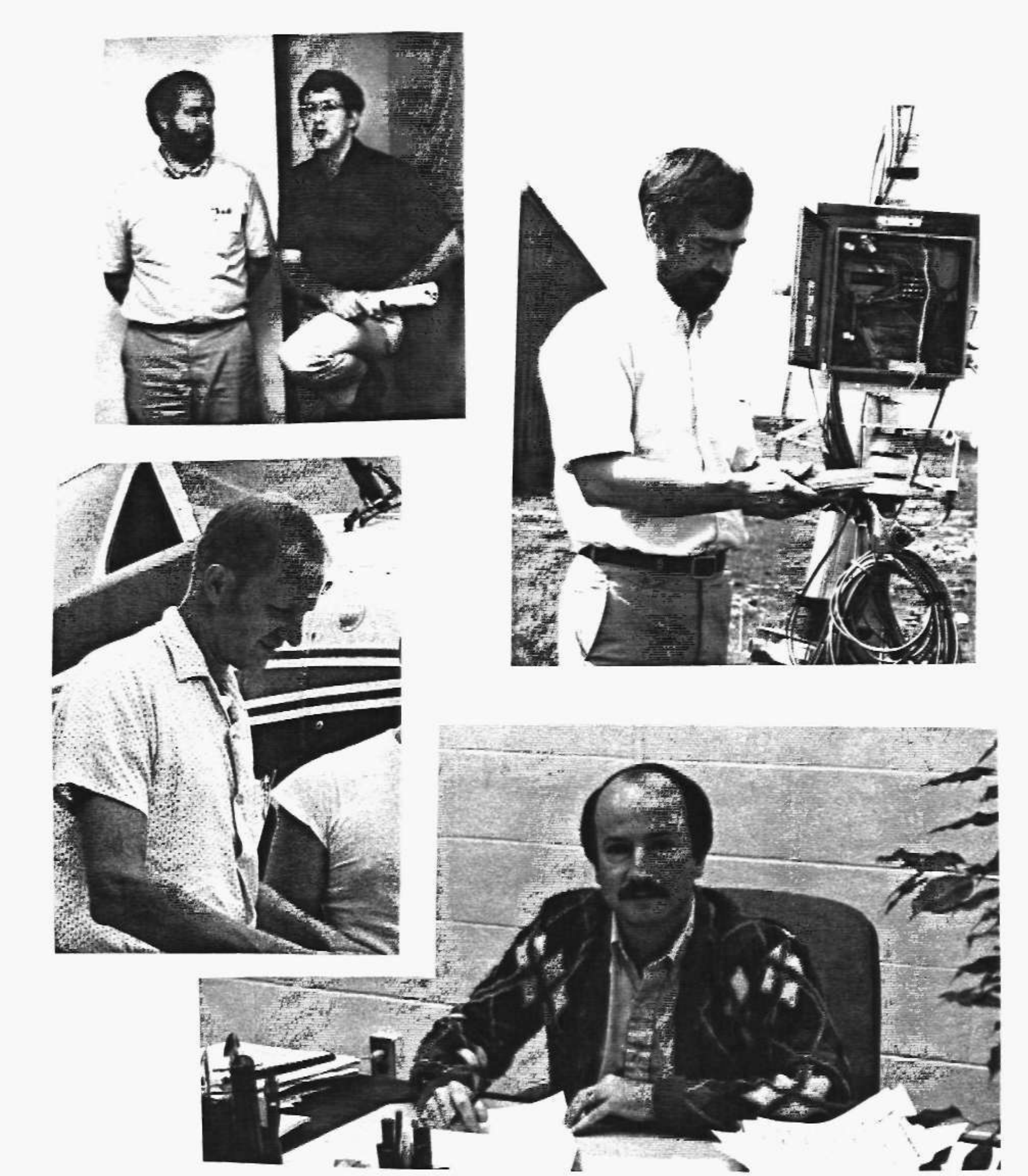

Figure 9-9. Several key scientists in the atmospheric chemistry program. In the upper left is Gary Stensland, once Atmospheric Chemistry Section head and now Atmospheric Sciences Division head, and Van Bowersox (office head). In the upper right is Al Williams seen working on field equipment. Don Gatz (middle left) has served as section head and now office head and is seen at a pilot's briefing in 1972. Mark Peden (lower photo) directed the Central Analytical Laboratory and is now division head for chemistry at the Water Survey.

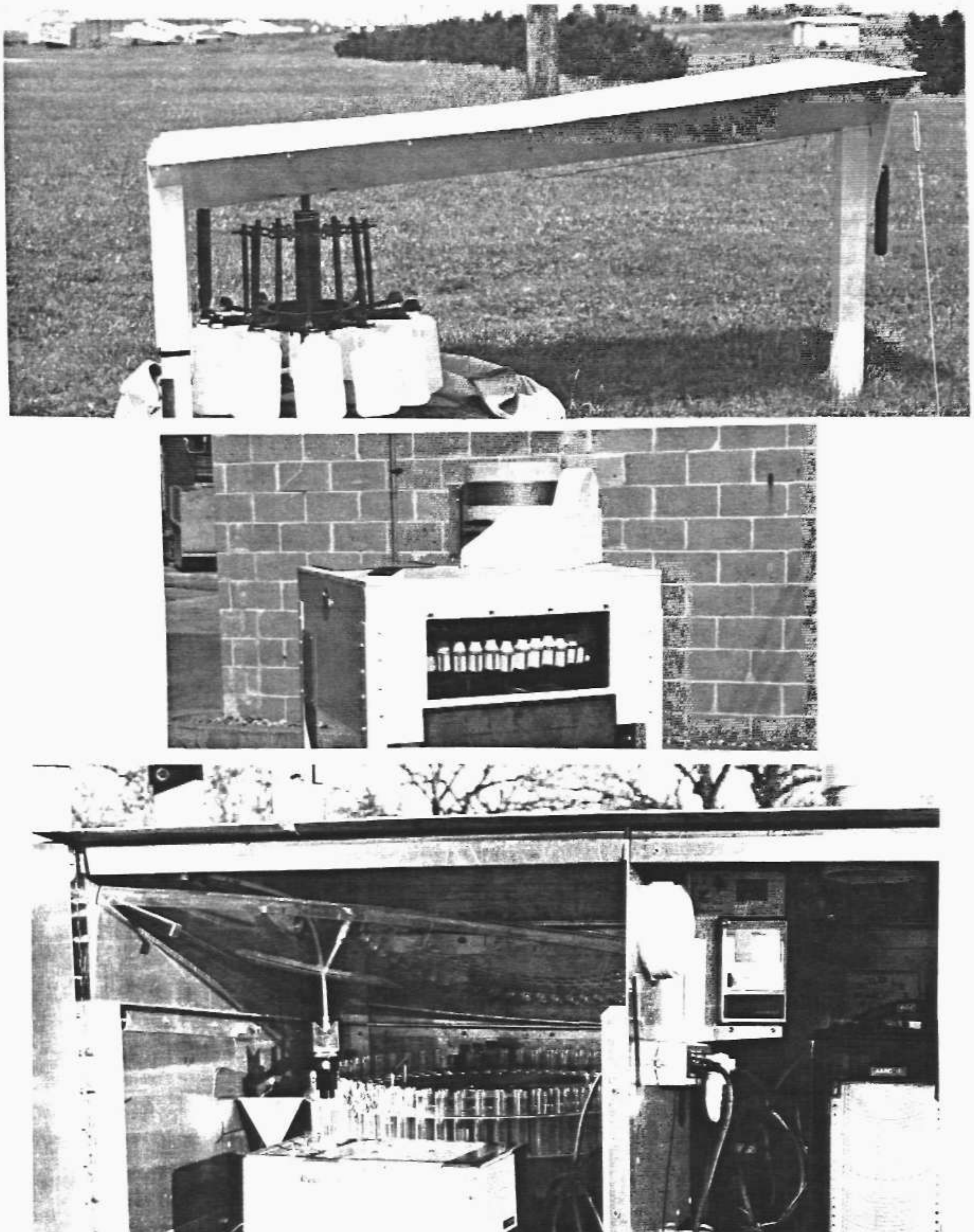

Figure 9-10. Water Survey scientists and technicians developed a series of sequential rainwater samplers over a 30-year period to measure how rainwater impurities shifted during a rain storm. Top is the first sampler, designed to be field operated with pulleys. Later models (below) operated with electrical power and employed smaller sampler bottles.

Chapter 10

IMPACTS OF WEATHER AND CLIMATE

Stanley A. Changnon

INTRODUCTION

Most research conducted by the Atmospheric Sciences Group at the Illinois State Water Survey falls under the classification of *applied research* rather than *basic research*. That is, the research focused on solving problems defined either by the staff or external funding sources. Nevertheless, analysis of the major areas of research and services in atmospheric sciences reveals many studies were directed at *understanding the relationships of weather and/or climate conditions and those of some other sector such as water management. Many of these studies also defined the effects, or impacts, of weather and/or climate conditions on human activities, the hydro-biological system, or the economy*. These impact studies ultimately included a wide range of atmospheric effects on agriculture, water resources, engineering design, government policy, economics, and human behavior. These types of studies are illustrated in figure 10-1 which was developed using titles of selected publications dealing with the impacts and relationships of weather and climate, and the application of this information for solving problems. This chapter addresses impacts and applications but does not include the effects of one atmospheric condition on another such as the relationship between temperatures and humidity or rainfall. Studies of such atmospheric interactions are described within the chapters devoted to the other major program areas (Chapters 3-9).

The research defined as being "impacts and applications" oriented began later than the other major atmospheric program areas of the Water Survey. In many respects, impacts research was launched due to growing awareness, during the late 1960s and 1970s, that federal and state attention to funding and support of atmospheric research was becoming more difficult to obtain, as it was in many of the sciences. To address this concern, the Water Survey needed definitive studies of the economic and environmental importance of weather and climate information developed through research. The impact-application research of the Water Survey was also driven in the case of weather modification by awareness that experimental and operational cloud seeding projects conducted elsewhere in the nation during the 1960s had been stopped or heavily criticized as not having considered the environmental, legal, economic, and policy issues that changed weather raised in the public and political circles.

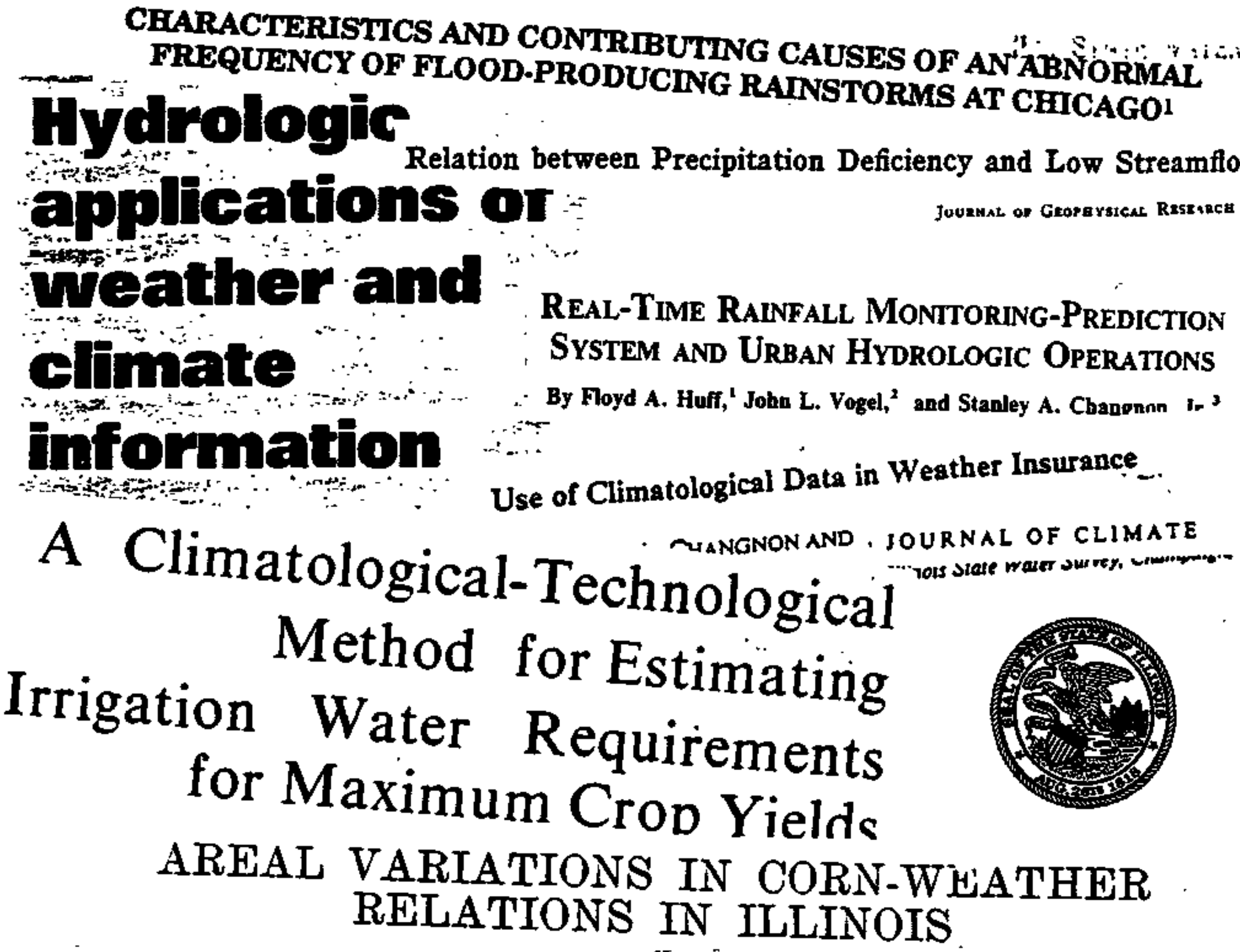

Figure 10-1. Titles of selected Water Survey publications dealing with impacts of weather/climate.

The first impact-focused efforts developed in 1963 as the result of exploratory research into how climatological droughts (defined on the basis of deficient precipitation) lowered streamflows and water supplies in Illinois (Huff and Changnon, 1964b). Simultaneously, an invitation from the Building Research Institute in 1963 led to a climatic study to describe the frequency of rain and wind conditions that affected weatherproofing of buildings (Changnon, 1964e). Both of these early studies won awards for their scientific excellence. By 1970, the Water Survey's impacts research effort had grown significantly largely as a result of the Survey's weather modification projects.

The number of impact-oriented publications issued by the Survey are summarized in Table 1, and these values show a slow but steady volume of publications from 1963 to 1977. A rapid increase in publications occurred after 1977, reaching a peak of 41 publications in the three-year period ending in 1989. Research in several theme areas maximized in the late 1980s. Since then the impact research has declined due to changes in staff. The following discussion explains the reasons behind these fluctuations in publications, a good reflection of the amount of research attention given to the impacts of weather and climate.

Table 10-1. The Number of Publications on Impacts of Weather and Climate Conditions and Applications Research Prepared by Atmospheric Scientists of the Water Survey

		Reports		
Years	*Papers*	*State series*	*Contract*	*Total*
1963-1965	3	0	1	4
1966-1968	3	0	1	4
1969-1971	2	0	3	5
1972-1974	3	0	3	6
1975-1977	4	0	4	8
1978-1980	10	1	2	13
1981-1983	9	2	1	12
1984-1986	7	2	0	9
1987-1989	33	3	5	41
1990-1992	17	3	0	20
1993-1995	12	1	0	13

Six distinct themes emerged, and each consisted of research that persisted for many years. Three themes emanated from other major research areas including 1) planned weather modification (Chapter 6), 2) inadvertent weather modification and climate change (Chapter 7); and 3) climate research and services (Chapter 5). In this historical review, the research devoted to relationship analyses and impacts were separated from these three fields and are described in this chapter.

The earliest and longest lasting impact research theme related to the need to define the *effects of possible changes in the weather due to cloud seeding,* either to make rain or to suppress hail. We pursued studies of how weather modification would alter agricultural production, change the economy, influence the hydrologic cycle, affect public attitudes, and how weather modification research and use were influenced by state and federal policies.

Survey investigations of inadvertent weather modification began in 1960 and these ultimately led by 1973 to *studies of the impacts of urban-altered weather and climate conditions*. This work was initiated to help justify the extensive field studies being pursued. For example, figure 10-2 shows how fluctuating precipitation in the area east of St. Louis, and some of it polluted, altered the contamination in local ground water. Consideration of the effects of a possible major change in climate led to the initiation in 1973-1974 of several studies concerning the *potential effects of climate change* (Changnon, 1975d), an area that expanded to consider effects on water resources, agricultural production, and extreme weather events.

The impact-applications research related to "climate research and services" (Chapter 5) included investigations of the *value and uses of climate information, value and applications of*

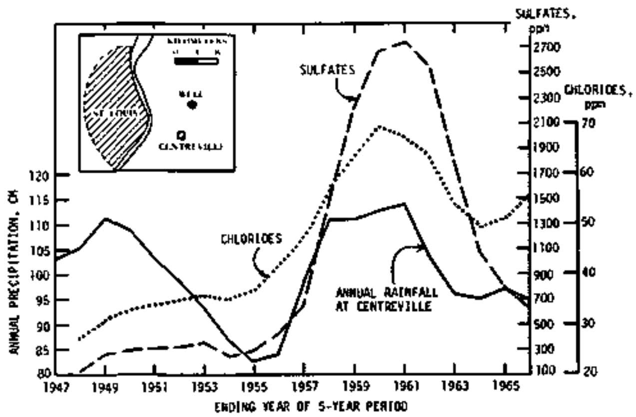

Figure 10-2. The temporal fluctuation of annual precipitation just east of St. Louis and the content of chlorides and sulfates in ground water, revealing a strong relationship between these chemicals and rainfall.

climate forecasts, and relations between climate conditions and the design of structures, human activities, biological conditions, economic conditions, and business activities. Figure 10-3 lists selected titles of Survey publications containing design-related information in the fields of hydrology, agriculture, and energy.

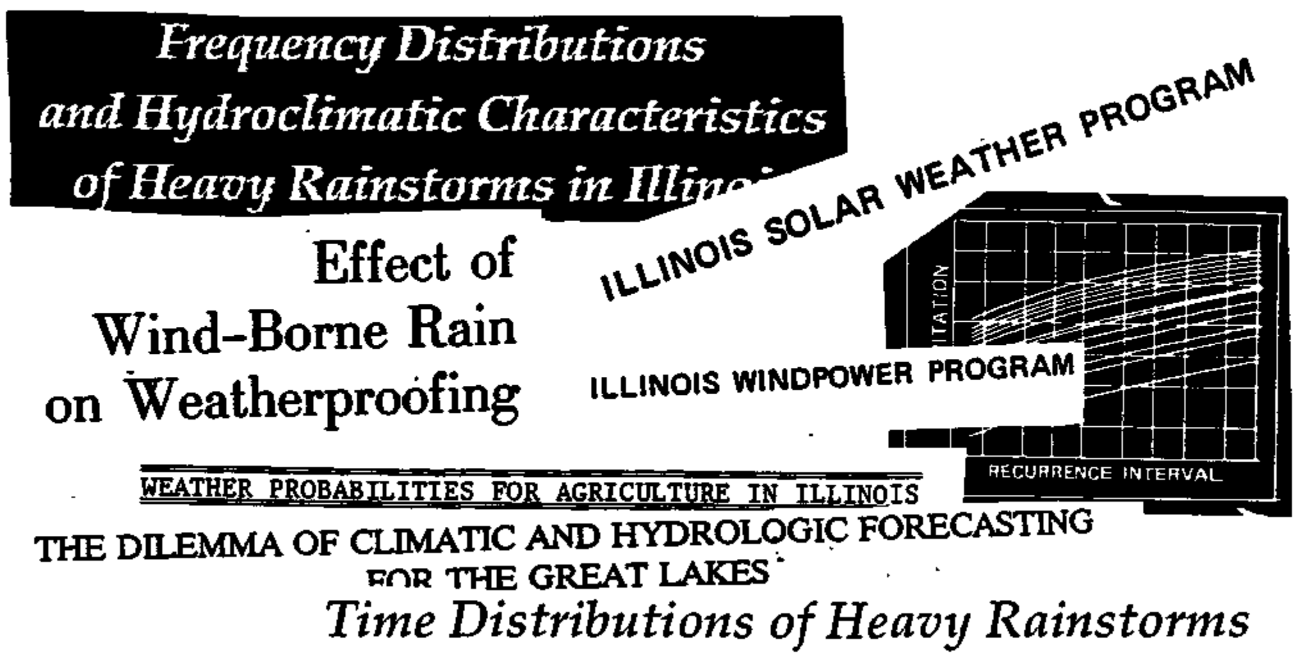

Figure 10-3. Titles of selected Water Survey publications presenting design information.

A major research theme which developed in the mid 1960s involved the *weather/climate relations with agriculture* in Illinois. This was initiated by insurance interests and funding to the Survey (Changnon, 1965b, 1967c). The research program eventually grew and by the 1980s we had a full-fledged agricultural meteorology program with staff experts. We defined in great detail the fact that the impacts of weather on Illinois agriculture were extensive and greater than in any other economic sectors of the state.

The oldest and longest lasting impact studies concerned *the effects of weather/climate conditions on the water resources in Illinois.* Subjects investigated have included droughts, floods, climate and ground water, and climate and water quality. This research was driven by Water Survey needs for information related to water supply and water quality issues in Illinois.

A final theme has been the *effects of weather/climate on local, state, and federal government policies and agencies.* Specific studies of this issue began in 1980 and continue to present. Some of this research is found under the themes of planned weather modification and climate change (see Chapters 6 and 7).

IMPACTS OF PLANNED WEATHER MODIFICATION

A conceptual approach to analyzing effects of altered precipitation in Illinois included all aspects of the hydrologic cycle, figure 10-4. Early crop yield-climate relationship statistical models for the insurance-related research (Changnon, 1965b provided the basis for investigating

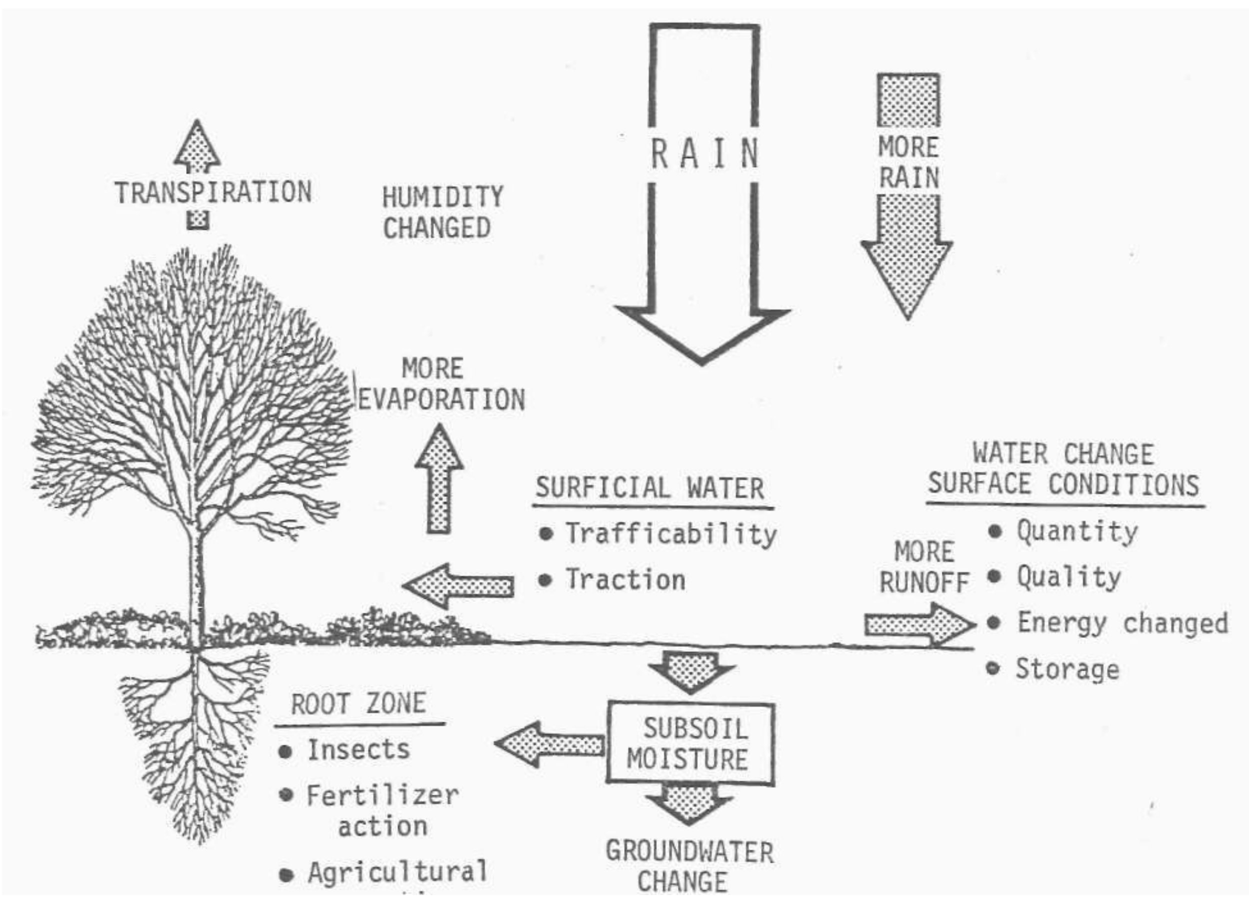

Figure 10-4. The hydrologic cycle showing how changes in rainfall permeate throughout the biosphere.

the potential effects on crop yields from increased rainfall. The possible rain increases were simulated in the regression models and used to generate yield changes (Huff and Changnon, 1972d; Changnon and Huff, 1971). This work, supported under a federal grant, was pursued for two reasons: (1) to assess the potential value of cloud seeding in humid Illinois an issue needing resolution (Changnon 1972b) and (2) to provide defensible information about the potential benefits of weather changes (see Chapter 6). This early work involved joint research with Earl Swanson, an agricultural economist at the University of Illinois. One of the results of this research is shown in figure 10-5, which reveals the probability distribution of shifts in corn yields in three state areas resulting from a 25 percent increase in summer rainfall.

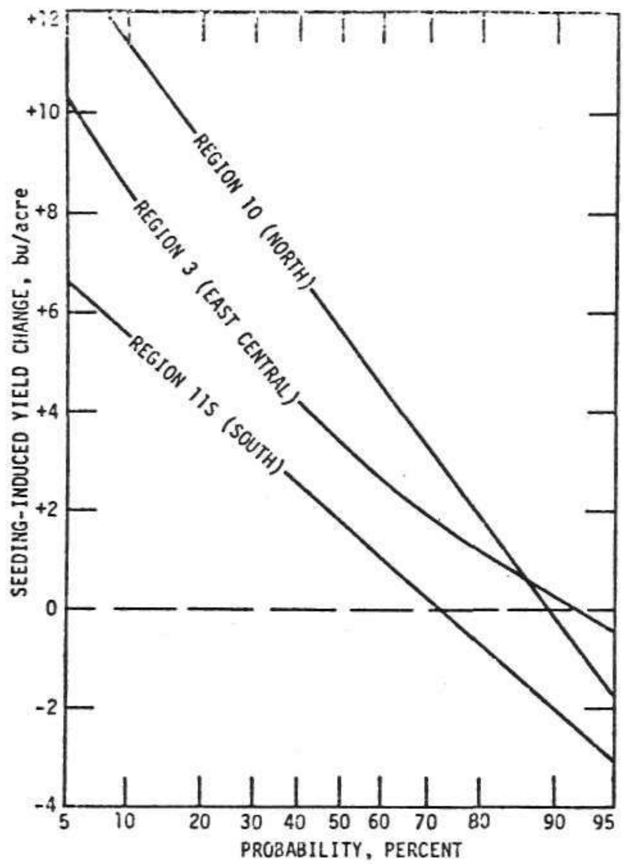

Figure 10-5. Frequency distributions for corn yield changes resulting from 25 percent increases in July-August rainfall, as tested for three soil regions in Illinois. These allow assessing the probabilities for attaining various yield increases, and for obtaining decreases in yield resulting from too much rain.

The research also considered effects of cloud seeding on water resources (Huff, 1973a), the effects of silver (used in seeding materials) on rain and water quality (Gatz, 1973d), the effects on biological conditions (Havera, 1971), and the effects on public attitudes (Haas, 1974). These investigations into the socioeconomic and environmental consequences of weather modification led to the recognition of the need for state controls of such activities. Survey leaders worked with the Illinois Farm Bureau to develop a model law for state control and regulation of weather modification in Illinois (Ackerman et al., 1974). The law, which had successfully controlled eight cloud-seeding projects conducted in Illinois during 1976-1981, survived a statewide sunset program for all regulatory laws (Changnon, 1983d). *Comprehensive assessments of all the potential environmental, legal, and economic impacts of weather modification became an area of Survey expertise.* Such assessments were done for Illinois (Changnon and Huff, 1979) and for the High Plains (Changnon, 1976g).

Many of the Illinois-based weather impact studies of the early 1970s were done for the federally funded Precipitation Enhancement Project (PEP) and moved Survey staff to the national forefront in research involving the "impacts of weather modification." By the mid-1970s, three major impact-oriented programs had been initiated at the Survey: 1) a technology assessment of hail suppression (TASH) for the United States, 2) studies related to an Illinois-based hail suppression experiment, and 3) a study of the utility of weather modification in droughts. TASH involved 23 specialists from various scientific and business sectors in what became the first major multi-disciplinary project conducted and directed by the Water Survey. This two-year, $0.5 million project was funded by the National Science Foundation (NSF), and comprehensive studies from this project were summarized in a major book (Changnon et al., 1977b), a special condensed report (Changnon et al., 1977a), and in several publications (Changnon et al., 1978b). One its major findings was the assessment showing the small national value of hail suppression. This led the federal government to terminate support of R&D of hail suppression.

The impacts expertise developed in the rain enhancement area became the basis for similar studies of the potential effects of hail suppression in Illinois (Changnon et al., 1976a). Water Survey scientists had been heavily involved in the national hail suppression research endeavors since they began in 1966, and this evolved into the design of a potential national experiment to be conducted in Illinois. An integral part of these design studies was definition of the possible impacts of hail suppression, which revealed that hail suppression would have to accomplish major reductions (>50 percent) in hail loss to be cost beneficial.

The PEP studies investigating the impacts of increased rainfall on crops and water supplies found adequate water supplies in soils and streams in many years, as revealed in figure 10-5. Importantly, the work revealed that most benefits of rain enhancement would come during dry conditions, which led to a two-year, NSF-funded project to assess the potential for cloud seeding in droughts in Illinois (Huff and Vogel, 1977b). Studies of economic benefits were also conducted (Huff, 1979c).

Survey scientists growing involvement in research about the effects of weather modification led to broad assessments of what and how to study the problem (Sonka, 1979; Changnon, 1978f, 1980c). Another study addressed how seeding-induced weather changes relate to existing federal and state laws and the legal environment (Changnon, 1979f). The social forces acting to limit the use of weather modification were also identified (Changnon, 1980i).

The earlier PEP program ended in 1974 with a loss of federal funding. This abrupt loss, which was a result of federal shifts in management of weather modification, led to an assessment of federal policies relating to weather modification (Changnon, 1975e). This developed into a continuing area of assessment. One study included a call for a stronger U.S. research effort in weather modification (Changnon, 1980c). Subsequent studies addressed the problems with the federal program and its policies (Changnon and Lambright, 1983).

With PEP's demise in 1974, there were still two other major effects on the Water Survey's research program: HIPLEX and PACE. Strong staff interests and expertise in the field of weather modification (and being temporarily unable to focus on an Illinois experiment) led the Meteorology Group to undertake (during 1975-1977) the task to design, for the Bureau of Reclamation, the High Plains Experiment (HIPLEX). Included in this project was how to conduct social, environmental, and economic monitoring and analyses in conjunction with the physical weather experiment (Ackerman et al., 1977).

A second outcome of PEP was the initiation of the Precipitation Augmentation for Crops Experiment (PACE), a new Illinois-based rain enhancement experiment with NOAA funding in 1978. The project focused on the fact that earlier studies had defined Illinois agriculture as the primary beneficiary of added summer rainfall (Swanson et al., 1972). By 1980, the "impact studies" needed for PACE had been (Changnon and Huff, 1980a).

Definitive studies of the effects of added rainfall on crops and water supplies were completed during the 1980s. Crop-weather models more sophisticated than earlier versions were developed (Garcia et al., 1985, 1987). Together, these allowed definitive economic analyses of the economic effects of changed rainfall at local, regional, state, and national scales (Garcia et al., 1988, 1989).

The most definitive test of the effects of added water on Illinois crops began with the use of the experimental plots at the University of Illinois agricultural farms. Special "rain shelters" were used to control the applications of water to corn and soybean crops (Changnon and Hollinger, 1988). Soybeans growing within one of the shelters are depicted in figure 10-6.

Figure 10-6. Soybeans growing inside a movable shelter used to control rainfall applications, 1987-1995. Different amounts of water simulating rain were disbursed using hoses seen hanging above the plants.

The climatological distributions of rain days (by date and amount) for dry, near normal, and wet summers were determined as a basis for the "control" amounts used in the water applications inside the movable shelters (Changnon, 1988c). Various types of rain changes (Hollinger and Changnon, 1988) were tested in a series of field experiments during the growing seasons of 1987 through 1995. Early results showed major yield gains from added water, particularly in the dry seasons (Changnon and Hollinger, 1990). These experiments ultimately defined the rainfall effects on all aspects of corn and soybean plants including their yields (Hollinger and Changnon 1993; Changnon and Hollinger, 1993). When the results were subjected to an economic and technological analyses, including the costs of cloud seeding to enhance rainfall, they showed that added rain was of little value except during the driest 35 percent of the growing seasons (Changnon, 1993d; Changnon and Shealy, 1993).

The PACE-related impact research also addressed effects of changed rainfall on the hydrologic cycle. A sophisticated basin model was developed and tests of the distribution of added water simulating cloud-seeding increases showed most of it was consumed in the evaporative process with little appearing as streamflow (Durgunoglu et al., 1987, 1988).

IMPACTS OF INADVERTENT WEATHER MODIFICATION AND CLIMATE CHANGE

Environmental concerns sprang up across the nation during the 1960s. One result was the development of major studies of inadvertent weather modification due to cities and other localized or regional land-use changes. The 1970s also ushered in a growing concern that human activities could change the climate on a hemispheric or global scale. Water Survey scientists were involved in both areas of study and launched impact-oriented research relating to both inadvertent localized weather changes and broader scale changes in climate.

Attention to the impacts of inadvertent weather modification began with studies of urban-generated pollutants and added rainfall on the local water resources in the St. Louis area (Schicht and Huff, 1975). A comprehensive assessment of various impacts from the St. Louis summer weather anomalies appeared in a major presentation of METROMEX findings (Changnon, 1977f). Urban-enhanced rainfall and storminess brought mixed effects, increasing crop yields, but detrimentally affecting transportation. Studies also encompassed the effects of altered weather at St. Louis on crop insurance, drainage, and local commerce (Changnon, 1980h) and on soil quality (Gatz, 1980). Of particular importance were the regional increases in heavy rain events (fig. 10-7) which affected erosion and flooding. Visibility shifts related to urban influences at St. Louis were also studied and showed that visibilities were often reduced 50 to 75 miles downwind of the city (Changnon, 1982c). The multitude of impacts resulting from urban-altered weather in the St. Louis area were summarized in a single document (Changnon et al., 1977c).

Some of the impacts of the altered weather conditions caused by Chicago were assessed (Changnon et al., 1979c). This included investigations of crop losses due to urban-increases in hailstorms, the detrimental impacts of urban pollutants on soil quality, and the effects of added

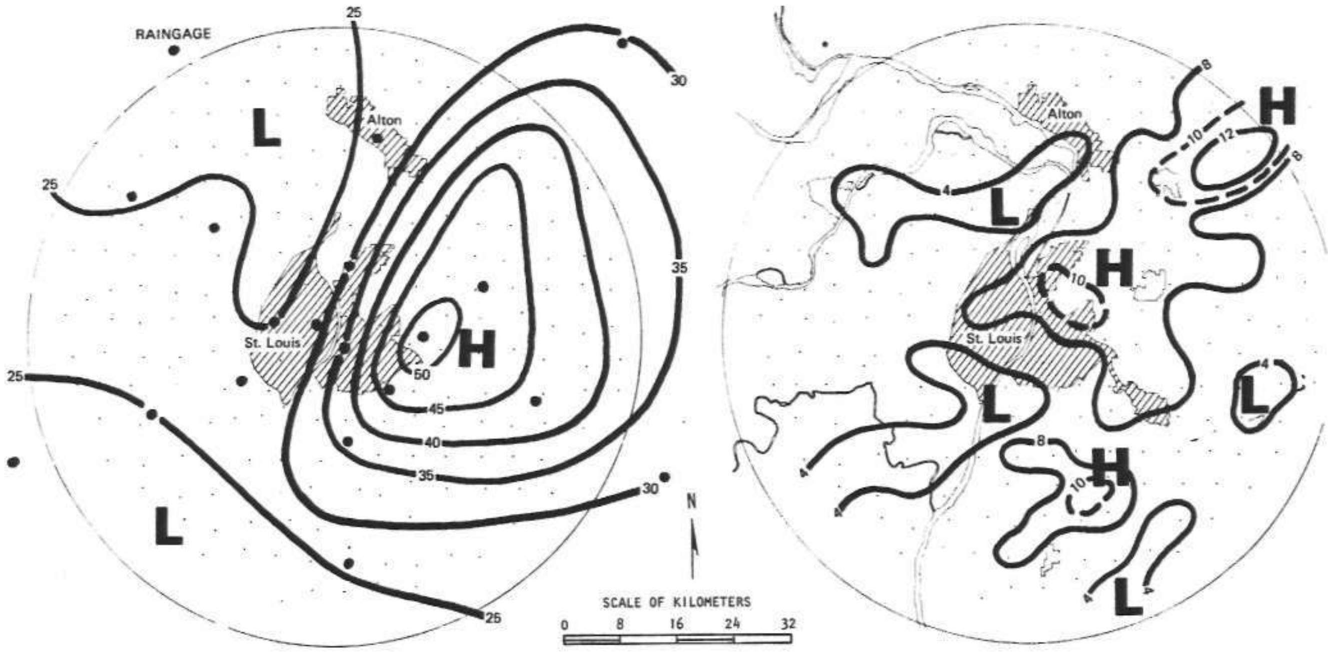

Figure 10-7. The METROMEX research and the preceding climatic studies discovered that the urban influence on summer precipitation formation led to sizable increases in heavy rains causing local flooding, traffic problems, and soil erosion. The left pattern is the number of 2-inch rains during 1951-1970, and the right pattern is from METROMEX showing the number of 1-inch or heavier rains during the project's first three years, 1971-1973.

rainfall on utilities and urban transportation. The influence of a greater number of locally enhanced heavy rainfall events at Chicago (due to urban and lake influences) on local flooding was also investigated. It was found to be a major factor in the frequent local flooding that occurs in Chicago (Changnon, 1982d). The knowledge gained from studies of impacts of urban-altered rain and hail was used as guidance for planning how to conduct weather modification projects (Changnon, 1980g).

Research into the effects of climate change began with a probing study of agricultural impacts (Changnon, 1974d). This was followed by a similar probing study of potential effects of climate change on water resources (Changnon, 1977g). Further studies of impacts of climate change were resumed in the 1980s. A 1983 study assessed shifts in heavy rains and their effects on flood frequencies in Illinois (Changnon, 1983b). As shown in figure 10-8, the frequency of floods in Illinois has steadily increased since 1940, and this shift has been matched by a prolonged period of ever increasing heavy rain (>2.0 inches) events. Changnon and Huff (1987b) explored the effects of a changed climate on design rainfall frequencies in Illinois. Changnon (1987e) investigated the range of possible effects of climate change on the levels of Lake Michigan. This information was used to assess the impacts of the lake on the Illinois shoreline and harbors (Changnon, 1988d).

The research into the effects of climate change rapidly expanded to address effects on agricultural production (Easterling, 1989; Easterling and Changnon, 1993; Hollinger et al., 1994); effects on water resources (Changnon, 1989a); effects on droughts and floods (Changnon and Huff, 1988; Changnon, 1993c); on forests (Angel et al., 1991), and on the Great Lakes'

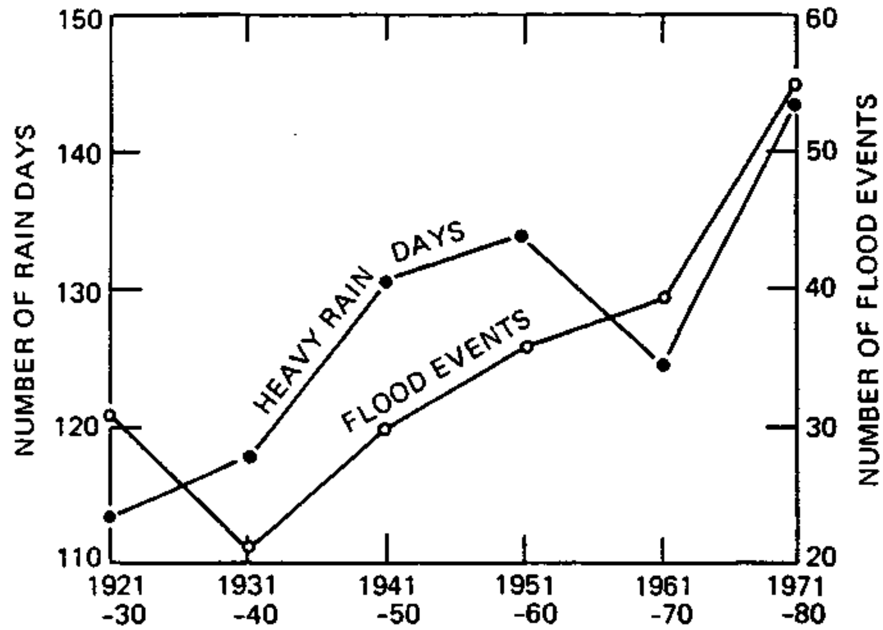

Figure 10-8. Frequency of summer heavy rain days and flood events in Illinois, showing increases since 1920.

levels (Changnon et al., 1989a; Croley et al., 1995). Changnon and Demissie (1995), as part of an assessment of how to detect climate change, compared streamflows of paired basins, one pair rural and one pair urban, and discovered that shifting land use changes since 1940 caused 70 percent of the increases in mean and extreme flows whereas the steady increase in precipitation since 1940 caused 30 percent of the flow increases. Special studies have addressed a range of possible impacts from climate change on the Great Lakes basin (Changnon, 1989h). Past problems in the Great Lakes basin caused by atmospheric and hydrospheric extremes that are potentially more common under a changed climate were identified (Changnon, 1989b). Another study focused on the economic impacts that climate change could create for investors (Changnon, 1989d).

Considerable attention has been given to the impacts of climate change on Chicago. This included investigations of the major detrimental effects of lowered lake levels on the Chicago area and the diversion system (Changnon, 1993a), and of changes in rainfall on the urban transportation systems (Changnon, 1995a). The responses of the Toronto city government and Chicago's to the climate change issue were assessed and contrasted showing Toronto has moved farther in adopting climate change mitigation activities (Lambright and Changnon, 1995). The potential effects of climate change on the crop insurance industry were analyzed (Fosse and Changnon, 1993). The development of state policies for dealing with climate change were addressed in several studies (Changnon and Lamb, 1986; Changnon and Semonin, 1982; and Changnon, 1995b). Changnon and Wendland (1994) summarized numerous Water Survey studies of the impacts and adjustments to climate change.

CLIMATE IMPACTS

Impact research emanating from the Survey's long-running climate research program (see Chapter 5) began in 1970. The initial studies included derivation of design information for winter storms (Changnon, 1971f). How severe winter conditions affect human beings economically and socially were surveyed (Changnon, 1979g). The economic losses resulting from hail in Illinois and elsewhere across the United States were analyzed (Changnon, 1971i).

The climate impact research was enhanced beginning in 1980 as the Survey began to expand its climate services program. We sought to understand more fully who the customers of climate information were and what products they wanted. Such "marketing" studies began even earlier with a 1979 analysis of the Survey's climate services (Changnon, 1979b). A major 1980-1981 study examined the uses of climate information by the nation's agribusiness sector (Lamb et al., 1981), and a similar study examined hydrologist's use of climate information (Changnon, 1981d). How the hail insurance industry employed climate information was documented (Changnon and Fosse, 1981). The values of near-realtime climate information for many Illinois and Midwestern users of information led to the development of two computer-based systems at the Water Survey, and Kunkel (1987) assessed the uses and values of these easy and quick access data systems.

The user assessment research broadened and focused on the use and value of long-range climate forecasts with special emphasis on benefits to agriculture (Sonka et al., 1982). A case study examined the benefits of using climate forecasts to solve an Illinois water management problem during a drought (Changnon and Vonnahme, 1986). Decision experiments were performed with agribusiness to ascertain the value of using climate forecasts of limited accuracy (Changnon et al., 1988a).

The research program concerning the climate of Illinois and the Midwest (see Chapter 5) also occasionally focused on impacts of climate conditions on areas beyond water resources and agriculture (treated later as separate themes). The effects of various weather conditions on structures was a theme of several projects that examined weather factors affecting building design, as illustrated in figure 10-3 (Changnon, 1964e), the factors affecting the design of stacks (Changnon, 1966f), and weather factors affecting roof failure (Changnon, 1978g). Studies investigated the general economic effects of hail damages to crops and property (Changnon, 1972f), as well as the value of atmospheric sciences research (Changnon, 1976a). Changnon (1979g) explored the effect of weather on human activities, and what actions could be taken to address the detrimental effects of inadvertent weather and climate change (Changnon, 1979h).

Weather impacts on business and industry were also explored. These studies included the effects of weather conditions on the insurance industry (Changnon and Changnon, 1989; Changnon and Changnon, 1990), and on business and commerce (Kunkel and Changnon, 1991). The myriad of weather impacts that occurred during a year with unusual weather conditions were defined for the entire Midwest (Changnon and Kunkel, 1992).

Another area of impact studies was the influence of weather conditions on soil erosion in Illinois. Jones et al. (1981) investigated the influence of heavy rainfall and raindrops on soil erosion. Changnon (1982e) investigated wind erosion of soils.

Studies of the impacts of high water levels on Lake Michigan at Chicago during 1984-1985, which included massive erosion of beaches and shoreline protection works, became a topic of extensive investigation (Changnon, 1987f). The low lake levels that developed by 1988 led to an Illinois proposal to increase the diversion of water at Chicago so as to increase drought-caused low flows on the Mississippi River, and the various impacts generated by this situation became the focus of another study of weather, the Great Lakes, and policy (Changnon, 1989).

Another area of study addressed how climate extremes affect human health and activities. The impacts of a severe winter on human behavior was assessed (Changnon, 1979). The climatological dimensions of a deadly heat wave during July 1995 across the Midwest were defined (Kunkel et al., 1995). The impacts of the event including 533 heat-caused deaths in Chicago were assessed (Changnon et al., 1995).

AGRICULTURAL METEOROLOGY AND CLIMATOLOGY

The initial studies involving agricultural meteorology began in the mid-1960s. They resulted from Water Survey responses to the interests of the crop insurance industry which was supporting hail research at the Survey (see Chapter 3). Hailfall characteristics causing crop damages were among the analyses performed (Changnon, 1971f). A problem facing the hail insurance industry was resolved in a study showing that the summer frequency of hail days, as determined from U.S. Weather Bureau station records, matched well with annual crop loss values for Illinois (Changnon, 1960f). This allowed the industry to reconstruct the historical loss experience that did not exist in the hail insurance data which had begun in 1948.

Another research impetus from the weather insurance industry concerned their decisions about whether to become involved in crop yield insurance against all weather perils. This concern of the mid-1960s led to Water Survey studies of crop yield-weather relationships as defined on central Illinois farms (Changnon, 1966b and 1966f). Ten years of corn yield data from 104 farms located in the East Central Illinois raingage network were analyzed to determine how various weather conditions related to yields, and selected results are shown in figure 10-9. These results became the first definitive information on how actual farm yields and agricultural practices employed during the 1950s and 1960s were influenced by weather conditions, and this study marked the serious entry of Water Survey scientists into the agricultural meteorology field. The studies and interactions with several staff of the College of Agriculture at the University of Illinois led to the development of a continuing relationship between Water Survey atmospheric scientists and College of Agriculture leaders and staff. This relationship has been maintained and enhanced over the past 30 years such that the Survey atmospheric scientists have in effect served as the "weather experts" for the College of Agriculture in numerous research, teaching, and service activities.

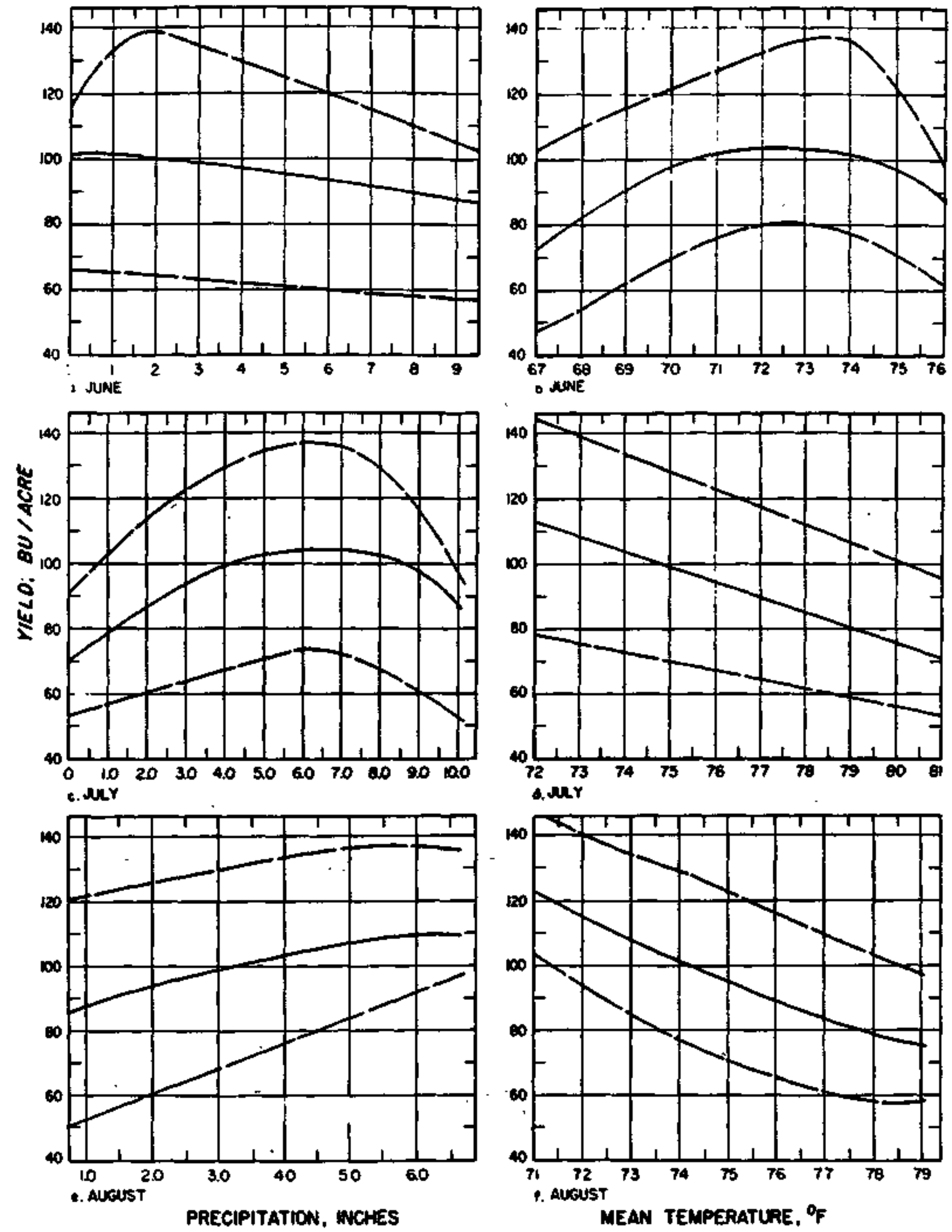

Figure 10-9. The Survey's first major agriculture-weather study used University of Illinois data from 104 farms located within the Survey's East Central Illinois network and the network rain and temperature data for 1954-1963. Here, selected relationships between monthly rainfall and temperatures and corn yields are displayed showing for example, that low rainfall in June, about one inch, was best for maximizing corn yields.

Another insurance-driven study investigated crop-weather relations found in all 101 Illinois counties. The results would determine whether weather-yield equations could successfully serve as a means for measuring crop loss in a weather-insurance program. Figure 10-10 shows the crop yield relations defined for July rainfall in selected counties based on weather-yield regression models (Changnon and Neill, 1967).

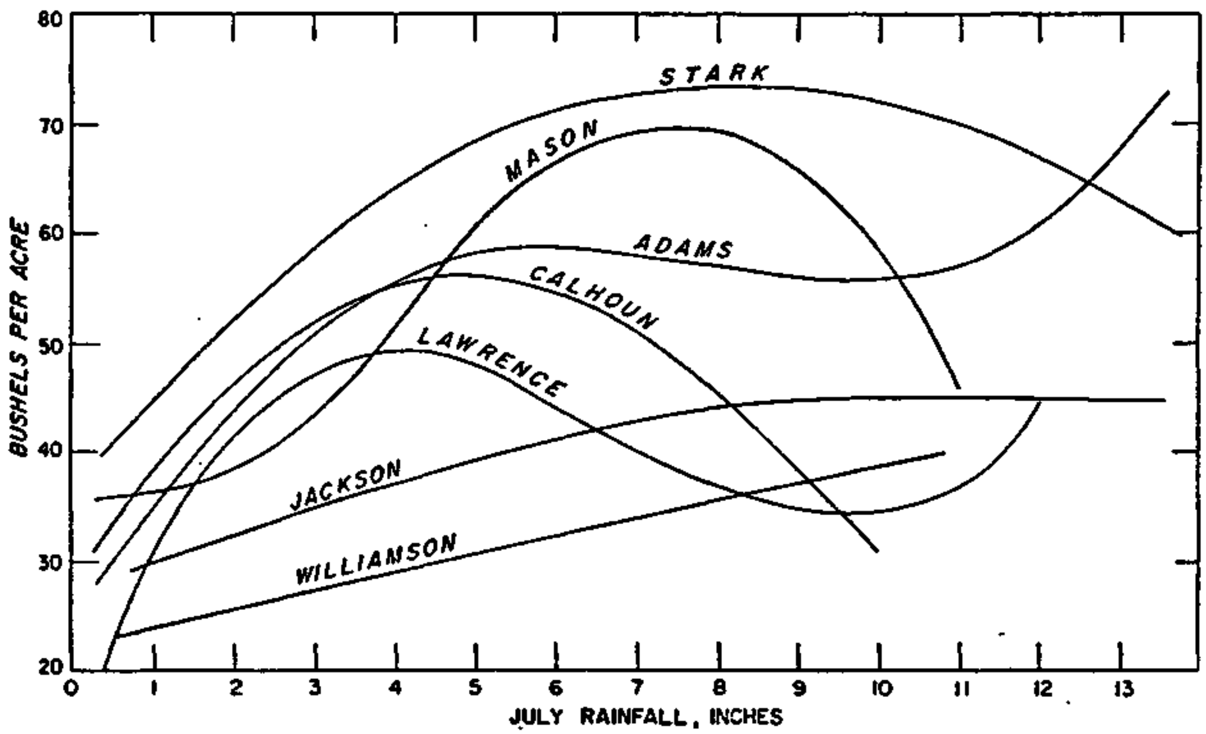

Figure 10-10. In a study conducted for the weather insurance industry, Survey scientists assessed the relationship between weather factors and corn yields for each Illinois county. Selected county curves of the relation between July rainfall and yields are shown revealing different outcomes due to widely differing soil types.

Another insurance question addressed concerned how well the temperature and rainfall data at weather stations estimated yield effects at varying distances away from the weather station (Changnon, 1968f; 1969h). This information was needed to know whether yield losses could be adequately estimated from the existing network of weather stations in the Midwest.

During the 1970s, the Survey's weather-agricultural research was devoted to getting answers to questions and needs related either to planned weather modification and/or inadvertent weather modification with growing involvement of agricultural experts at the University of Illinois. Various publications based on what we had learned about the impacts of weather on agriculture were issued. One study provided the probabilities of critical weather conditions throughout the growing season (Changnon, 1967f); another described the weather-crop-soil interactions (Changnon, 1976e); and another documented the important crop-weather relationships found in Illinois (Changnon et al., 1982).

Greater emphasis on an applications-oriented program in agricultural meteorology began in 1980 with the employment of a senior staff member trained in the field, Steve Hollinger. Under his leadership, the research, data collection, and services endeavors in agricultural meteorology were expanded. This expansion included ever greater involvement of several agricultural economists at the University of Illinois (Steve Sonka, Philip Garcia, and their students). One example of the many studies they conducted with Survey scientists (Changnon, Hollinger, and Lamb) was a study of the effect of changing agricultural technologies on the weather-crop yield relationships (Offutt et al., 1987).

Crop insurance interests wanted Survey scientists to further define weather-crop relations for possible use in crop-yield insurance, and research on grants from the industry resumed in 1980. This led to a study of weather-crop yields at a series of farms located in the dense weather network operated by the Survey in central Illinois (Changnon and Sonka, 1981). That study revealed sizable between-year differences due to rainfall variations and to varying farming practices, a problem for the crop insurance industry. Then, an atlas of climate and crop yield conditions for the entire Midwest was assembled and issued (Changnon, 1982f). The interesting results from these studies were summarized in a public-oriented information brochure on crop-weather relations (Changnon et al., 1982c). This was followed in 1985 by a state publication on the uses of climate information by the agribusiness sector (Lamb et al., 1985).

Sophisticated studies of crops and weather relations led to the further development of weather-crop models (Hollinger, 1985; Mjelde, 1986). Studies of weather relations to agricultural pests began in 1986 (Hollinger, 1986), a subject further treated under mesoscale research (see Chapter 8) and precipitation measurement (see Chapter 3). Isard et al. (1990) assessed the distribution of aphids in the boundary layer. A part of this research entailed use of helicopters to track insect flights aloft (fig. 10-11) and a special sampling device was developed (Hollinger et al., 1991). The potential effects of the dry deposition of pollutants (sulfates and nitrates) on soybeans was investigated (Dolske, 1988). The relations of weather, crops, and farm management practices also became a major research topic of Hollinger, Sonka, and their students. The relations of drought, climate conditions, and agricultural production were investigated in 1990-1991 (MCC, 1991).

WEATHER, CLIMATE, AND WATER RESOURCES

One of the long-lasting areas of impact research concerned the interactions of weather and climate conditions with water resources. The first effort addressed drought and wet conditions on water supplies at two Illinois communities (Changnon, 1952). Research then began in 1963 concerning droughts and how they affected streamflows in Illinois (Changnon and Huff, 1963).

This innovative research on low flows and their relationship to basin physiographic-climate conditions later led to a study that won the famed Horton Award from the American Geophysical Union in 1964 (Huff and Changnon, 1964). This work allowed prediction of low

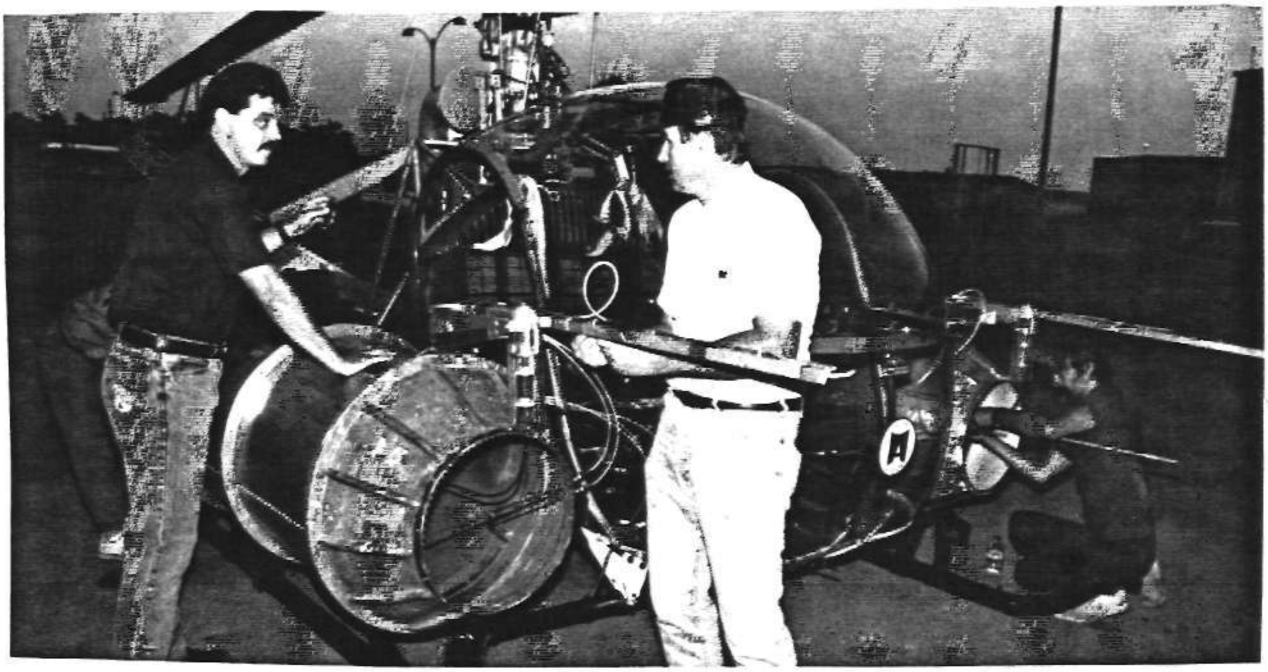

Figure 10-11. Studies of the impacts of weather conditions on insect pests in Illinois involved field sampling projects. A helicopter outfitted with samplers was used to track flights of various agricultural pests. Here Steve Hollinger (center) discusses flight plans with the pilot at dawn flight in 1990. The insect collectors are mounted on the left and right sides of the helicopter, and Scott hard (right) is kneeling before one of the pods.

flows for any Illinois stream using its geomorphic setting and historic climatological data, a tool of great value since many Illinois streams have no long-term streamflow measurements. Figure 10-12 is a graph from this award-winning paper showing how the frequency of the runoff value (labeled the "G factor") varies between different geomorphic areas of Illinois.

Studies of how to use climate data to estimate irrigation requirements in Illinois were accomplished as part of the Survey's growing attention to the irrigation issue (Changnon 1969e). A later study aimed at hydrologic issues focused on how air pollution affected water quality in Illinois (Huff, 1976b). The relationship of precipitation and the levels of shallow ground water across Illinois was subsequently defined showing a lag of two to three months between precipitation amounts and levels (Changnon et al., 1988c).

Considerable climate-water research was being conducted for weather modification (planned and inadvertent) during the 1973-1990 period. For example, Vern Knapp and his co-workers (Knapp et al., 1988) employed hydrologic models of small basins in Illinois to calculate the impacts, within the hydrologic cycle, of altered summer rainfall. A related and long-running area of study concerns the various effects of droughts in Illinois on communities and larger areas. Several Water Survey publications about specific past droughts addressed their economic, natural resource, and policy impacts in Illinois (Changnon et al., 1982a; MCC, 1991; Angel et al., 1992; Changnon, 1983e). The lessons taught about handling droughts in Illinois have been summarized (Changnon, 1991c), and their various local and state impacts have been assessed

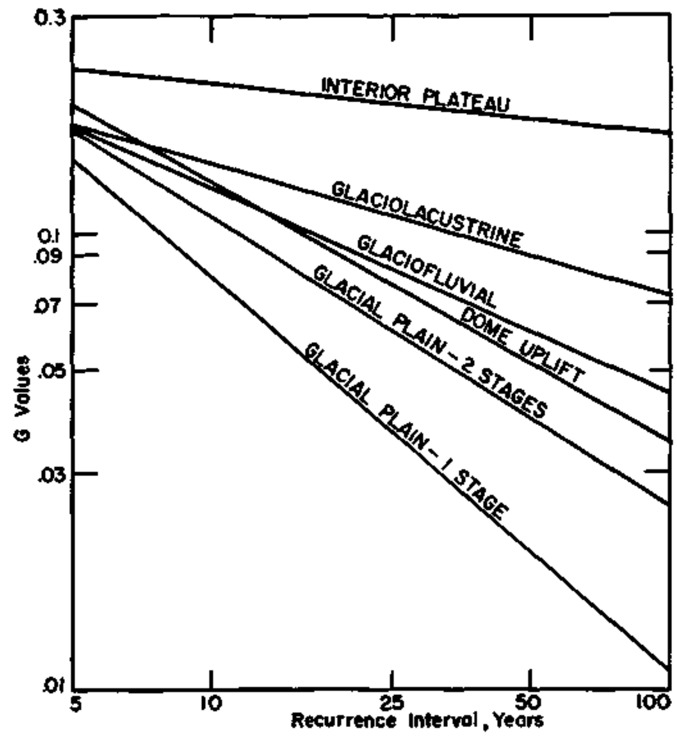

Figure 10-12. A monumental study of low streamflows, climate conditions, and geomorphic regions for major Illinois rivers found widely different relationships across the state. Curves based on G values (an index integrating low rainfall and low streamflows) shows the frequency distribution of G for the different geomorphic regions of the state. These relationships allowed calculation of low flows for many ungaged streams using climatic data and the geomorphic index.

(Changnon and Easterling, 1989; Changnon, 1984f). The roles of local and state government in drought management in Illinois have been identified (Changnon, 1991d). To serve one of the needs of Illinois water managers who must manage systems during droughts, the procedures for detecting incipient droughts in Illinois were defined (Changnon, 1987d).

The socioeconomic and environmental impacts resulting from floods in Illinois have also been assessed (Changnon, 1984f; Bhowmik et al., 1994). A recent assessment considered changes in precipitation since 1921 and their effects on flood-related flows in 89 basins across the Midwest. It revealed an upward trend in floods and precipitation across Minnesota, Iowa, and northern Illinois (Changnon and Kunkel, 1995a). This verified an earlier study showing increases in floods and heavy rains across northern Illinois (Changnon, 1983b). The impacts on water supplies and water quality of the severe Midwestern floods of 1993 have been extensively studied (Changnon and Laver, 1994; Changnon, 1995c). Survey scientists (Bhowmik, Kunkel, and Changnon) wrote six chapters in a book about the 1993 flood (Changnon, et al., 1996).

The influence of climate fluctuations on the levels of Lake Michigan and in turn on shoreline damages, shipping, and economic conditions at Chicago, has also been assessed (Changnon, 1987f; Changnon et al., 1989a). This included the economic and environmental problems associated with too little or too much water in the Great Lakes due to climate shifts (Changnon, 1991e). The influence of atmospheric pollutants being deposited on the Great Lakes water quality was studied (Gatz et al., 1989; Sweet et al., 1993; Gatz et al., 1994). The mixed effects of shifting climate conditions (generally to a wetter regime since 1940) and shifting land uses in urban and rural basins were investigated (Changnon and Demissie, 1995). Results showed that the land use and drainage system changes since 1940 have been important in altering streamflow, and make it difficult to detect the influence of climate shifts.

IMPACTS AND INTERACTIONS WITH GOVERNMENT

The atmospheric impact and applications research also embraced studies of the effects of weather and climate on government bodies at the local, state and federal levels. The water supply policy of the federal government was the subject of Congressional testimony (Lamb, 1990). Changnon (1982g) examined how local governments dealt with drought conditions.

The involvement of the state in atmospheric issues has also been analyzed and described. A major activity since the 1970s has been efforts to obtain state involvement and attention to atmospheric issues of importance. For example, Changnon (1979f) wrote an article for wide state distribution about "what to do about weather and climate changes." These efforts also led to the development of the Illinois Weather Modification law (Ackermann et al., 1974). The Survey played a major role in state policies about acid rain (Semonin, 1987), and in the establishment of the Illinois Task Force for Global Climate Change during 1992-1994 (Changnon, 1995b).

The Survey's role in drought studies led to our involvement in the Water Plan Task Force in the 1980s and staff participation in the standing Illinois Drought Task Force that acts as droughts develop. The importance of the atmospheric issues of planned weather modification and climate change became one of the eleven major water issues identified by the State Water Plan Task Force (Changnon and Semonin, 1982). Testimony on atmospheric issues was presented in Congress on numerous occasions (Changnon, 1976d, 1977b, 1982a). The involvement of Water Survey atmospheric scientists in government policy issues is described more fully in Chapter 12.

SUMMARY

Accomplishments

Water Survey research into the effects of weather and climate on the physical and socioeconomic systems has achieved national recognition, particularly the endeavors related to weather modification and inadvertent modification due to large urban areas. Survey expertise in defining the impacts of weather modification led to an invitation from the World Meteorological Organization to prepare a special report on this subject (Changnon, 1979j).

A critical component of this research was the involvement of scientists of other disciplines and an established record of quality multi-disciplinary research, efforts well reflected in the technology assessment of hail suppression project which received national acclaim.

With the applications and effects research, came the involvement of atmospheric scientists of the Water Survey in state policies. This included the development or modification of laws relating to pollution control and weather modification, membership on state task forces and key committees, and the formation of the Illinois Task Force on Global Climate Change.

Another area of major accomplishment has been in assessing the value of climate and weather information for different user groups. A benefit of the studies was that they helped shape and improve Survey services and make them more valuable to Illinois.

Research and field studies relating to how weather affects Illinois major crops has been continuous since the mid-1960s, a result being unique definitions of the relationships between weather and crop yield components. This has undergirded the Survey's reputation for impact studies relating to purposeful weather modification, inadvertent weather modification, and climate change.

Awards

Hail Suppression Impacts and Issues, the book serving as the final report of the Technology Assessment for Hail Suppression project, received the 1978 Award for Professional Excellence from the American Agricultural Economics Association.

Floyd A. Huff and Stanley A. Changnon were chosen by the American Geophysical Union as recipients for the prestigious Robert E. Horton Award of 1964. This award is for the year's most outstanding paper in hydrology which was identified as their paper on the relationship of climate conditions to low flows in Illinois (Huff and Changnon, 1964).

The American Meteorological Society chose the Water Survey for its "Corporate Award" in 1977 based on the "outstanding applied research of the Survey."

The American Water Resources Association presented their annual award for best paper to Stanley Changnon in 1976 for a paper on urban impacts on water resources (Changnon, 1976b). In 1989 the AWRA gave their annual award for best paper of 1989 to Changnon and Easterling (1989) for their paper on drought impacts in Illinois.

The Building Research Institute presented Stanley Changnon a 1966 award for a contribution to the science of building. This was for his paper on weather impacts on structures (Changnon, 1964e).

The American Meteorological Society presented the 1981 Cleveland Abbe Award to Stanley Changnon for "research applied to the use of climatic knowledge for agricultural and industrial needs". The Society selected him for the Award for Outstanding Contribution to the Advance of Applied Meteorology in 1991 for his extensive studies related to the problems of industry and design criteria relating to weather perils." Both awards stemmed largely from the applications and impacts-oriented research at the Water Survey.

Key Projects

The weather insurance industry funded a series of important projects during 1965-1970 and again in 1979-1982. These addressed various aspects of how weather and climate conditions affected crop yields. These projects brought the Meteorology Group into agricultural meteorological research and further were important in establishing the impact research program.

The largest single project dealing with weather impacts was the three-year Technology Assessment of Hail Suppression (TASH) funded by the National Science Foundation during 1976-1978 at $0.5 million. The Water Survey acted as the prime contractor for support to scientists in various disciplines and at numerous institutions, including several universities (Illinois, Colorado, Arizona, and California at Santa Barbara).

Another major effects-type project initiated in 1981 and based on NSF and private sector funds defined'the uses and needs of U.S. agribusinesses for climate data and information. This large two-year project evolved into a series of three projects funded over seven years to assess the usage, develop informational value models and eventually to tackle the specialized topic of usage of long-range forecasts. Total funding for these interrelated projects was $0.7 million.

A third series of projects supported sizable endeavors in the weather impacts area by assessing the weather modification potential in Illinois. The first was the 1970-1974 PEP effort funded by the Bureau of Reclamation for $480,000. The ensuing series of impacts research was funded as part of the 1980-1995 PACE/PreCCIP projects. The total awards were $7.5 million, and approximately 35 percent was spent on studies of impacts of weather modification and climate change.

Pivotal Publications

The award-winning publications previously mentioned were important documents. The TASH book (Changnon et al., 1978) was also a key document that won an award and had a major affect on national hail research policy.

Huff and Changnon (1972b) received wide recognition for its methodological approach to the assessment of the value of weather modification. Changnon's 1979 summary report on how to assess impacts for weather modification programs set a precedent illustrating broad skills in this complex area. Lamb et al. (19782) assessed the uses and needs for weather information in agribusiness, which launched major studies and achieved national recognition for interacting with users. The METROMEX final report (Changnon et al., 1977) defined the broad range of weather and climate impacts caused by the St. Louis-created weather anomaly set the stage for later climate change assessments.

Key Staff

Certain staff members played instrumental roles in the development and the quality of this program by directing research projects and serving as principal investigators on externally funded projects: Floyd Huff, Stanley Changnon, William Easterling, Steve Hollinger, Don Gatz, Peter Lamb, and Ken Kunkel. Several Survey hydrologists have contributed significantly to these research projects including Nani Bhowmik, Mike Demissie, Vern Knapp, and Dick Schicht. Major contributors from the University of Illinois included Earl Swanson, Scott Isard, Phillip Garcia, and Steve Sonka who also became adjunct Survey staff. Key participants from other institutions in several interdisciplinary studies were Professor Ray J. Davis (retired from Utah State), E. Ray Fosse (insurance consultant), Eugene Haas (formerly of the University of Colorado), Henry Lambright (Syracuse University), and Michael Glantz (NCAR).

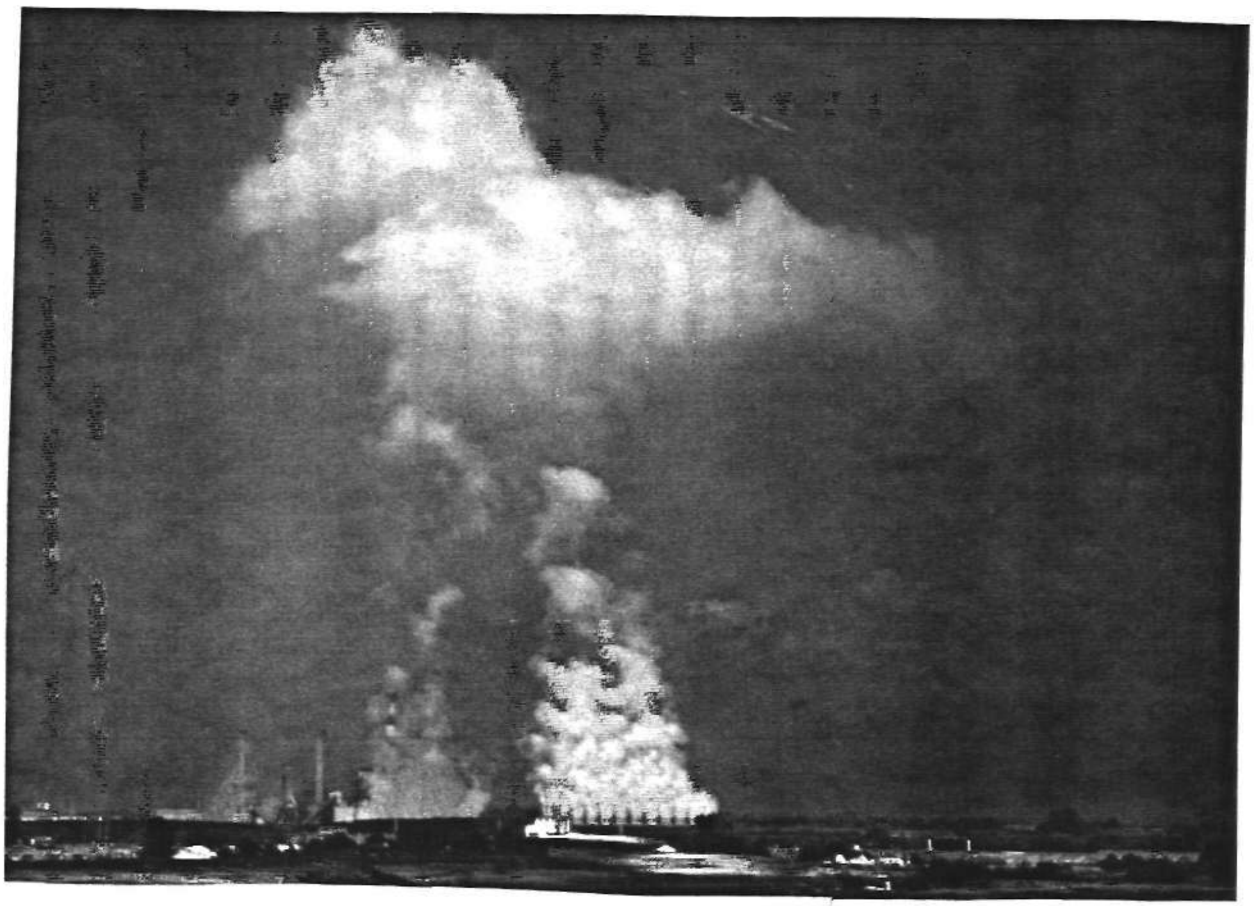

Figure 10-13. The emissions of moisture and pollutants from refineries at Wood River frequently led to cloud development, as seen here, and was defined to be an integral part of a localized influence on summer rain development with local rain increases sufficient to increase corn yields by 2 bu/acre in a 2-county area.

Chapter 11

PLANNING AND ASSESSMENT OF RESEARCH AND GOVERNMENT POLICIES

Stanley A. Changnon

INTRODUCTION

The last major program area to develop in the Water Survey's Atmospheric Sciences program concerned various activities, largely well-planned, related to the Water Survey's prominence in the atmospheric sciences. Most of these actions were designed to promote and protect the Survey's atmospheric programs.

One series of activities (such as congressional testimony, membership on national advisory panels, and scientific assessments and recommendations in widely read publications) was intended to garner governmental actions and policies favorable to Survey interests. Another set of activities attempted to inform the nation's atmospheric sciences community about The Survey's scientific goals, major programs, and achievements as a scientific group. Such efforts were designed to help enhance the image of quality science carried on by the Survey's atmospheric scientists. This was seen as essential to help the staff be successful in the competitive worlds of external research support and refereed publications. A third major activity related to Survey preeminence in certain areas of the atmospheric sciences largely related to responses to invitations from scientific societies or science groups to review the status of a field of scientific research and to offer informed recommendations for needed future research. In essence, the Atmospheric Sciences Group set out by 1970 to become well-known and highly respected voices for the atmospheric sciences research at the Water Survey.

The history of this program begins with the growth of the atmospheric sciences program after 1968, done under the leadership of Stanley Changnon, Richard Semonin, and Floyd Huff whose careers had flowered and matured at the Survey. By the mid-1960s, each scientist had achieved national stature in their respective fields (climatology, cloud physics, and hydrometeorology), and each had sought and obtained sizable federal grants to support much of the Survey's research[1].

[1] Assessment of the meteorology program from 1947 into the mid-1960s reveals that a majority of the projects were done to meet specific objectives of Department of Defense agencies and were mostly aimed at operations and data collection with scientists at other institutions doing research based on the data provided by the Survey projects. Thus, the early program was more "support-service" oriented and not as strongly "research" oriented as in later years.

The union of the varied expertise of Changnon, Semonin, and Huff created a broad base of expertise and one capable of addressing the complex multi-faceted scientific issues in the three "growth areas" of meteorology during the 1960s and 1970s: planned weather modification, inadvertent weather modification, and atmospheric chemistry. The 1968 departure of Glenn Stout as Section Head, coupled with the ending during 1967-1968 of the long-term endeavors in radar-rainfall data collection, gave these three leaders programmatic control of the Atmospheric Sciences program they had planned for since 1966. As a result, ambitious new major research programs developed during 1969-1970. Most of the senior atmospheric scientists involved in the growth of major research projects during the late 1960s and 1970s are pictured at a staff meeting in figure 11-1.

Figure 11-1. Leaders of the atmospheric sciences research program during the 1970s ponder results from METROMEX at a planning session in 1973. From left to right is Paul Schickedanz, Dick Semonin, Floyd Huff, Stan Changnon, Griff Morgan, Jack Adams, and Don Gatz.

The research accomplishments of Huff, Semonin, and Changnon, and the 20-year history (1947-1966) of solid, albeit limited, research by the Meteorology Section at the Survey provided the platform for launching a new program area, *the promotion of the program in the scientific community and in governmental circles*. Such promotion and planning endeavors were a necessity. The post-World War II and Korean War period (1947-1965), which featured extensive federal funds for science, particularly science relating to national security, was ending in the late 1960s. More than 80 percent of all external support to the Survey's Meteorology Group from 1951 to 1965 came from contracts from the Department of Defense (Army, Navy, and Air Force). After 1968, DOD-funded projects at the Survey essentially disappeared, and external funding (about 85 percent of the Section's total funding) came from competitive grants and contracts awarded by agencies such as the National Science Foundation (NSF), Department of Energy (DOE), and National Oceanic and Atmospheric Administration (NOAA).

The shift to a stronger research orientation and to competitive grants as the principal sources of funding, brought greater requirements for a staff of top quality scientists capable of doing highly credible and productive scientific research. In 1968, the Atmospheric Sciences Section had 21 scientific-engineering staff members (one Ph.D); by 1975, there were 47 scientists and engineers (six with Ph.D.s); and by 1985, there were 31 scientists and engineers (12 Ph.D.s). This successful shift in sources of federal funds away from the agencies of DOD is illustrated by the fact that between 1967 and 1975, Changnon and Griff Morgan were awarded seven NSF grants for hail research totaling $955,000. *The world of science had changed and so had the Survey's Atmospheric Sciences program.*

As the Survey's growing staff and research became better known nationally, invitations came to assess and comment on research endeavors as well-respected spokespersons in the atmospheric sciences. Another attention getting activity pursued was hosting national scientific conferences in Champaign-Urbana (fig. 11-2). Five national weather conferences were hosted between 1963 and 1977. These concerned severe storms, radar weather, weather modification, and hydrometeorology. Assessment of the awards and honors conferred on Survey scientists and to the institution (described in the summaries of Chapters 3-10) reveals that most of these awards occurred after 1970, which reflects the success of the "new image" efforts created by staff, as well as the enormous scientific progress made after the mid-1960s. For example, the American Meteorological Society (AMS) gave a Special Award to the Water Survey Meteorology Group in 1974 for the "initiation, support, and successful completion of imaginative research in applied meteorology, storms, rainfall and hail, weather modification, and hydrometeorology problems."

Assessment of the diverse activities classed within this program area revealed three somewhat overlapping themes. One of these was oriented to *getting the word out about the Survey's atmospheric program and/or major projects, and reporting on their progress*. This theme was geared to promoting the Survey's endeavors within the atmospheric sciences and occasionally the broader scientific community.

A second theme was geared to trying to *assess and influence local, state, and government policies*. This was intended to bring awareness of atmospheric issues (and the Survey's program addressing these issues) and/or to affect government policies that in turn affected the Survey's atmospheric program in some favorable way.

A third theme related to performing *assessments of the status of an atmospheric issue or field of endeavor, often with recommendations of what should be done*. These endeavors usually resulted from invitations to Survey scientists to perform such an assessment. These activities collectively acted *to promote the research and services program and the staff of the Water Survey.*

Not all promotional activities of the Survey's meteorological staff are obvious from the publications, as will be illustrated by other activities described in the following text. However,

Figure 11-2. The top photo depicts William Ackermann, Chief of the Survey (left) and Stan Changnon (pointing) briefing foreign scientists at a Survey-hosted international hydrometeorology conference in 1973. The lower photo shows Griff Morgan (left) talking with Vincent J. Schaeffer, famed as the father of modern weather modification, at a national weather modification conference hosted by the Survey in 1977.

the intent of many papers written was to describe a plan for a new Water Survey program and/or to report on its findings. Other papers assessed the status of knowledge in some specialty field and offered recommendations for future research, and others were aimed at influencing political decision makers and altering governmental policies.

Table 11-1 presents the temporal distribution of papers in the three theme areas, plus reports. Between 1966 and 1995, 23 papers were published describing Survey program plans or major accomplishments. Between 1973 and 1995, 50 papers addressed governmental issues and audiences, an average of more than two per year, and 49 papers assessed the status of knowledge in a field such as weather modification or applied climatology. Thus, 112 papers and 2 reports have been prepared and published over the past 30 years based on the prestigious position of the programs and staff of the Atmospheric Sciences program. After peaking during the 1981-1986 period (44 publications), the frequency has decreased.

An important aspect of the promotion of the science of Atmospheric Sciences Section since 1969 was the wide distribution of the group's publications. Typically hundreds of copies of the scientific papers and the Water Survey reports were distributed to known interested scientists, members of state and federal agencies, relevant private sector companies, scientific societies, and libraries. This distribution activity, which had largely ended around 1990, was based on a carefully developed master mailing list with thousands of entries, each noted as to their areas of interest.

PLANNING AND PROGRAM REPORTING

Certain endeavors were pursued principally to report widely on progress of Survey projects and plans of emerging Survey projects and programs, and thus to gain national visibility for these projects. The first such document described the Survey's many raingage networks and how the data had been applied to solve a variety of weather issues (Huff and Changnon, 1966).

Table 11-1. The Temporal Distribution of Papers and Reports Published to Promote and Describe Water Survey Programs and Scientific Plans, to Assess Government Issues and/or Influence Policy, and to Assess the Status of a Scientific Area or Issue.

	Papers			
Years	*Plans*	*Policy*	*Science*	*Reports*
1966-1968	1	0	0	0
1969-1971	1	0	0	0
1972-1974	0	3	4	0
1975-1977	3	6	3	0
1978-1980	9	4	5	1
1981-1983	5	14	3	1
1984-1986	1	5	16	0
1987-1989	1	7	6	0
1990-1992	2	6	6	0
1993-1995	0	5	6	0

The *goal* was to reveal our unique databases and expertise for tackling many precipitation issues, and this paper helped get Survey scientists involved in several new research areas including the evaluation of weather modification. When the massive planning for METROMEX was completed, an effort which included extensive networking with other scientists, a paper for the *Bulletin of the American Meteorological Society* (AMS) was prepared announcing the project goals, its plans, and the groups to be involved (Changnon et al., 1971a). This was designed to bring Survey efforts before the nation's entire atmospheric sciences community. A 1974 issue of the *Bulletin of the AMS* was devoted to METROMEX findings (fig. 11-3). And as me project

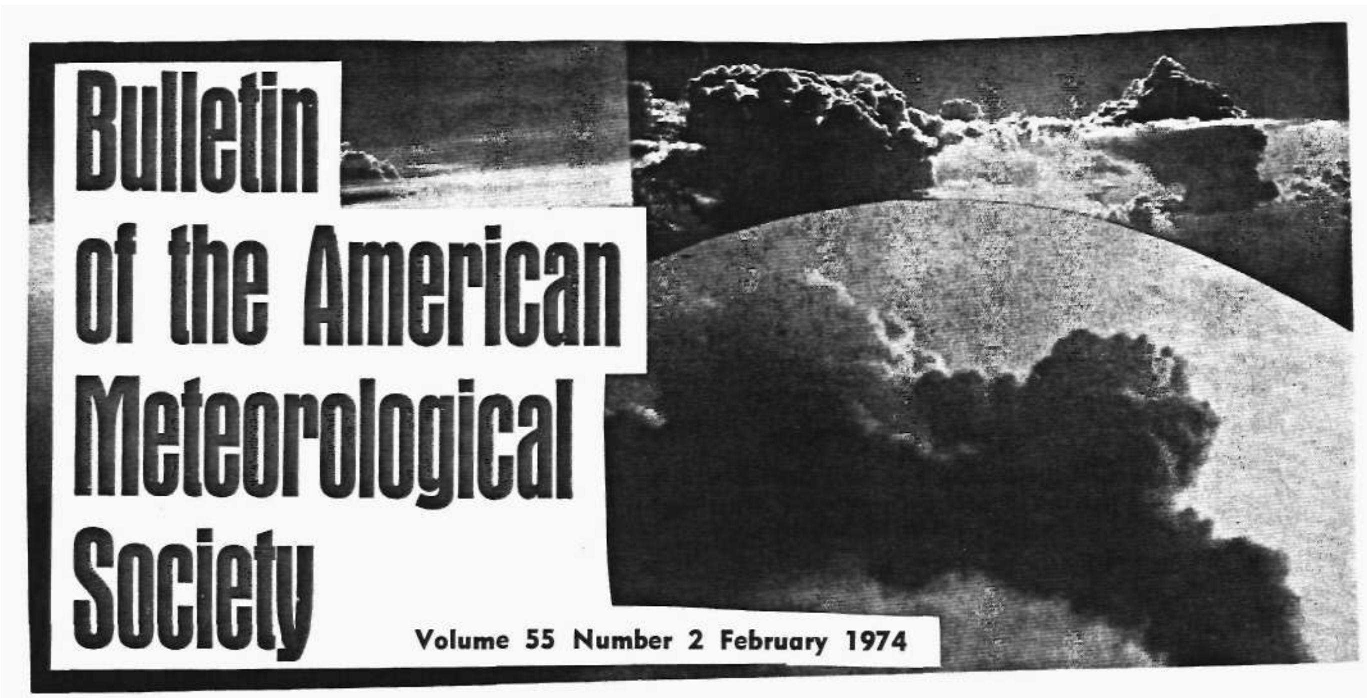

Figure 11-3. The Water Survey-led METROMEX project was promoted to gain wide national attention, and this is from the cover of the 1974 issue of the AMS Bulletin devoted to METROMEX findings.

ended, a report about METROMEX was presented to the scientific community (Changnon et al., 1976f). An invitation from me AMS requested a paper describing how me Survey's many weather networks including that at METROMEX, had been designed and operated (Changnon, 1975g), yet another form of "program advertising."

The rapid growth of me atmospheric sciences research during me 1970s was based on careful planning. Figure 11-4 shows how me research, organizational, and supporting elements were organized during by 1975. Survey leaders actively promoted our major research projects dealing with weather modification in various formats and places. An invited paper by the American Association for the Advancement of Science (AAAS) for presentation at their 1978 annual meeting described me Technology Assessment of Hail Suppression project (Changnon, 1978o). A paper describing our programs in weather modification was prepared for a national farm journal to reach agricultural interests (Changnon, 1978i). Our experience in hail research had led to the development of a comprehensive hail library at the Survey, considered the most

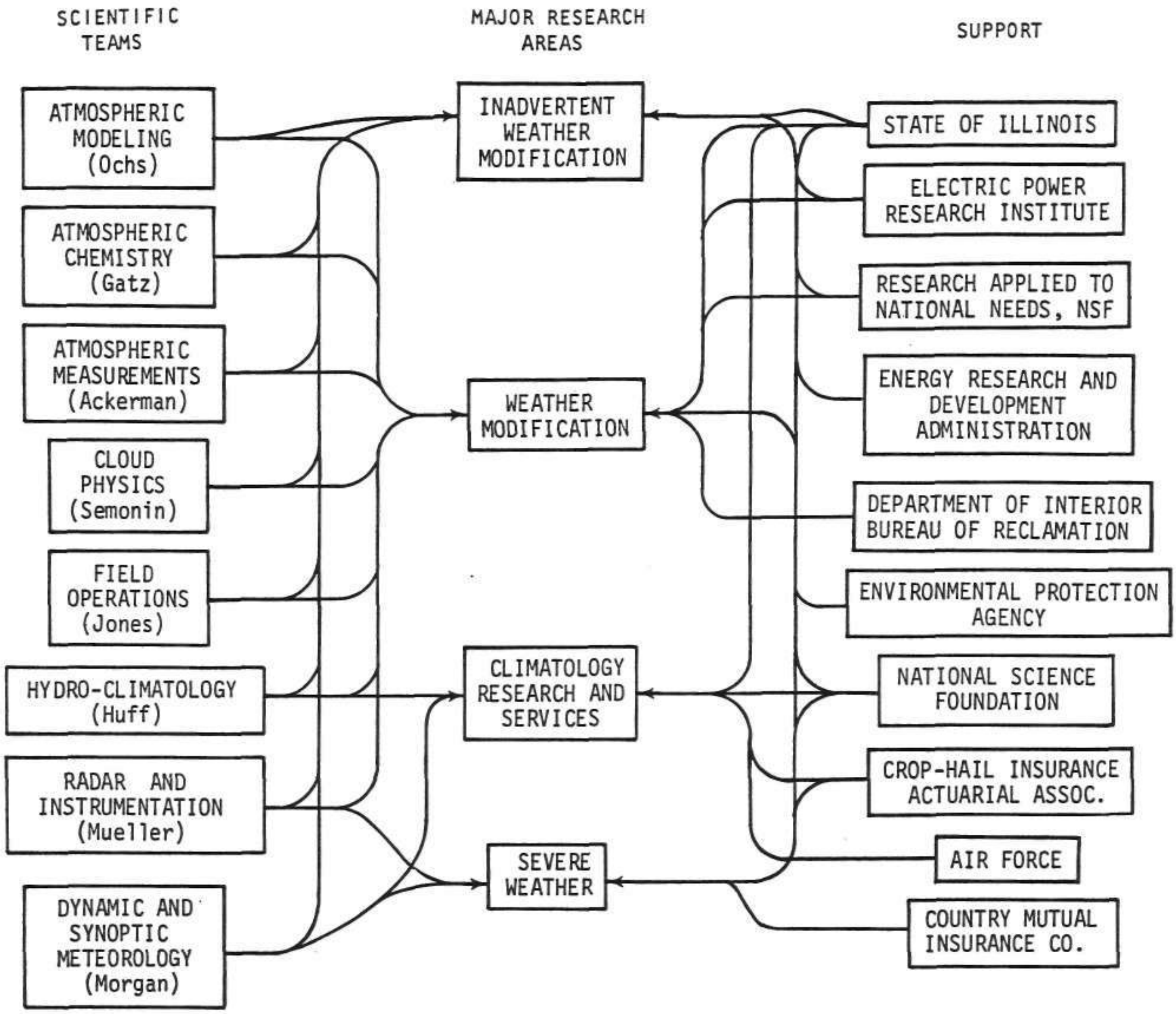

Figure 11-4. A diagram showing the organization of the atmospheric sciences program during the mid 1960s. Such diagrams were used with staffs of federal and state agencies to promote interest and support for the projects.

extensive in the nation, and this was announced to the scientific community (Changnon, 1978m). When the Survey won the contract (under national competition) to perform the extensive interdisciplinary planning of the High Plains Experiment (HIPLEX), this was announced widely (Ackerman and Changnon, 1977).

Changnon and Semonin (1978) prepared a paper for the *Bulletin of the American Meteorological Society* describing the Survey's major field-research project to be established in the Chicago area, named CAP (Chicago Area Program). One major project within CAP was an atmospheric-hydrologic project intended to demonstrate use of radar and raingage data, in real time, to provide Chicago and its water managers with highly accurate short-term forecasts of rain amounts over the city (Changnon and Huff, 1977b). Figure 11-5 is the organizational chart

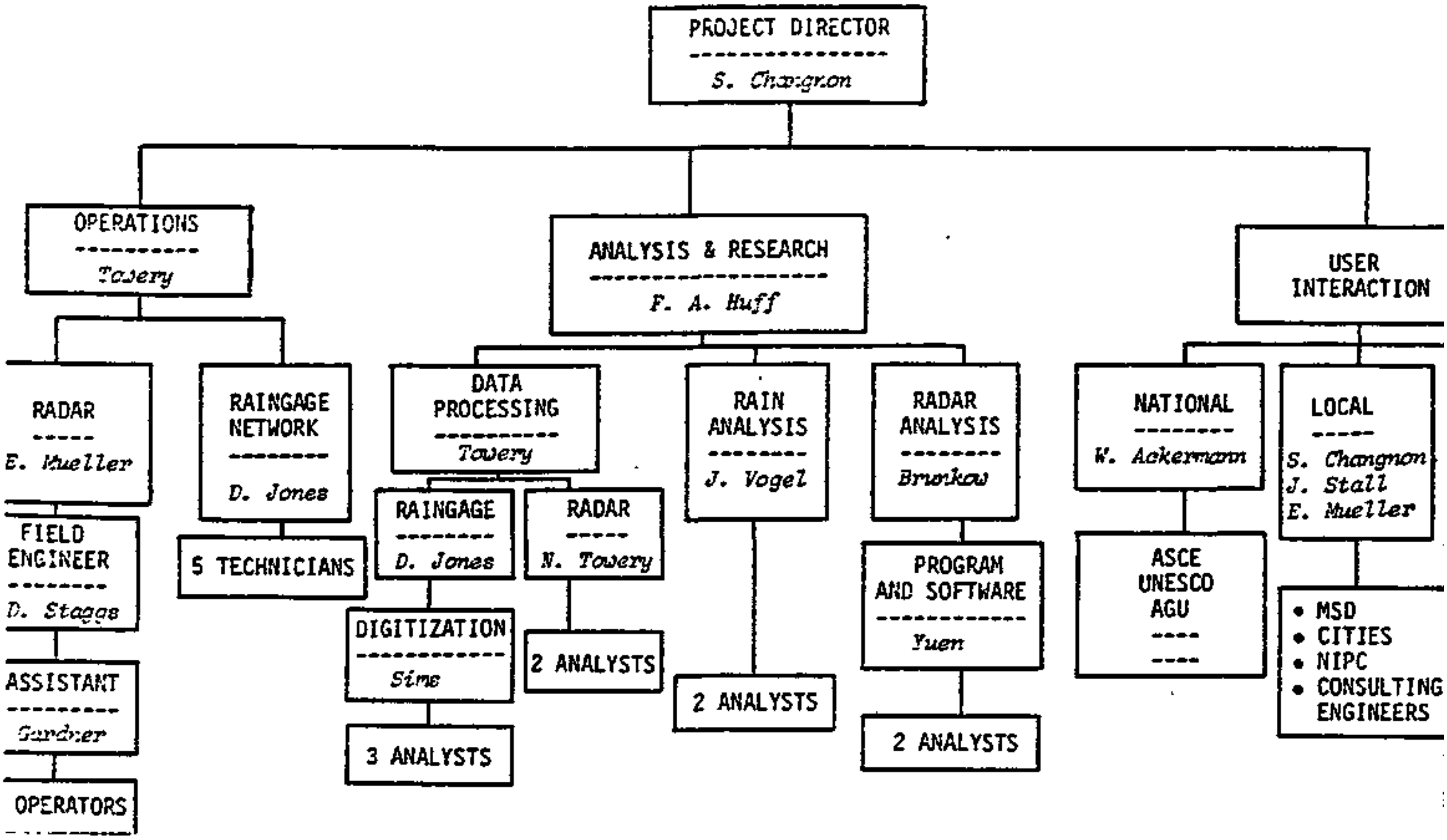

Figure 11-5. The organizational chart for the large Chicago Hydrometorological Area Project (CHAP) during 1976-1979, showing how 32 Survey staff including Chief Ackerman and Hydrology Section Head Stall were involved in this sizable effort funded largely by the National Science Foundation.

for this elaborate project, which reveals that 32 staff were involved to carry out the science, engineering, and user interfaces. This successful urban forecast system was widely promoted to the hydrologic community (Huff et al., 1981). Our growing attention to weather and climate issues at Chicago was described in an article appearing in *Science News* (Changnon, 1978n).

When CAP was underway, Survey scientists were launching the sizable Precipitation Augmentation for Crops Experiment (PACE), and this too was widely announced to the scientific community (Changnon, 1978h). Establishment and use of external advisory groups composed of national experts were an integral part of the promotional efforts as well as a means for ensuring the performance of high-quality science (fig. 11-8). The interesting history of the Survey's extensive efforts in weather modification research was reviewed in a talk initially given in response to an invitation for a presentation at an annual science conference, and later published (Changnon, 1979c).

The late 1970s ushered in a new national (and state) awareness and concern over climate fluctuations and the human influence on atmospheric conditions (acid rain, urban weather modification, and climate change). Changnon and Semonin (1982a, 1982b) seized opportunities to describe the major scientific facing Illinois and being addressed by Survey scientists. The opportunity to widely advertise the long-term operation of a "climate center" at the Water Survey was also recognized. A paper describing the Illinois Climate Center and its research and services activities was published in the *Bulletin of the AMS* (Changnon, 1979b) to help prove to Washington bureaucrats that states had an important stake and roles in the evolving National Climate Program (NCP). To draw attention to extensive Water Survey studies of many warm season precipitation conditions (ranging in scale from small rain cells to 50-year averages of state rainfall), a report reviewed and illustrated key findings from research from 1947 to 1979 (Changnon and Huff, 1980b). This information was updated in 1990 to include the weather modification research and a paper reviewing the important findings of Survey precipitation research was published in the *Bulletin of the AMS* (Changnon et al., 1991a).

In the late 1970s atmospheric science leaders decided to improve the Survey's local and state climate services and applied climate research in order to become a national leader in this arena. Survey scientists conceived and implemented the Regional Climate Center (RCC) concept (see Chapter 5). We championed our achievements regarding the new uses of weather and climate information in water resource management (Changnon, 1981j). The goals of the incipient RCC program were defined (Changnon et al., 1983c) and the RCC program was described in a paper designed to inform the science community (Changnon et al., 1990a). As part of these endeavors, the Survey assembled a group of leading climatologists and government agency leaders for a workshop in Champaign, and developed a plan for a "National Climate Information System" (Changnon et al., 1987b).

Water Survey leaders decided in 1990 to launch a research program dealing with global climate change studies and the provision of information. This was to be done under the banner of the Illinois Global Climate Change Center established by Chief Semonin at the Survey. A comprehensive program plan describing the plans and services was subsequently developed, published, and widely distributed (Changnon, 1991f). The achievements of the Survey's atmospheric sciences program were described in an invited talk presented at an Illinois water meeting in 1995 (Changnon, 1996d).

INVOLVEMENT IN GOVERNMENT ISSUES AND POLICIES

As the Survey's atmospheric program became more involved in the competition for federal funds, it became necessary to relate Survey views and scientific findings to existing issues or potential government policies for wide circulation, particularly in "Survey-relevant" governmental circles. This represented a distinct shift from a long-term Water Survey policy that had steered away from active involvement in state or national political issues (unless forced to do so).

Involvement in assessing, informing, and influencing governmental activities and policies began after a federal re-organization of weather modification research in 1972, an event that caused the Survey to lose support for its growing PEP program in 1973. The situation in Washington was analyzed and a paper prepared describing the programmatic-budgetary confusion, including the conflicts between agencies. This was published in the *AMS Bulletin* (Changnon, 1973b). Weather modification issues facing state government were also assessed in a journal widely read by government managers (Changnon, 1973h).

After 1973, Survey staff became increasingly involved in the policy issues of weather modification. Continuing federal "mishandling" of the weather modification field remained a policy challenge, leading to a second paper assessing the "paradox" of the reduction of federal support for the field in the face of increasingly productive scientific results (Changnon, 1975e). Chief Ackermann and Changnon worked with Professor Ray J. Davis of Arizona during 1972 to draft a model state law for the control of weather modification operations in Illinois, and the law was enacted in 1973 (Ackermann et al., 1974). This direct involvement in state policy development was promoted statewide and described in an article published in *Illinois Issues,* a magazine widely read by state decision makers (Changnon, 1975h). Present and future weather modification research was assessed in an attempt to address and influence federal research priorities (Changnon, 1975f).

The issue of how to "sell" weather modification research at the federal level was debated in the scientific literature, with the Survey calling for the strong integration of socioeconomic and environmental assessments when considering the adequacy of weather modification (planned and inadvertent) programs (Changnon, 1976a). Involvement in weather modification research and policies issues led the Congress to invite Changnon to serve as one of 16 members of the prestigious National Weather Modification Advisory Board established under special legislation in 1976 to assess the field and recommend what should be done to enhance weather modification research and development. Subsequent efforts to influence state government leaders about the potential of weather modification and its policy issues led to an article designed for publication in *State Government* (Changnon, 1980i).

Chief Ackermann and Section Head Changnon were invited to testify before the U.S. Senate and House of Representatives in 1977 about climate issues and the need for a National Climate Program (NCP). This was particularly effective because Illinois' Senator Stevenson was a Program advocate. This testimony led to more involvement in Congress, and Changnon (1977b) provided more testimony before the Senate and House of Representatives. In following years, more Congressional testimony was invited and given (fig. 11-6). Changnon testified about modifications needed in the NCP in 1981 and again in 1987 (Changnon, 1987e). Lamb (1981) presented testimony in 1981.

Interactions with political leaders about scientific issues revealed that the support of private sector interests was needed to help influence government policymaking. To this end, papers were written and numerous talks were given specifically for private sector interests. For example, the impacts of urban-induced weather and climate changes were presented to the nation's urban planners (Changnon, 1979e), to the civil engineering community (Changnon, 1980h, 1990a); and to the agricultural seed-growing industry (Changnon, 1992h). The potential

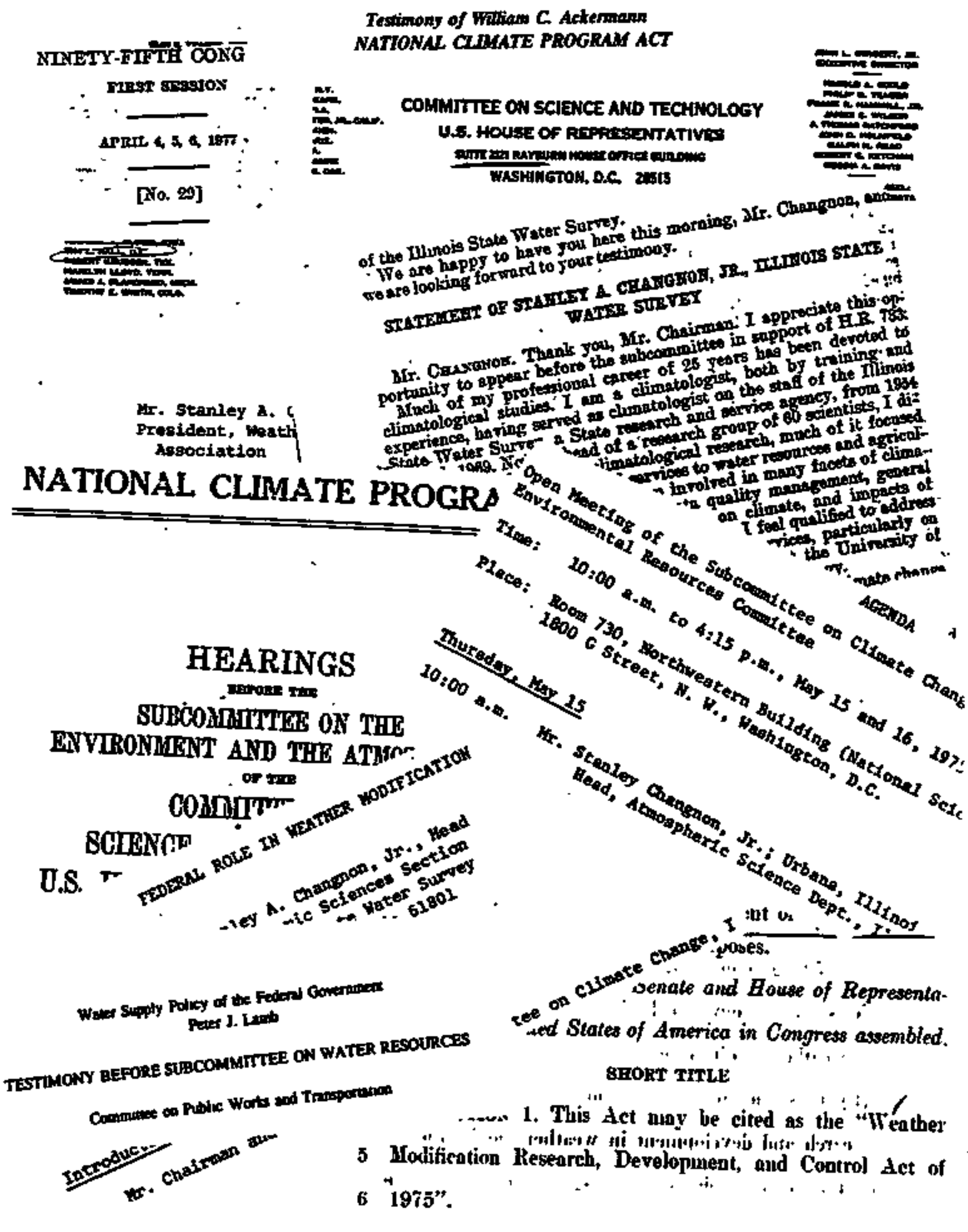

Figure 11-6. A collection of materials illustrating some of the Congressional interactions involving Survey staff including William Ackermann, Stanley Changnon, and Peter Lamb.

role of state governments in handling weather modification was advanced before the civil engineering (hydrologic) community (Changnon, 1983c) to gain their support for urging these actions on state governments and government managers (Changnon, 1983i), as well as the support of agricultural decision makers (Changnon, 1983h).

Another area of advocacy developed in 1980 included *the value of climate information.* As part of the NCP, Congress had authorized increased funding for state climate services, but the federal Office of Management and Budget (OMB) systematically blocked the matching funding called for fear of loosing control of the budget. To obtain this funding, the Survey led an assessment of state climate services (Changnon et al., 1980g), met with OMB examiners, and addressed the federal/state policy confusion over handling of floods and droughts (Changnon, 1980j). Changnon (1981e) described the role and importance of the nation's state climatologists as additional input to influence OMB and other federal agencies.

The role of the Water Survey in helping state leaders consider and adequately address difficult atmospheric issues such as acid rain and climate change was also strongly promoted. The *Illinois Municipal Review* invited a paper on drought problems, and Changnon (1981f) illustrated drought management issues by describing the problems at Eldorado, Illinois, as a case study. A follow-up article on "drought management in Illinois" was published in *Planning and Public Policy* (Changnon, 1982g). Another article was prepared for the highly visible *Illinois Issues* to describe potential future changes in the state's climate, what they might mean for Illinois, and how Survey scientists could help (Changnon, 1981h), which helped make the climate change issue more visible across Illinois. A series of short reports describing Water Survey research and service achievements were prepared and widely distributed in Illinois to improve awareness of the Water Survey and its utility to the state (Changnon, 1983j, 1984e, 1985i).

The new Illinois State Water Plan Task Force established in 1980 began by identifying the major emerging issues facing water resources in coming years. As members of the Task Force, Survey leaders (Chief Emeritus Ackermann and Chief Changnon) were able to get climate change, weather modification, and drought identified among the eleven issues selected for recognition and for future research and development support (Changnon and Semonin, 1982). The effects of a changing climate on water resources management in Illinois were a major message presented at a state natural resources conference held in Chicago (Changnon, 1982h).

In 1981, the Illinois General Assembly decided to review all regulatory acts and sunset those deemed of little value (Semonin, 1981). Chief Changnon was chairman of the Illinois Weather Modification Control Board and became heavily involved in a myriad of activities including providing testimony in Springfield on four occasions and responding to many governmental requests for information. As a result, the Illinois Weather Modification Control Act, enacted in 1973, survived (Changnon, 1983d).

Frequent polarity between scientists involved in natural resources and state bureaucrats involved in deciding such resource issues became the subject of an assessment of the issue presented as an article in *State Government* that provided suggestions about how to improve these relationships (Changnon, 1983f). These interactions led to an invitation to assess the roles that state government could and should play in dealing with planned weather modification (Changnon, 1983c).

Another opportunity for addressing government policies was the severe drought of 1988-1989, which extended across most of the nation and included Illinois. The lessons "taught" by the drought were assessed for hydrologists and state water managers after an invitation to do so (Changnon, 1990a). The controversy involving Illinois, the other Great Lake states, and Canada over a proposed increase in the diversion of water from Lake Michigan during the 1988 drought was assessed (Changnon, 1989d). Changnon also joined other scientists in preparing a book about the policy issues related to the severe 1988 drought (Riebsame et al., 1991). In response to an invitation from the American Water Resources Association, a chapter was prepared for a 1993 book on U.S. drought management policy and problems (Changnon, 1993b). Ironically, that same year a record flood struck the Midwest, and Changnon (1995c) addressed both the state and federal policy issues dealing with flooding, as well as the local and state policy issues involving flooding on the Illinois River (Changnon, 1994b).

Floods, like droughts, are major problems that frequently affect Illinois and state government. Problems with flooding, particularly in urbanized northeastern Illinois, became the subject of a climatic analysis of why flooding was increasing and an article for policy-makers in *Illinois Municipal Review* (Changnon, 1984f). Misconceptions about droughts, floods, and other climatic fluctuations were the subject of an invited talk given at a state meeting of water managers (Changnon, 1984f). Drought management was assessed at a national level reflecting an area of policy "failure" (Changnon, 1985g). As a member of a panel of the National Academy of Sciences dealing with cumulative environmental problems, Changnon addressed public policy and climate issues (Changnon, 1985e). A chapter on "atmospheric issues and the potential for their management"was prepared for a book (Changnon, 1986f). An invitation to lecture on Great Lakes policies relating to hydrospheric and atmospheric issues led to yet another paper (Changnon, 1987g).

Federal handling of weather modification again became the subject of an historical assessment that revealed gross mismanagement (Changnon and Lambright, 1987). Lessons these mistakes teach about federal management of "big science programs" were identified (Lambright and Changnon, 1989).

Another major policy-related activity involving the Survey's atmospheric scientists beginning in 1982 requires some historical background. In 1981, NOAA chose to end its support of all weather modification research, a result of the research budget cuts of the new Reagan Administration. This action suddenly ended support for the Survey's rapidly developing PACE program just as a field experiment was being planned (a similar situation occurred in 1973 when federal shifts cut support for a growing PEP). Chief Changnon and leaders of weather modification research projects in three other states (North Dakota, Utah, and Nevada) formed a "State-Federal Cooperative Program in Atmospheric Modification" to seek and obtain

Congressional interest and support for restoring the research funding to the NOAA budget. After Illinois Governor Thompson sanctioned Illinois' participation in these activities in 1982, Director Michael Witte, head of the Department of Energy and Natural Resources, and Chief Changnon went to Washington in March 1983 to discuss the program with Illinois' Congressional delegation (two members also sat on the appropriations subcommittee for NOAA). There was strong interest in "maintaining good science in Illinois," and Congress added funds ($300,000) to NOAA's budget for PACE and similar funding for the other three states, which set a precedent. Thereafter, and through 1995, NOAA removed the federal-state Atmospheric Modification Program (AMP) from their proposed annual budgets, and Congressional members from the states systematically restored the funding. However, restoration required annual meetings and exchanges involving Changnon, project leaders from other states, and members of Congress and their staffs.

Still another important policy-related issue developed when Dick Semonin, as the leader of the Survey's atmospheric chemistry endeavors, began addressing the acid rain issue nationally and across Illinois. A major interaction with state officials about the issue began with a briefing conducted in 1980 in Springfield. Thereafter, Semonin and Changnon were assigned to the Governor's Energy Task Force. Stensland and Semonin (1982) published a major paper challenging the conventional wisdom about the causes for the national trends in pH, which attracted national visibility and became the center of a scientific controversy (see Chapter 9). Semonin was asked to chair a special AMS committee to prepare a statement about acid rain. The Survey remained active and nationally vocal on this issue.

The Regional Climate Centers (RCCs) proved to another matter of great importance. The Survey had developed the concept of using RCCs to improve the delivery of climate information at the local and state levels (see Chapter 5). Congressional intervention and support on behalf of the regional centers was sought in 1987 when no federal agency (NOAA or USDA) would fund the budding RCC program. Changnon and leaders from the five new centers elsewhere in the nation made a special pilgrimage to Washington in March 1987 to promote the concept and explain the national values to be realized from funding the RCCs. This action resulted in strong Congressional support, and $1.5 million was added to NOAA's FY88 budget for the RCCs. In subsequent years, NOAA has not funded the RCCs as part of their base budget, but Changnon and Ken Kunkel, Director of the Midwestern Climate Center at the Survey, have worked diligently with leaders from other RCCs to maintain Congressional support. The amount of support for the growing RCCs services programs has grown, reaching $3.1 million by FY95.

"Add-on" funding for the PACE program (re-named PreCCIP in 1990) and for the Midwestern Climate Center was successful largely as a result of Survey staff's direct involvement in federal science research policy. Success in achieving Congressional support required extensive attention each year to a wide variety of issues relating to protecting and maintaining the two programs, including authorization for the programs, answering numerous questions from congressional aides, frequent visits with major in-state program constituents such as the Illinois Farm Bureau, numerous communications between project leaders, the preparation of special program documents each year, and resisting occasional efforts of NOAA to delay or retain the funding for the AMP. However, in 1995 Governor Edgar forbade state officials from seeking program restorations in Congress. This greatly limited efforts to restore funding for the two programs in 1996 and beyond, and the massive changes in Congress calling for major reductions in federal spending ended the future funding of the PreCCIP project. Fortunately, funds for the RCCs and hence for MCC were partly restored by Congress for FY96.

The Survey has also added its voice on numerous policy issues surrounding the global climate change issue, including joining with the National Climate Program Office and the Canadian Climate program to organize and host an international conference in 1989 about climate change on the Great Lakes, an activity that provided high visibility for the Water Survey on this key issue. As a result of Congressional invitations, Changnon (1989) and Lamb (1989) each provided testimony in Congress about the seriousness of climate change. To further alert state leaders, an article about the possible impacts of a warmer and drier climate in Illinois was prepared for *Illinois Issues* (Changnon and Lamb, 1990).

Concern over global climate change and the need for state attention to this important issue led Chief Semonin and Stan Changnon to advocate establishment of an Illinois Task Force on Global Climate Change in 1991. With assistance from certain legislators including Rep Satterthwaite, and the support of the Illinois Farm Bureau, the Illinois General Assembly established such a Task Force in 1992, and this standing body has thoroughly addressed various state policy issues (Changnon, 1995b). Governor Edgar nominated Changnon as the Science Advisor to the Task Force in 1992, a role he still holds. A key policy position of the Task Force concerning the need to adapt to climate change was the topic of an invited lecture given at a Midwestern conference on climate change (Changnon, 1995d).

ASSESSMENTS OF THE STATUS OF SCIENCE

The emergence of the Survey's strong research programs in both planned weather modification and inadvertent weather modification focused national scientific attention on the Survey. This also brought prominence to Survey scientists and, in turn, invitations to assess the scientific status of those fields and recommend needed research.

These activities began during the 1970s with invited assessments concerning planned and inadvertent weather modification. In 1972, the National Center for Atmospheric Research (NCAR) invited Section Head Changnon to perform a major assessment of what was known about how humans had accidentally changed weather and climate (Changnon, 1973f). Changnon was chosen as the chairman of the AMS committee on weather modification in 1971, and prepared a new policy statement about the status of the field (Changnon, 1973k). Four staff members (Ackerman, Appleman, Changnon, and Semonin) were asked to participate in a national assessment of the cloud physics field during 1973-1974 (Changnon et al., 1974). For a conference of state resource managers, Changnon (1974e) was invited by the AMS to assess priorities for research in planned and inadvertent weather modification. He and five other scientists were later invited to prepare a sweeping assessment of the field of weather modification (Sax et al., 1975). An invitation from the AAAS led to a paper defining the status of knowledge about urban weather modification (Changnon, 1975c). Changnon (1977c) assessed the status of the field of hail suppression for the *Bulletin of the American Meteorological Society*, and (Changnon, 1978k) debated the progress made in defining the costs and benefits of atmospheric sciences research. Changnon and Semonin received an invitation from the AMS to serve as Co-Chief Editors of the *Journal of Applied Meteorology*, and they served in this prestigious role for three years, 1977-1979. In 1995, Bob Czys was asked by the AMS to become an editor of the *Journal of Applied Meteorology*.

The National Academy of Sciences (NAS) invited Changnon to join a national panel assigned to perform a broad assessment of the atmospheric sciences (Changnon, 1977k). Two years later, Changnon was invited to be a member of an Academy panel that was to assess precipitation forecasting (Changnon, 1980k). In response to an invitation from the U.S. Air Force, Changnon (1979i) assessed the status and prospects for various types of weather modification, and presented a lecture at the Air Force Academy. Changnon and Semonin (1979) were asked to review the human impact on local and regional weather for the *Review of Geophysics and Space Physics* (RGSP). The World Meteorological Organization commissioned Changnon to prepare two sweeping analyses: one for the economic, legal, and environmental aspects of weather modification (Changnon, 1979j), and another about the design and evaluation of precipitation enhancement projects (Changnon, 1979k).

These requests for assessments of various subject areas of the atmospheric sciences continued into the 1980s and 1990s. Changnon and Semonin (1982c) provided their views in a national debate over the science of cloud seeding. They also began to extend their views to topics other than weather modification. For example, the American Water Resources Association asked Changnon to analyze the applications of weather and climate information in hydrology (Changnon, 1981d). An outlook for future trends in flooding in Illinois was presented in response to an invitation from organizers of a state conference of hydrologists and civil engineers (Changnon, 1984c). The widely read *Illinois Research* magazine requested papers on weather and climate issues (Changnon, 1985a, 1985h). The new journal *The Nature of Illinois* asked for a paper discussing various forms of inadvertent weather modification (Changnon, 1986c), and the AMS asked Changnon (1986d) to provide an assessment of the accomplishments and contributions of famed climatologist, Helmut Landsberg.

Semonin and Stensland offered widely read assessments of the nation's acid rain situation and created an interesting scientific controversy because their views were counter to commonly held beliefs (Stensland and Semonin, 1982, Stensland and Semonin, 1984a and b). Further acid rain assessments included one defining the spatial patterns across North America (Summers et al., 1987). Semonin (1987) prepared a treatise about the long-term trends in acid rain, and Bowersox et al. (1990) addressed the U.S. perspective on acid rain as part of a global assessment of the issue. Kunkel was asked by the AMS to review a series of books (Kunkel, 1990c, 1994b, 1995b). Other review-status papers came from Survey atmospheric chemists with Semonin (1985) assessing the broad field of wet deposition chemistry. Gatz et al. (1986) reviewed the precipitation climatology based on contents of alkaline materials. Gatz (1991) subsequently prepared a broad review of what is known about the chemistry of urban precipitation. Semonin provided an invited review of the Survey's program in atmospheric chemistry at a national conference in 1993.

Floyd Huff received the 1986 AMS Horton Award for his outstanding achievements in hydrometeorological research, and responded by preparing a review of the field of urban hydrometeorology (Huff, 1986a). Part of Changnon's role as chairman of the NSF review panel included reviews of that organization's atmospheric sciences program (Changnon, 1984g; Jordan and Changnon, 1986). Beard (1987) assessed the nation's research dealing with cloud and precipitation physics during 1983-1986, and an earlier invitation led to an assessment of the charging mechanisms in clouds and thunderstorms (Beard and Ochs, 1986). Beard and Ochs (1993) also prepared an invited overview of the microphysical mechanisms associated with the formation of warm rain.

Additional invited reviews concerned climate issues. Illinois Governor Thompson hosted in 1986 a conference in Chicago concerning key state issues, and Changnon (1986i) was asked to present a treatise on weather and climate issues affecting the Great Lakes and Illinois. In 1987 the Canadian Climate Program invited Changnon (1987g) to assess the research needs in the hydrospheric and atmospheric sciences for the Great Lakes basin. The American Society of Civil Engineers invited Changnon (1990d) to describe the problems associated with fluctuating levels of the Great Lakes at a national water conference. And, for the International Joint Commission, an assessment was made of the climate and hydrologic forecasting being done for the Great Lakes (Changnon, 1990f). v

For a national water conference, Changnon (1987b) was asked to develop a paper addressing the future flood research agenda for the U.S. In pursuing an assessment of Great Lakes' high water problems, the National Academy of Sciences invited Changnon (1989c) to address the scientific "knowns and unknowns" about climate change in the Great Lakes basin. Changnon was invited to assess applied climatology in a lecture at an AMS conference (1991g), and the Congressional Office of Technology Assessment requested an assessment of the implications of climate change on national flood policies (Changnon, 1993c). As part of their 75th Anniversary Celebration, the AMS invited an assessment of the history and future of applied climatology at its 1995 annual conference (Changnon, 1995e). In response to an invitation from the University of Minnesota for a memorial lecture, Changnon (1994d) presented an analysis of the importance of public understanding of climate and the values associated with the many uses of climate information.

Requests for assessments of weather modification continued. The American Association of Geography requested an assessment of purposeful and accidental weather modification for a lecture at their 1984 annual conference (Changnon, 1984h). Changnon (1986e) review the key findings in the papers presented at the Tenth Conference on Weather Modification in response to an AMS invitation. An assessment of the nation's research program in weather modification resulted from an invitation for a talk by the Weather Modification Association (WMA) (Changnon, 1991h), and the WMA invited Changnon to address "lessons from the past" at its annual conference (Changnon, 1995f). Czys was asked in 1995 to perform a review of the recent scientific achievements in the field of weather modification for the *Review of Geophysics and Space Physics* (Czys, 1995).

SUMMARY

Achievements

Extensive involvement of Survey leaders in governmental activities and policies since they were begun in 1970 have been successful in achieving the objectives set for these activities. Atmospheric science issues faced by Illinois and the nation have been subject to extensive assessments by Survey leaders. Survey atmospheric scientists became heavily involved in addressing governmental policy matters during the 1973-1995 period and achieved marked success in several areas:

- helping to establish the National Climate Program Act in 1978, and improving it in 1981.
- establishing Regional Climate Centers in 1987.
- affecting state and national policies on acid rain.
- obtaining long-term funding via Congressional support for the Survey's weather modification program and the Midwestern Climate Center.
- affecting several state policies: 1) establishing a law for the control of weather modification, 2) acceptance of weather-climate issues as part of the state water plan, and 3) addressing climate change (including establishment of a state Task Force).
- creating awareness of atmospheric issues and Water Survey staff expertise at the highest levels of state government.

It is difficult to measure success of the Survey's efforts to get its program plans, scientific projects, and scientific capabilities widely known, but one indicator is certainly in the form of numerous invitations to Survey scientists to prepare and present assessments and reviews of the scientific issues and progress (38 such review papers have been requested and published since 1973). Other measures can be found in the numerous awards presented to Survey staff and the scientific achievements described in the summaries of Chapters 3-10.

Creation of a well-known scientific staff has led to invitations to serve on several National Academy of Sciences panels assessing precipitation forecasting, reviewing NOAA laboratories, addressing the needs of the atmospheric sciences, investigating Great Lakes problems, and assessing management of the atmospheric sciences. Several staff have been invited to serve on prestigious advisory panels to federal agencies. Bernice Ackerman served on EPA's science advisory panel (1976-1978); and Changnon chaired EPA's global change research panel (1989-1992) and NSF's atmospheric science program committee (1980-1982, 1987-1990) and served on the NOAA education committee (1990-1992). Changnon was also invited by NOAA to serve on its Flood Survey Team in 1993, by NSF-UCAR to chair the NCAR program review of 1987-1988, and to serve as a member of EPRI's program on climate change (1989-1992). Gene Mueller served on NOAA's NEXRAD design committee in the 1980s, and Semonin served on the National Acid Rain Committee. Thirty-eight staff members have been asked to serve on various scientific committees of the American Meteorological Society. Ackerman, Changnon, Huff, Lamb, and Semonin have been selected as fellows of the American Meteorological Society, and Ackerman, Changnon, and Semonin were also selected as fellows of the American Association for the Advancement of Science (AAAS). Organized endeavors since 1970 to promote and enhance Survey projects and programs appear to have succeeded. The group is well known nationally and internationally for the quality and diversity of its scientific research and services.

Key Staff

Several staff members have been instrumental in these planning and promotional endeavors. Published papers and actions with governmental policies have been used to compile this list, which includes Bernice Ackerman, Stan Changnon, Floyd Huff, and Dick Semonin. Selection of Stan Changnon as Chief of the Survey (1980-1985) and Dick Semonin as Chief (1986-1990), the only atmospheric scientists chosen for this position in the history of the Survey, reflects their success in developing and leading the Atmospheric Sciences Program.

Pivotal Papers

Each of the 112 papers listed under this program area were important in achieving the program objectives. Certain early papers helped open later doors. For example, Changnon's (1973f) paper reviewing what was known about human influences on the atmosphere set the stage for many more assessments of planned and inadvertent weather and climate modification. The first paper about the questionable federal handling of weather modification research and funding (Changnon, 1973b) ushered Survey scientists into an era of assessing governmental actions. Semonin and Stensland's acid rain papers (1982,1984) challenged conventional wisdom about acid rain and gained great attention. Floyd Huff's (1986) review of urban hydrometeorological findings also targeted areas needing attention, which was quite a milestone.

Figure 11-7. Four long-term scientists who played key roles in advancing the weather program at the Survey are seen here at a Survey Centennial party in 1995: (l. to r.) Don Staggs, Marvin Clevenger, and Floyd Huff. Art Sim's back is to the camera.

*Figure 11-8. **(top)** Dick Semonin, Stan Changnon, and Floyd Huff are seen planning program strategy in 1969, the start of a new era for the Atmospheric Sciences Section. A major factor in our program success was use of nationally-known scientists serving on project advisory groups, **(below)** and here is a weather modification advisory group to project OSET seen on break (l. to r.) Chin-Fei Hsu and Floyd Huff (Principal Investigators for the project), Bernie Silverman (head of the Weather Modification Program at the Bureau of Reclamation), Stan Changnon (Section Head observer), and Paul Mielke (noted statistician from Colorado State University).*

Chapter 12

A SUMMARY: STAFF, FACILITIES, AND ACHIEVEMENTS

Stanley A. Changnon and Floyd A. Huff

This chapter has two objectives: 1) to summarize the key achievements of the 50-year old Atmospheric Sciences Group at the Water Survey, as gleaned from the from the previous chapters, and 2) to describe the circumstances under which the effort developed and flourished (and why). This includes the major controlling institutions, the atmospheric sciences staff, the facilities, and other key issues not specifically discussed in the previous chapters.

INSTITUTIONAL ISSUES

Structure and Leadership of the Atmospheric Sciences Group

When Chief Arthur Buswell decided in 1947 to help Lester Pfister in his quest for a cloud-seeding project, a small Meteorology Group evolved under the leadership of Glenn Stout as part of the Survey's Engineering Section (see Chapter 2). In 1953, this "weather group" headed by Stout became the Meteorology Section until 1965 when it was renamed me Atmospheric Sciences Section. Stout left in 1968 for a position at the National Science Foundation, but returned to me Water Survey as an assistant to the Chief in 1970).

Stanley Changnon became Section Head in 1968 and continued until 1980 when he became Chief of the Water Survey. The rapid growth of the weather research program during the 1970s peaked at 67 staff members and 23 students by 1978 and led to reorganization of the group and its endeavors in 1980. As shown in figure 12-1, the new entities established and related to the atmospheric sciences were the 1) Meteorology Section headed by Bernice Ackerman, 2) Climate Section led by Wayne Wendland, 3) Atmospheric Chemistry Section headed by Donald Gatz, 4) Climate Information Unit headed by John Vogel, and Analytical Chemistry Laboratory headed by Mark Peden.

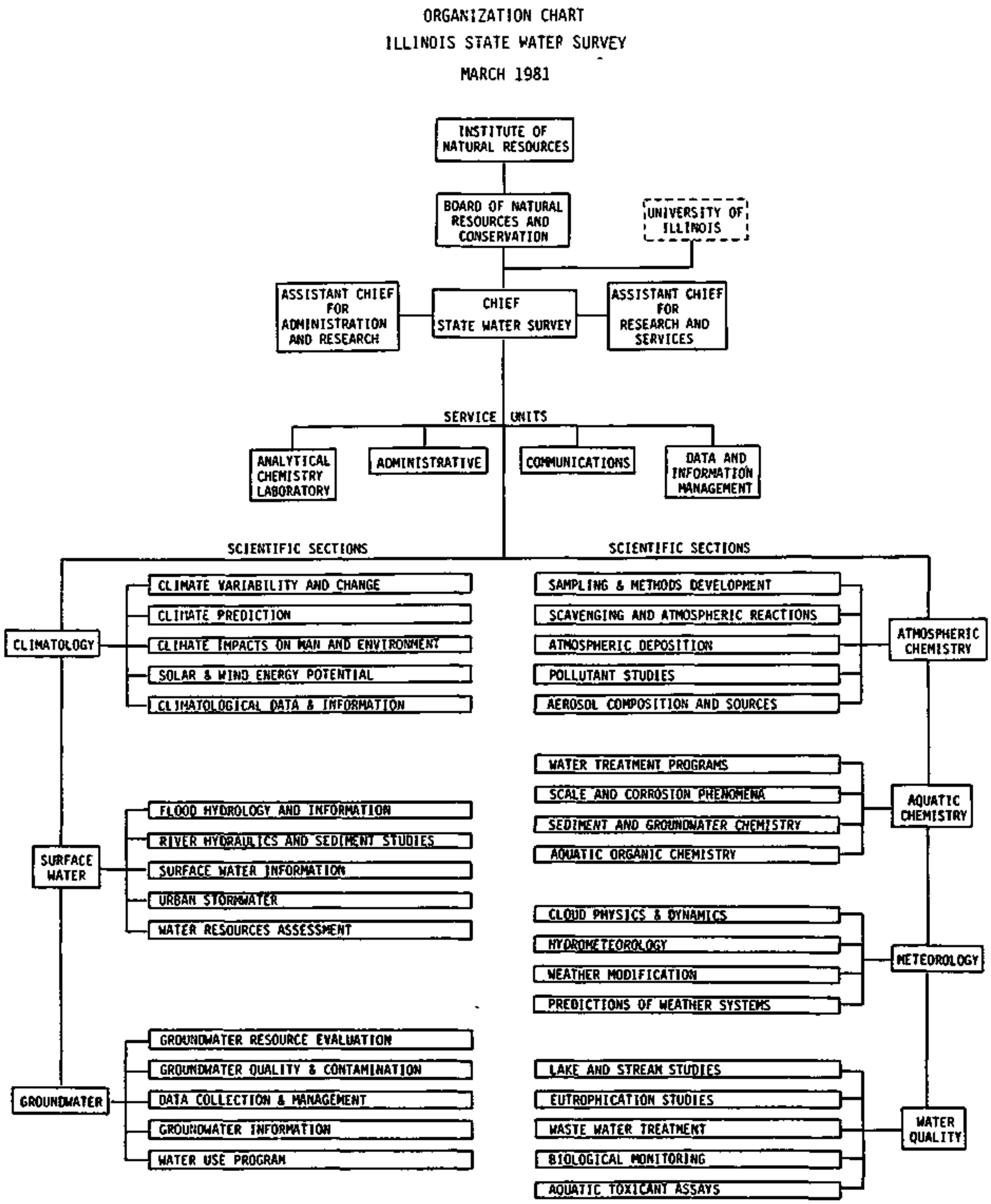

Figure 12-1. The Water Survey's structure after a major re-organization in 1980 with three sections addressing atmospheric sciences, and two units in support roles.

In 1983, the Meteorology and Climate Sections were combined as the Climate and Meteorology Section headed by Wayne Wendland and then Peter Lamb from 1985 until 1990. Wendland continued as the Illinois State Climatologist. With the formation of the Midwestern Climate Center at the Survey in 1987, the Climate Information Unit was dissolved. Gary Stensland succeeded Don Gatz as head of the Atmospheric Chemistry Section in 1986.

Dick Semonin, who became Chief of the Survey in 1986 reorganized the Survey's structure in 1989, forming the Atmospheric Sciences Division (appointing Stensland as Head), and establishing four offices: Applied Climatology Office headed by Kenneth Kunkel, Air Quality Office headed by Don Gatz, Cloud and Precipitation Research Office led by Harry Ochs, and Precipitation Quality Office headed by Van Bowersox. This is still how the group was structured when this review was prepared in 1995-1996.

State of Illinois

From 1895 when the Water Survey was established at the University of Illinois until the 1970s, the Chiefs of the Scientific Surveys and their senior staff members selected almost all the issues and problems to address, including the amount of emphasis on data collection, research, and services, with the Board of Natural Resources and Conservation generally approving their choices (Hayes, 1980).

From 1917 onward, the Water Survey was one of the divisions of the Department of Registration and Education (R&E). This agency's main mission was to license persons in various professions, and R&E typically had a lawyer or an ex-judge as its director. Consequently, the three Scientific Surveys were anomalous to the agency's main mission and were seldom understood, often ignored, and generally not well supported by state leaders in Springfield. Nevertheless, this had advantages in that what the Surveys chose to do, or not to do, did not come under close state scrutiny.

The 1917 reorganization of state government (which moved the three Scientific Surveys into R&E) also established the Board of Natural Resources and Conservation (somewhat similar to a board of Trustees for a state university). The Board was responsible for the Surveys and their staffs. State control existed since the director of R&E was also the chairman of this Board. As "employees of the Board," Survey staff were not subject to the normal political process associated with many state employees (see Chapter 1) and only the support staff of the Surveys were classed as civil service appointees.

The development at the Water Survey in late 1947 of a Meteorology Group, which largely collected data and performed research for various Department of Defense agencies from 1950 to 1966, was an activity with generally minimal state significance. The group's presence in state government became most visible at the Illinois State Fairs during the 1950s where a portable weather radar was operated, favorably impressing fair-goers and state officials with its novel ability to detect nearby rains. The issuance of reports presenting hydrometeorological and climatological design information was the other activity which gained some state attention during the 1950s and 1960s.

Based on Chief Buswell's desires and Engineering Section Head Hudson's beliefs, the Water Survey's Weather Group's focus from 1947 to 1958 was on the needs of hydrology. The emphasis was on precipitation measurements (radar and raingages), hydrometeorological studies, and the production of climatological information. When William C. Ackermann became Chief of the Water Survey in 1958 he greatly broadened the mission of the Meteorology Section by re-defining its activities to be: 1) studies focused on water resources (which included the three original areas of emphasis: precipitation measurements, climatology, and hydrometeorology), 2) studies of the mechanisms of precipitation formation with an emphasis on precipitation modification, and 3) studies leading to improved forecasting of precipitation and severe weather.

The departure of Glenn Stout as Section Head in 1968, coupled with changing sources of federal funds for weather research and the shift to Stan Changnon as Section Head brought the Weather Group of the Survey into a new era of research planning and identified a new set of research themes: planned weather modification, inadvertent weather modification, hydroclimatology, atmospheric chemistry, and severe local storms. Undergirding these five programs was continuing research in hydrometeorology, climatology, cloud physics, and instrument development. Studies of the impacts of weather and climate were added as a fifth program area in 1970. Additional new program themes emerged in the mid-1970s, including acid rain (atmospheric chemistry), evaluation of operational cloud-seeding projects (including the eight in Illinois), agricultural meteorology, and solar and wind energy data for Illinois.

Governor Dan Walker was elected in 1972 and appointed Ronald Stackler as Director of R&E in 1973. Stackler was dissatisfied with the Scientific Surveys and their long heritage of self-driven science. He openly fought with the Chiefs and forced more definitive planning, introducing the Management by Objective (MoB) approach to the Surveys (against their will). However, the Water Survey's growing Atmospheric Sciences Section already included a project planning and monitoring system, which had established milestones and strict deadlines by 1972, an approach that had become a necessity to manage and survive in the difficult world of federal grants and contracts. Hence, the shift to MoB was easy for the Section. After visiting the Section in 1973, Stackler praised its operations and the external fund raising nature of the weather research such as the in progress research and development of the infrared aerial photography method for assessing crop-hail damage (which industry was supporting).

To the relief of the Survey Chiefs, Joan Anderson, a friend of the Surveys, became the new Director of R&E in 1977. Unfortunately, her appointment came at a time of major cuts in the state funds for the Surveys, the second time in five years, and at a time of planning for reorganization of state government.

In 1975 the concept of a major reorganization of state government had begun, and a non-partisan government study committee was established in 1976. One of their recommendations called for forming a three-entity resource-environmental group: 1) the Institute of Natural Resources (INR) largely comprised of the three Surveys to do the needed research, 2) the Illinois

Environmental Protection Agency to monitor and regulate, and 3) the Illinois Pollution Control Board to assess environmental problems and issues. Governor Thompson assessed the proposed changes and agreed. Establishment of INR occurred on January 1, 1979, which dramatically changed the *institutional environment* of the Water Survey and its two sister Surveys. Now the Surveys were in a state agency that better understood and recognized the Surveys as integral to its mission because the could provide natural resource information as the "research arm" of state government. This action brought the three Scientific Surveys closer to state issues, provided more direct involvement with state government, and gave access to state research funds distributed by INR.

The first Director of INR, Frank Beal, was an outstanding choice. He understood Water Survey values and insisted the Water Survey dramatically improve how it functioned (better planning, development of an up-to-date accounting system, involvement in state issues, etc.). With Board support, Beal helped "bring the Water Survey into the 20th Century." As a result of this reorganization and Beal's mandates, a new world of state government interactions was developing when Changnon became Chief in 1980. INR had research funds, and Beal approved Changnon's 1980 request "to establish a major program in climate research," providing $125,000 new funds in the Survey's base budget. In response to Water Survey proposals, atmospheric sciences also received a 1981 INR grant to establish a solar and wind energy measuring network.

During the late 1970s and throughout the 1980s, Water Survey leaders became heavily involved in several state issues (see Chapter 11). Changnon was named chairman of the Illinois Weather Modification Control Board in 1975, a position he held until 1985. Changnon also became a member of the newly formed Illinois Water Plan Task Force in 1980, a role assumed by Chief Semonin in 1986 when Changnon retired. Because of alternative energy issues and acid rain concerns in Illinois, Changnon and Semonin were both appointed to the Governor's Task Force on Energy in 1981 with terms lasting to 1985 when the Task Force was terminated.

Such direct involvement in state policy development led to changes in emphasis of the Survey's atmospheric programs, which led to a greater focus on air quality and atmospheric chemistry, climate change research, and enhanced climate information services. Research and experimentation in planned weather modification remained strong, but inadvertent weather modification efforts decreased because the major issues had been resolved. Research in cloud physics, climatology, and hydrometeorology continued. Agricultural meteorology research and data collection efforts grew.

Change relevant to the Survey continued in Springfield, and in 1982, INR became the Department of Energy and Natural Resources (DENR), enlarging the agency's staff and diffusing its attention towards the Surveys. Mike Witte replaced Beal as director in 1982 and continued Beal's enthusiasm for the Surveys. More of the DENR research funds were devoted to the Surveys in support of atmospheric-oriented projects for drought studies, soil moisture measurements, and studies of weather influences on pests. When Governor Thompson moved Witte to head of the Illinois Department of Conservation, Don Etchison became the director of

DENR in 1984. Etchison became engrossed in Illinois' efforts to lure the federal supercollidor facilities to Illinois and paid minimal attention to the Surveys. He left in 1986 and Karen Witter became the new director of DENR. When Jim Edgar was elected Governor in 1990, he replaced Witter with John Moore. Another re-organization of state government affecting the Scientific Surveys occurred during 1994-1995: DENR was out, but a new Department of Natural Resources (DNR) was established on July 1, 1995, headed by Brent Manning, who also serves as chairman of the Surveys' Board. Ramifications of these changes on the Atmospheric Sciences program are as yet unknown.

Chief Semonin and Stan Changnon had long been concerned about global climate change and in 1989 decided to act on the issue at the state level. They worked with Representative Helen Satterthwaite and other members of the General Assembly and with the Illinois Farm Bureau to establish an Illinois Task Force for Global Climate Change. A Task Force was established by the General Assembly in 1991. Governor Edgar appointed Changnon as science advisor to the Task Force, an activity that continues in 1996.

University of Illinois Interactions

Interactions with the University of Illinois were of critical importance to the Atmospheric Sciences program for several reasons. First and foremost was the fact that grants and contracts, the keys to the group's development and financial survival, were and are handled by the university, not by the state. This situation made most Atmospheric Sciences staff "university" employees, and project activities followed university regulations for operations (travel, vehicle rentals, equipment purchases, etc.). The state and the university, as double masters, often created management problems. The university shared 50 percent of the earned overhead with the Survey, funds sometimes made available for salaries, equipment purchases, or travel, and this situation meant that Section heads had many interactions with university staff on financial and personnel matters. On a positive side, this affiliation with the university allowed atmospheric scientists access to all university facilities and even more importantly the computers and allied equipment necessary for many research tasks.

The University of Illinois formed an atmospheric sciences research group in 1965 and hired Yoshi Ogura as its head. A numerical modeler, Ogura developed a small group focused on modeling. Motivation behind the group's formation lay in the fact that the University of Illinois envisioned itself as a pioneer and leader in the field of computer development and applications. And during the 1960s atmospheric modeling had become a growing user of sophisticated computer systems. Ogura's modeling interests were far removed from Survey research programs, and he showed little interest in the Survey's atmospheric program. When Ogura sought departmental status for his group in 1972, the Survey helped get that accomplished, an act that improved relations between the two groups. It was agreed to recruit a "shared" cloud physicist, and Ken Beard, who was hired in 1975, became the first split-appointed staff. After some prompting, Ogura also appointed Semonin as an adjunct professor of the new department in 1975 (Semonin resigned in 1986), and Peter Lamb was invited to become adjunct associate professor in 1989. Stan Changnon became an adjunct full professor in the Atmospheric Sciences Department in 1994, and Harry Ochs in 1995.

Strong interactions between the University of Illinois Geography Department and the Water Survey began in 1960 under Joe Russell, head of that department, and were continued during the 1970s by John Thompson who replaced Russell. Changnon became an adjunct professor of geography in 1973, and Bill Lowry, hired by the Survey to head METROMEX in 1972, became a full-time member of the Geography Department in 1975. Various departmental professors teaching climatology joined with Survey scientists in research, including Jim Lahey (1966-1974) who had research interactions with the Survey. Then Wayne Wendland, a visiting staff member in geography, was recruited to join the Survey staff in 1977 and later became an adjunct professor of geography. These close working relationships continued into 1996 with Professor Scott Isard and over the years have involved several graduate students at the Survey including Jim Angel who recently obtained his Ph.D. in geography

Changnon and Huff in 1969 began a joint research effort with Earl Swanson, a professor of agricultural economics. This relationship grew and several joint projects were conducted over a period of 20 years. These efforts embraced other departmental staff such as Steve Sonka and Phil Garcia, who became adjunct members of the Survey's Atmospheric Sciences Section until they terminated in 1991. These interactions lasting between 1969 and 1990 also led to hiring of many agricultural graduate students. Strong relations also developed with staff in other parts of the College of Agriculture, and particularly in agronomy. Survey weather scientists served as the "weather experts" for the university's Cooperative Extension program from 1962 on, delivering hundreds of talks, lectures, and briefings. Since 1985, Survey weather modification research used a portion of the university's South Farm facilities in tests of effects of added rainfall on crops.

Efforts to establish a National Oceanic and Atmospheric Administration (NOAA) Cooperative Institute at the University of Illinois during 1992-1994 were jointly pursued by Changnon (acting on behalf of the Survey), Bob Wilhelmson (acting head of the Atmospheric Sciences Department), and Chester Gardner (Dean of the Graduate College). After much negotiation with NOAA, heads of the Office for Oceanic and Atmospheric Research (Ned Ostenso), the National Weather Service (Joe Friday), and Gardner agreed to establishing an institute in August 1994. However, the new dean of the Graduate College (Richard Alkire) who had replaced Gardner was not as interested in the cooperative institute as formulated. Problems between the Water Survey Chief and the Graduate College, coupled with changes in the Atmospheric Sciences Department at the University plus Changnon's need to give full attention to his research commitments left the formation of the institute totally in the hands of the University with no Survey involvement. Nothing was done by University officials during 1995-1996 to re-formulate the concept for a NOAA cooperative institute.

STAFF

Staff Size

In 1951 the staff of the new Meteorology Group included Glenn Stout, Floyd Huff, Doug Jones, Gerald Farnsworth, and Homer Hiser (fig. 2-1). The addition of federal funds under contracts with the Signal Corps and the Navy led to more hirings in 1951. As part of a major U.S. Air Force contract, the University of Chicago awarded a subcontract to the Water Survey early in 1952, leading to construction of a quonset building at the University of Illinois Airport (fig. 3-10), a new home for the growing meteorology staff. Staff working on the subcontract in 1954 included Stan Changnon (operational leader), Donald Staggs (chief electronic engineer), Stuart Bigler (meteorologist), Jack Fatz (electronic engineer), Lyle Smith (technician), and Stewart Dodge (radar operator). Other Meteorology Section staff working in 1954 included Glenn Stout, Floyd Huff, Jim Neill, Eugene Mueller, Gerald Farnsworth, Larry Dean, and Doug Jones.

By 1960, the ever-fluctuating staff of the Meteorology Section included ten senior staff (Bill Bullock, Stan Changnon, Floyd Huff, Doug Jones, Irene Koch, Gene Mueller, Dick Semonin, Don Staggs, Glenn Stout, and Ken Wilk), and six support staff. Rapid growth of the section began in 1967-1968 with large NSF grants. By 1970, the Atmospheric Sciences Section included 31 scientists and engineers, plus nine support staff. Several senior scientists were added from 1968-1973, Bernice Ackerman, Don Gatz, Paul Schickedanz, Gary Stensland, and John Vogel.

The Atmospheric Sciences Section's report to the Board for 1974-1975 indicated that there were 37 scientific and engineering staff (6 with Ph.D.s) and 19 technicians/support staff. The first "objective" method for evaluating staff at the Water Survey began in 1973 in the Atmospheric Sciences Section. Previous evaluations were based on a Section Head's qualitative assessment of each staff member, an approach favored by Chief Ackermann.

Staff size in the Atmospheric Sciences Section peaked in 1978 with 67 full-time staff (36 percent of the Survey's total staff), and state funds supported only 11 of the total. There were 26 atmospheric scientists (22 meteorologists and 4 climatologists), 4 electrical (radar) engineers, 3 atmospheric chemists, 7 programmer-statisticians, 4 graduate students, and 22 technicians/support staff. Section publications in 1978 accounted for 62 percent of the Survey's total publications.

Senior Atmospheric Sciences staff and affiliates included 30 scientists and engineers in 1983. The total in 1985 was 31, with 11 in the Climate and Meteorology Section, 6 in the Climate Information Unit, 7 in Atmospheric Chemistry, and 7 in the Office of the Chief. The 1992 staff count showed the Atmospheric Sciences Division with 31 scientists and engineers, plus 14 support staff. Photographs of various staff members appear at the end of this chapter. Six of the Atmospheric Sciences staff who joined during the 1947-1955 period stayed on for 35 years or more: Changnon, Huff, Jones, Mueller, Semonin, and Staggs.

Key Staff

Defining "key staff" members during the 50-year history of the weather and climate program at the Water Survey is difficult. Several scientists have received the Survey's highest level appointment, principal scientist: Bernice Ackerman, Ken Beard, Stan Changnon, Floyd Huff, Peter Lamb, Harry Ochs, Dick Semonin, Gary Stensland, and Wayne Wendland.

Principal Investigators noted for sizable and long-term grants/contracts include: Bernice Ackerman, Ken Beard, Stan Changnon, Bob Czys, Don Gatz, Steve Hollinger, Floyd Huff, Ken Kunkel, Peter Lamb, Griffith Morgan, Gene Mueller, Harry Ochs, Paul Schickedanz, Dick Semonin, Donald Staggs, Gary Stensland, Glenn Stout, and Van Bowersox. This group also wrote many of the Survey's reports and papers. Other frequent authors included: Gary Achtemeier, Wayne Bradley, Robert Cataneo, Chin-Fei Hsu, Art Jameson, Dave Johnson, Doug Jones, Griff Morgan, James Neill, Randy Peppier, Michael Richman, Bob Scott, Art Sims, Neil Towery, John Vogel, Wayne Wendland, and Nancy Westcott.

FINANCIAL RESOURCES

Principal Sources

The early years of the program (1950-1967) involved sizable funding from contracts from the U.S. Army Signal Corps for 17 years on radar-rainfall efforts, contracts from the U.S. Air Force for a series of projects, grants from the Crop-Hail Insurance Actuarial Association (major private sector funds), and some National Science Foundation (NSF) grants for cloud physics and studies of hail and the effects of the southern Illinois hills on rainfall. *The second phase (1968-1980)* was heavily dependent on funds from grants from the NSF and the Atomic Energy Commission, which became ERDA in 1971, and then ERDA became the Department of Energy (DOE) in 1978. *The third phase (1981-present)* of major external support shifted with most coming primarily from NOAA and DOE with some substantial funding from USEPA and NSF.

Section Heads Stout and Changnon frequently attempted to obtain from Survey Chiefs a greater share of the overhead funds from earnings of grants and to get more state support for Section staff, equipment, or both. State funding to the atmospheric sciences program represented between 10 and 20 percent of its total funding for most years. Chief Ackermann used considerable overhead to help give raises to Survey staff during low increase years, or when cuts came in 1974 (the "Stackler period") and again in 1977. These actions moved state paid staff over to soft money and effectively reduced the state head count and the number of full-time staff on state payroll.

Amounts

In FY70 the Water Survey received $1.26 million in state funds, of which $164,000 was allotted to the Atmospheric Sciences Section, which had 10 grants in 1969 and 14 by 1970.

Chief Ackermann's admonishment in a memo to Section Head Changnon in 1970 (after a request for added share of state funds coming to the Survey) was, "you can go get all the federal money you can find, but you will get no more state money than your current share," which was 15 percent of the section's total.

The Survey's 1974-1975 report to the Board showed that the Atmospheric Sciences Section received $1.1 million in external grants/contracts and prepared 19 research proposals, of which 12 were funded and the rest were under review. Section staff had published 32 refereed papers (a new high), presented 18 papers at seven conferences, and had given interviews in response to 44 news media requests.

In 1975, the Section developed its own computerized accounting system on the Wang computer to monitor the complex expenditures of the $1 million in federal funds. The money came through 15 to 25 grants awarded annually, and there were ever changing shifts of staff between grants.

In 1978, the Atmospheric Sciences Section's 22 research grants totaled $925,000 (65 percent of all grants money to the Survey), and its state funds totaled $241,000 (16 percent of the Survey's total) for a total of $1.165 million. In 1980, the Atmospheric Sciences funding had reached $2.2 million. In subsequent years the annual amount has been between $2 million and $3 million.

FACILITIES

Headquarters for Staff

Staff members from 1947 to 1950 were housed at the University of Illinois' Noyes Laboratory where the entire Survey had been since 1896. State funds for a separate Water Survey building at 605 East Springfield Avenue in Champaign were awarded in 1948, and staff moved in 1950 (fig. 12-2). Space was inadequate and some staff were located in a white frame house adjacent to the new building, as shown in figure 12-2. The University of Chicago contract awarded in late 1951 led to construction of a quonset building (40 by 80 feet) at the University of Illinois Airport, and the entire Meteorology Section moved there in spring 1952 (see fig. 3-7). A 40 by 40 foot addition was constructed in 1958 to help house the growing staff who remained at the quonset until 1964.

Governor Kerner allotted funds for an addition to the Survey's "main building" on Springfield Avenue in 1962. When it was completed in 1965, most of the Atmospheric Sciences staff moved from the Airport to the new wing of the main building (fig. 12-2). Growth of the Atmospheric Sciences Group during the 1970s produced major space problems. Some staff moved back to the Airport quonset, space was rented beginning in 1974 in a building south of the main building, the conference room was divided into offices, and laboratories in the Chemistry Section were used for Atmospheric Chemistry laboratories. In July 1978, the Water

Survey successfully bid to become home of the nation's Central Analytical Laboratory, and chemical analyses of nation's rainwater samples began by using more of the chemistry labs of the Chemistry Section.

Growth of the entire Water Survey, as well as the Atmospheric Sciences Group, had become a major institutional problem during the late 1970s, In fact, it was one of the major

Figure 12-2. The Water Survey's main building as seen in 1956 from Springfield Avenue (top) looking to the southeast. Survey staff also occupied the two white frame buildings in the foreground. The Survey's main building in 1966 (lower) showing the addition built on the west end where the two white houses had once stood.

problems facing Changnon as new Chief in 1980. The library was moved to the basement, the editorial/drafting group was moved to rental properties in southwest Champaign, and other staff were located in rental space in buildings adjacent to the Survey's main building. When Governor Jim Thompson announced he was going to close the state's Adler Mental Health Clinic on the South Campus in 1982, Chief Changnon interacted with state officials and with University of Illinois leaders to obtain the larger facility. There was considerable competition with other university elements for this new larger facility since the university inherited the vacant facility by pre-agreement with the state. The Survey's existing building close to campus was the "bait" used to get Engineering College leaders behind the Survey's bid, and the Adler "estate" of six buildings on 18 acres became the Survey's future home in 1982. Work then began to obtain the necessary state funds ($2.4 million) to renovate the buildings and make them suitable for the Survey, including the development of extensive chemical labs and a cloud physics lab. With the work of Director Witte and his chief assistant, Roy Miller, state funds were obtained in 1983 that included additional resources to also build a chemistry building and a garage. Water Survey staff moved to the new South Campus facilities in December 1984.

Remote Facilities

Buildings, radar pads and towers, and facilities to house instrumentation were built to handle seasonal or long-term field projects at sites remote from Champaign-Urbana. A major facility was built by Survey staff at Pere Marquette State Park and used as field headquarters for METROMEX during 1971-1976 (fig. 12-3). Another major facility was built near Joliet and used during 1976-1980 as headquarters for CAP (fig. 12-3). Several other remote radar sites were established, each in use for one to three years, at various locales including Ft. Morgan, CO, Muskegon, MI, Ogden, IL, and Buncombe, IL (fig. 12-3).

Major sites of other field instrumentation have included the chemistry sampling facilities at Bondville, the Champaign-Urbana weather stations (at Morrow Plots, fig. 2-1, and then on the South Campus), the 20 sites of the Illinois Climate Network across Illinois, and large areas with 50 to 250 recording raingages established for five to ten years in southern, central, and northern Illinois (see fig. 3-1).

MAJOR ACHIEVEMENTS

Chapters 3-11 have identified major accomplishments within the dimensions of the major program areas addressed by the Atmospheric Sciences Group. We reviewed these and have attempted to identify the top achievements. The eleven identified in the summary represent our conclusions about the major successes of the past 50 years.

Developed and Maintained A Top Quality Research Group

We consider the creation and sustainment of an Atmospheric Sciences research/services group in a state agency, and one that has achieved national recognition for its scientific quality, to be an institutionally unique achievement unmatched anywhere else in the nation. This

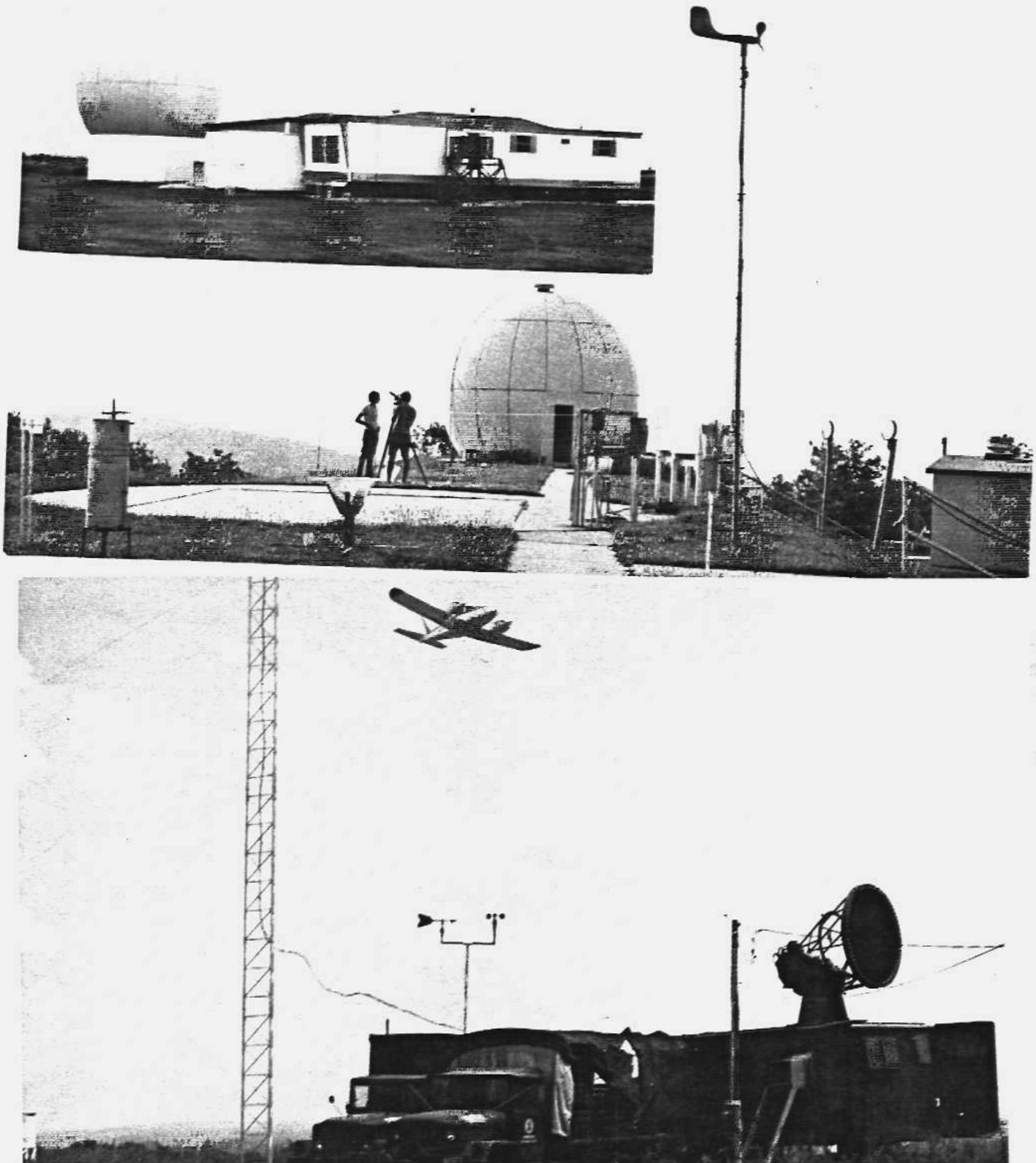

*Figure 12-3. **Upper left (inset)** is the Joliet site for CAP (1977) with radome over the HOT radar and trailer for operations. **Above** is HQ for METROMEX, the "hill," with (l. to r.) rainwater samplers, 2 raingages, students tracking balloons, radome for the TPS-10 radar, housing for cloud cameras, an aerovane, and clocks for the cloud cameras. **Lower** is Buncombe, field site of the 1970 field operations in the Shawnee Hill project involving surplus army trucks, a M-33 radar, and an aircraft used to sample atmospheric conditions over the hills.*

honorific achievement is partly revealed in the words of a special award from the American Meteorological Society to the Survey for the "initiation, support and successful completion of imaginative research in applied meteorology, including storms, rainfall and hail, weather modification, and hydrometeorology problems." *Fifty years of progress and scientific and technological achievements have formed a nationally and internationally recognized center of expertise in the atmospheric sciences.*

Secured Major Amounts of External Funding

A second major achievement of the Atmospheric Sciences Group is the fact that it has attracted approximately $65 million from federal and state agencies and private firms to support its activities over the past 50 years. State support to obtain this external funding was approximately $10 million, showing a 6.5 to 1 ratio, indicating a wise state investment.

Successfully Involved in Government Policy Issues

A third major achievement has been a long record of successful involvement in major government policy issues: weather modification policies including the development of a state regulatory act; the complex acid rain issue; global climate change (at both the state and national policy levels); and the development of the National Climate Program and the subsequent development of the Regional Climate Centers. Group actions have helped enact or alter several state and federal laws. Staff leaders provided testimony to Congress on numerous occasions, and have been able to obtain Congressional support to restore funding for our programs cut by federal agencies.

Made Major Scientific Discoveries

Several important scientific discoveries have been made at the Survey since 1947. The list includes the first detection of a tornado by radar (1953); discovery that convective cells and the lines of these cells typically moved in different directions (1959); delineation of the surface structure of hailstorms including hailstreaks, hailstripes, and hail cells (1968-1970); development of a technique to sense and measure crop-hail damage remotely with aerial infrared photographs (1969-1972); the first definition of the sizable urban effects on summer clouds, rainstorms, thunderstorms, and hailstorms including the mechanisms causing the changes (1968-1977); discoveries about how cloud droplets and raindrops interact to form rain (1966-1986); and development of an alternative rationale for the long-term trend in the national pattern of pH in precipitation (1980s).

Pioneered in Data Digitization and Computer Usage

The Atmospheric Sciences Group initiated the use of data digitization with punch cards (1955) and use of computers (1956) at the Water Survey. The group provided the initiative and funding for the Water Survey's first computer system in 1970, and developed special systems for creating digitized databases from paper data, from raindrop measurements, and for radar data. The Survey's Regional Climate Center pioneered the development of computer-based climate data-information systems for the nation: CLASS in 1983 for Illinois and men the Midwestern Climate Information System (MICIS) in 1988 for the entire Midwest.

Developed Specialized Instruments

The scientific and engineering staff designed and developed an amazing array of unique instruments for use in field operations, data analyses, radar operations, and for laboratory measurements. The nation's first passive hail sensors (hail pads, hail cubes, and hail stools) were originated at the Survey along with the nation's first recording hailgage. Survey staff designed and built the first operational raindrop camera later used to sample raindrops in various parts of the world. An area integrator was built in the 1950s to average and process radar-rainfall signals and get direct measurements. Several sequential rainwater samplers were designed and successfully operated. Special equipment such as droplet generators were developed for use in the Cloud Physics Laboratory. Staff designed and developed various automatic cloud cameras, as well as remote operating devices to record directionally the incidence of thunder. Various atmospheric samplers for making unique measurements aloft such as cloud water samples, were designed and built for use on aircraft. The development of the dual wavelength, dopplerized CHILL radar during 1969-1975 was a major engineering feat of the group. This effort also included the data processing system and computer-based operational controls, an innovative weather radar system that set the standard for modern radar systems being installed across the nation. An urban-rainfall monitoring and forecasting system for Chicago was developed using the HOT radar, a computer with special software system, and telemetered raingages. Automatic wet and dry samplers were designed, tested, and built for atmospheric deposition sampling, along with other specialized equipment for collecting data on atmospheric chemistry in various parts of the nation.

Conducted Major Field Operations at Remote Sites

A seventh area of major achievements involved extensive field programs using numerous weather measuring systems, housing for staff and equipment, complex logistics, multi-talented scientific and engineering staff, and long hours of hard work, often hundreds or thousands of miles away from home. The Atmospheric Sciences staff planned and successfully conducted several major national field projects involving other scientific groups: the Hot Wire Project (1960-1962), ITREX (1969-1970), METROMEX (1971-1975), CAP and CHAP (1976-1980), VIN (1981), PACE (1986-1990), and SCORE (1985-1988). Survey staff and equipment have participated in numerous national field programs including Project Springfield, National Hail Research Experiment, NADAP, HaRP, CaPE, and STORM FEST. As part of the extensive field efforts, staff installed and operated 14 major raingage networks for three or more years in various parts of Illinois and surrounding states. These networks have been the Central Illinois Network, Boneyard Network, Little Egypt Network, Shawnee Network, the METROMEX network, Chicago Area Network, Chicago Diversion Accounting Network, and the Havana Area Network. Since the early 1980s, the Survey has also operated the 20-station Illinois Climate Network with stations distributed across the state. The recent Lake Michigan atmospheric sampling project involved the installation and operation of samplers at sites around the lake.

Created Major Institutions of National Importance

The Atmospheric Sciences Group imaged and created major institutions which have achieved national significance. The Central Analytical Laboratory developed in the late 1970s has lasted to serve the state and nation as the location where the nation's rainwater samples are sent for quality analyses. The Survey conceived the national network of Regional Climate Centers for climate analysis and services, which led to the test center, the Regional Climate Coordinating Office, and later the current Midwestern Climate Center housed at the Water Survey. In 1990, the Survey established the Illinois Center for Global Climate Change to organize and conduct research and provide information about climate change.

Involved in National Debates over Major Scientific Issues

One sign of a successful and credible scientific institution is its involvement in major national scientific debates and controversies. The Survey's Atmospheric Sciences Group found itself involved in six such controversies over the past 50 years. First was the rainmaking debate involving the Hot Wire Project (1961-1962). The scientific community challenged Survey leaders' claim that initial findings indicated the cloud electrification experiment made rain. Next came the debate in the late 1960s over whether large cities could substantially alter rainfall and storminess triggered by the Survey's report about the "La Porte anomaly". This debate led to the formation of the successful METROMEX project. Still another area of controversy concerned statistical methods for developing rainfall frequency relations. Survey methods developed in the 1950s and improved over time have been frequently different than those used by the National Weather Service. There has been continuing debate over which methods are best, but agencies and engineers in the Midwest have adopted Survey results for most applications. Survey scientists issued findings in the 1980s showing that the national trends in pH (acid) rain were different, less upward, than the conventional wisdom, which launched a national controversy over which findings were correct. Finally, a major controversy evolved over the Survey's claims about federal mismanagement of weather modification projects and programs, and two federal agencies objected and claimed the Survey's position was biased and a debated ensued.

Developed Vast Amounts of New Information About the Atmosphere

The tenth area of significant accomplishment relates to the development of scientific information in a wide spectrum of areas. *Survey research has provided more information and data about the weather and climate of Illinois than exists for any other area in the world.* Table 12-1 summarizes the published scientific papers (refereed and non refereed) and reports since the Meteorology Group was formed in 1947. Atmospheric scientists have generated 849 papers and 396 reports over 50 years. Analysis of the temporal trends in the papers reveals a gradual increase from two in 1951-1953 up to seven for 1957-1959. Then the number doubled to 14 in 1960-1962, followed by another doubling from 19 in 1963-1965, to 38 in 1966-1968. The rapid increase in scientific papers continued, growing by 50 percent between 1966-1968 and 1969-1974, and then again by nearly 50 percent from 80 papers in 1978-1980 to 116 papers in 1981-1983 (the peak three-year production). Since 1989, the production of papers has decreased dramatically, falling to 65 in 1993-1995. Review of Survey reports (state series and contract series) shows steady growth from 1948 to 1968, then a leveling off until the peak value of 42 was reached in 1978-1980 and again in 1981-1983. Thereafter, the number has decreased, becoming less than half the 1981-1983 number by 1993-1995.

Table 1. The Number of Published Papers and Reports Dealing with Atmospheric Sciences During 1948-1995.

Years	*Scientific papers*	*Scientific reports*	*Total*
1948-1950	*0*	*1*	*1*
1951-1953	*2*	*5*	*7*
1954-1956	*6*	*16*	*22*
1957-1959	*7*	*17*	*24*
1960-1962	14	22	36
1963-1965	19	24	43
1966-1968	38	31	69
1969-1971	53	31	84
1972-1974	59	31	90
1975-1977	89	24	113
1978-1980	80	42	122
1981-1983	116	42	158
1984-1986	96	31	127
1987-1989	112	32	144
1990-1992	93	27	120
1993-1995	65	20	85

Much of the information known about the nature of convective rainfall in the Midwest came from the Survey's atmospheric research. This includes its variability in time and space, its physics and dynamics (causes), and how to forecast it. Survey scientists have defined the physical and economic potential for weather modification (rain and hail) in Illinois and the Midwest along with vast knowledge about the characteristics of severe rainstorms at all time and space scales. This pioneering research led to delineation of the rainfall frequency relations for the Midwest including what to expect on areas of all sizes from a point up to regions of thousands of square miles. Survey scientists defined how Lake Michigan and the hills of southern Illinois affect weather conditions and the climate of Illinois; provided the first definitive information on how large cities alter convective clouds, increase rainfall, and enhance summer storm activity; and assessed and measured how agricultural interests use and value climate information. Survey scientists have been national leaders in defining how weather and climate conditions affect the environment including water resources, human activities and health, and agriculture and Illinois crops. As partly revealed by the awards to our scientists and the Survey have received, our staff has been recognized nationally and internationally for our scientific achievements and expertise in seven areas. These include:

- •applied climatology
- •hydrometeorology
- •impacts of weather on agricultural crops, water resources and government policies
- •operations of raingage and rainwater sampling networks and radars and analyses of the these data
- •design and evaluation of weather modification projects
- •inadvertent urban modification of weather and climate change
- •collection and chemical analysis of precipitation samples

Services to Illinois and the Nation

The eleventh and potentially most important area of significant achievement has been services to the public and private sectors. Many of the more than 2,500 publications issued were designed to provide users with specific design or operational information. Several of these efforts have been nationally recognized as outstanding including the famed Horton Award from the American Geophysical Union (1964) and from the American Meteorological Society (1986), two for the best paper of the year by the American Water Resources Association (1986 and 1991), and a report selected as best of the year by the American Association of Agricultural Economics (1978).

The Survey was the home for the U.S. Weather Bureau's state climatologist from 1952 to 1972 and thereafter provided the senior staffing for this important services position. Since 1980, the Survey has been the home of the services-oriented Regional Climate Center for the Midwest with unique computer access dial-in system providing 20,000 accesses per year. The Survey group pioneered in the assessment of users of climate information, as a means to improve its services, and has created a unique number of climate products available on MICIS, the dial-in system. Staff have presented more than 4,000 talks, speeches, and lectures at public meetings and scientific conferences, as well as serving on 57 state and federal advisory panels/committees, including five panels of the National Academy of Sciences. Staff had the expertise to always respond to needs for special data and information about: 1) major severe storms in Illinois; 2) climatic extremes (such as the 1976-1980 series of severe winters, the 1988 drought, the 1993 flood, and the 1995 heat wave); and 3) key national scientific issues such as weather modification, acid rain, alternative energy sources, and global climate change.

FUTURE ISSUES AND OUTLOOK

In 1996, the Atmospheric Sciences Group is still involved in three major areas of activity: services, applied and basic research, and data collection. Major program changes have occurred over the past five to ten years, several senior scientists have left the staff, and the number of published papers and reports has been declining steadily for several years. After the departure of the entire radar engineering staff, for the first time since 1947 the Survey has no capability in radar meteorological operations or systems. The major themes of research are atmospheric chemistry with specialization in data collection and analysis; applied climatology, weather modification and climate change, and basic cloud physics studies. These efforts remain largely funded by grants and contracts from federal agencies.

The nation during 1995-1996 is undergoing major changes with sizable reductions in the federal budget for scientific research. The Survey will feel the impact with the end of several Survey projects seen to occur in 1996-1997. There is a need for major efforts to reassess future research opportunities and to seek new sources of funding if the current program and staff levels are to survive. Potential funding sources include me healthy programs of selected federal agencies, private companies (particularly those interested in applied climatological studies), and private foundations interested in environmental impact studies.

The 1991 Survey plan for global climate change research should be used for guidance as to future research. It calls for efforts that would maintain existing climate change research, and developing new research involving regional climate impact projects with a multi-disciplinary nature focusing on the Illinois River basin, on Chicago, and on the Great Lakes. The Illinois Task Force on Global Climate Change made recommendations for research and arguments that could be used by the Water Survey to seek increased state funding.

Efforts should be designed to become involved in the GCIP involving climate, weather measurements, and Midwestern hydrology. Survey scientists capable of mesoscale research need to become involved in the emerging U.S. Weather Research Program.

In this era of decreasing federal funding and shifting research priorities of the federal agencies, it will be extremely important to assess existing staff strengths and facilities, and to plan accordingly. The planning needs to consider on-going changes in state government and the needs that the new agency (Department of Natural Resources) serving as the home of the Water Survey envisions as *key* state weather and climate issues. Obviously, these relate to how weather and climate affect the state's natural resources and human health and welfare.

*Figure 12-4. Selected staff photographs. **Upper left** is the Meteorology Section in 1983 (l. to r., bottom-top) Mike Richman, Diane Portis, and Bob Scott; row 2-Pete Vinzani, Alice Wallner, Pete Lamb, Steve Sonka; Nancy Westcott and Randy Peppier; row 3-Wayne Wendland, Gary Achtemeier, Becky Runge, Art Jameson, John Vogel, and Keith Hendrie. **Left middle** is (bottom row) Julia Chen and Jim Harry; row 2-Phyllis Stone and Becky Runge; row 3-unknown, Bob Scott, Roy Reitz; row 3-Bruce Komadina, Chin-Fei Hsu, Doug Jones, John Vogel, Dave Brunkow, and Wayne Wendland. **Lower left** is a 1960 rainstorm survey group debriefing in a motel in Johnston City, (l. to r.) Doug Jones, 2 students, Stan Changnon, and Dick Semonin. **Upper right** is Jim Harry, and **lower right** is Roy Reitz, both outstanding technicians with long quality service to the Survey.*

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