State Water Survey Division

OFFICE OF THE CHIEF
AT THE
UNIVERSITY OF ILLINOIS

Illinois Department of
Energy and Natural Resources

SWS Contract Report 365

ANNUAL REPORT
May 1984 - April 1985

PRECIPITATION AUGMENTATION FOR CROPS EXPERIMENT

Assembled by

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July 1985
Champaign, Illinois

CONTENTS

E. Appendix

1. A Review of Precipitation Estimation Techniques Using Satellite Data Applicable to PACE - Stanley Q. Kidder

2. Radar Summary - Nancy Westcott

3. Details of Projects Reviewed - Chin-Fei Hsu

4. Characteristics of Rain Events (Storms), CHAP 1977-79.

5. Data Base Format for NCDC Element Archives - Philip Garcia

A. OVERVIEW

1. Goals and Objectives of PACE

Stanley A. Changnon, Jr.

The major goal of the weather modification research in Illinois is to determine the feasibility of utilizing cloud seeding to enhance rainfall in a beneficial way for the agricultural midwest. Specific program objectives are:

1) to determine in a scientific manner the precipitation alterations that are obtainable;

2) to determine the impacts of these alterations on all facets of agriculture; and

3) to determine the societal and environmental desirability of these alterations.

To perform this program, agricultural and atmospheric scientists from four states (University of Illinois, Purdue University, Michigan State University, and Ohio State University), plus scientists of the Illinois State Water Survey formulated in 1977 a plan for a long-range research program entitled Precipitation Augmentation for Crops Experiment (PACE). At that time, the multi-year experimental framework of PACE was viewed by NOAA scientists as integral to their own weather modification research efforts.

Interactive planning with NOAA scientists and those in the maidwestern institutions began immediately. The Illinois State Water Survey was funded by NOAA in a series of three contracts amounting to approximately $650,000. This supported preliminary PACE research at the Water Survey and at other institutions including the University of Illinois, Purdue University, and the University of Wyoming. This funding along with approximately $300,000 of Illinois funds provided a good start in the first phase of the PACE program.

PACE was designed as a 4-phase effort including 1) the Pre-Experimental Phase, 2) the Exploratory Experimental Phase, 3) the Confirmatory Experimental Phase, and 4) the Interpretation and Translation Phase. Detailed plans have been developed for the Pre-Experimental Phase, and these allow monitoring and assessment of the progress to the first major decision point: whether Phase 1 results meet specific informational objectives to allow proceeding into the Exploratory Experimental Phase.

2. Project Activities

NOAA-supported PACE efforts temporarily ended in 1981. Limited state support was sustained until NOAA funding was obtained again in April 1984 for another year of more concentrated research. It required 4.5 months after our proposal for FY84 funding was received by NOAA for us to receive the funding. This greatly delayed the assemblage of staff and launching of research activities.

Review of our past studies on PACE and their findings, coupled with the research needs described in the PACE planning document, led us to identify five top priority research and related support activities for this 1-year period (May 1984-May 1985). Briefly, these are:

1. Studies of cloud and precipitation elements and systems;

2. Review, interpretation and summarization of all past relevant research in the midwest;

3. Studies of economic and environmental impacts of summer rain changes;

4. Development of facilities for PACE field operations and evaluations; and

5. Integration of results and scientific hypothesis development.

Some accomplishments in the past year include:

1. Installation of soil moisture tubes at four sites, acquisition of a neutron probe, and the initiation of routine measurements of soil moisture at these sites beginning in April 1984.

2. Employment of a satellite expert, Dr. Stanley Kidder, to direct the satellite-related research concerning precipitation systems.

3. An assessment of all past weather modification research in the midwest for use in hypothesis development including development of an annotated bibliography of all relevant documents.

4. Launching of a 3-phase agricultural economic impact research effort for assessing the effects of precipitation in recent wet and very dry summers and under present farm practices.

5. The initiation of research utilizing available radar echo data, to define experimental units, as needed in the exploratory phase of PACE.

3. Cooperation with Other States, Scientists and NOAA

The Illinois-based PACE program offers opportunities for close cooperation and benefit with the other state research programs and certain

NOAA programs and groups. The results from the evaluation of the North Dakota operational program dealing with cumuli-form clouds have considerable relevance to the design and evaluation of the Illinois program. Thus, monitoring of the North Dakota results and interaction with the scientists in North Dakota and South Dakota performing the research is needed and beneficial. Interactions with the other two states, the Utah and Nevada programs, will be one of a) general program planning, and b) potential exchange and interaction of field equipment. Certain field equipment used in the winter programs of these two states could be beneficially used in Illinois.

The complex scientific program in Illinois involving cloud physics and cloud dynamics research, coupled with statistical research and climatological studies of clouds and precipitation, offers numerous opportunities for interactions with scientists involved in a) precipitation forecasting research, b) climatological studies of precipitation variability, c) atmospheric chemistry dealing with tracers and scavenging processes, and d) the development and operation of remote sensing equipment. Dr. Ruben Gabriel, statistician at the University of Rochester, served as a consultant to the project. NOAA/ERL scientists from EPL, climate programs, and atmospheric chemistry have worked frequently and cooperative with Illinois State Water Survey scientists over the past several years. We welcome a strengthening of this alliance including the exchange of scientists and facilities between our two institutions. Development of a NOAA cooperative institute at the Illinois State Water survey is seen as a logical future opportunity of great benefit to both NOAA and the State of Illinois.

B. IMPACTS RESEARCH

1. Agricultural Economic Modeling

Philip Garcia, Susan E. Offutt, and Musa Pina

Statement of the Problem

Climate and weather variability are important facts of midwestern agriculture. Recent extremes in weather and concern over possible shifts in climatic patterns have led to an awareness that a more in-depth understanding of climatic and weather related impacts on society by sectors of the economy is essential.

Concurrently, an interest has developed in assessing the potential benefits of weather modification through augmenting precipitation on the agricultural sector of the U.S. economy.

Sonka (1979) in a review of the available literature on economic impacts of planned weather modification noted the large number to studies which document the relationships between precipitation and economic activity in the agricultural sector. These studies differ in their locational focus, crops considered, approaches used to measure potential gains, and linkages to national markets. Several studies are notable for their efforts to model the impact of augmenting summertime precipitation.

Huff and Changnon (1972) considered the benefits from average increases in rainfall and the uncertainty associated with precipitation modification. Crop yield and weather data for a 30-year period were used to develop relations between yields of the two major Illinois crops (corn and soybeans) and technology, temperature, and precipitation. Results indicated successful modification would be beneficial in most growing seasons.

Several studies (South Dakota State University, 1972; Kansas Agricultural Experiment Station, 1978; Cooter, 1984) have considered the effects of increased rainfall on state economies. Effects of additional precipitation on agriculture were evaluated using input-output multipliers. Results varied with assumptions regarding timing of rainfall and differing price effects. In general, increased precipitation raised income rather substantially.

At the national level the impact of increased precipitation was assessed in a study of hail suppression (Changnon et al., 1977). Using programming techniques, the study found that the major impact of rainfall increases of 8 and 16 percent was a slight reduction in production costs for food commodities. The major benefits accrued to landowners in adoption areas.

In general, research in this area is site specific (e.g., state units or smaller), views the impacts of.weather modification strictly within a cross-sectional framework, and does not directly link national markets for important commodities or their end-products to value determination.

Objectives of the Research

The overall objective of the research is to develop a clearer understanding of the impact of weather modification on an important portion of the agricultural sector of the U.S. economy, the corn-livestock complex. This sector of U.S. agriculture is large and changes in corn production induced by successful weather modification can have substantial effects on farm incomes, prices and livestock production. In order to appropriately measure the benefits of weather modification it is important to properly reflect the temporal and spatial dimensions of the corn-livestock complex. Similarly, it is crucial to directly link the value determination process to national markets for commodities and their end-products.

The specific objectives of the work are:

1. Specification of acreage and yield relationships for the major corn producing states at the Crop Reporting District level. These relationships will respond primarily to changing technology, weather, economic, and governmental factors.

2. Assessment of the impact of the interaction of weather and changing technology on corn yields.

3. Development of an econometric representation of the corn-livestock complex.

4. Assessment of the potential benefits from weather modification of summer time precipitation.

Completion of these four specific objectives will permit the assessment of the temporal impacts of weather modification, and classification of the interactions that exist between changing weather, production, prices and the value of the commodity.

The remainder of this research report presents a description of the corn and livestock industries, a discussion of the methodology for completing the objectives of the research, and data sources and a progress report. The methodology section provides a discussion of alternative approaches for disentangling the effects of technology and weather on crop yields using disaggregated data, and the methodological framework for measuring the benefits from successful weather modification.

Description of Relevant Markets

Corn is the most important crop in the U.S. agricultural economy. In 1982-83, for example, the value of production was $27.7 billion compared to $12.7 billion for soybeans, and $9.9 billion for wheat. In the same year corn comprised roughly 80 percent of the total feedgrain production and consumption in the United States. Corn exports typically contribute 20 percent of the value of total U.S. exports and are the leading money earner in overseas markets. Corn usually accounts for almost 80 percent of world feedgrain imports and so represents an important input to the world livestock economy. The U.S. dominates the export market for corn, accounting for roughly two-thirds of world exports in recent years.

The specific market for United States corn has domestic and foreign components, both of which arise primarily from the demand for the feed-grain as an impact to the livestock sector. In addition, corn for food, seed and industrial use as well as for private and government stocks is demanded by U.S. domestic market participants.

Consumption of U.S. corn by domestic livestock and poultry has accounted, on the average over the period 1975-79, for about 61 percent of total corn disappearance, or about 100 MMT (4 billion bushels) annually. Over the past 20 years there has been a general upward trend of corn consumption by the livestock and poultry sectors.

Four broad livestock categories have historically accounted for more than 95 percent of feed corn consumption, although the shares of these categories have changed over time. These livestock groups are milk cows and other dairy cattle, cattle on feed and other beef, hogs and poultry (which includes laying hens, pullets raised for layer replacement, broilers and turkeys). Poultry and dairy use of corn has exhibited gentle increases over time while hog and beef cattle shares display a more variable and inverse relation to each other.

The poultry category includes in the aggregate all layer and broiler chickens and turkeys. Almost all the increase in corn consumption by poultry is attributable to an increase in the amount fed to broilers, moving up from 5.22 percent of total corn fed to livestock in 1960, 6.38 percent in 1970, and to 8.77 percent in 1980. Meanwhile, consumption by layers was fairly steady at about nine percent and turkeys at two percent. These consumption statistics do not reveal increases in feed efficiency over the past twenty years. Broiler production has increased over 600 percent in that time to about 4 billion birds in 1979 (USDA 1980a, p. 480), but corn consumption has not increased commensurately. At the same time, there was a small decline in the layer population and turkey numbers increased slightly.

The dairy cattle category is comprised of milk cows and other dairy cattle (e.g., bulls, all together have accounted for about 10 percent of the total dairy cattle production over the past twenty years). While the dairy percentage of total corn fed has remained relatively constant over the period, the number of dairy cows has declined. Each cow today produces "two and one-half times as much milk as her foremothers only 30 years ago" (Crittendon, p. 56). While future changes in feeding regimens and corn/milk conversion efficiency are hard to predict, it does not seem reasonable to expect major impacts on the corn market, especially since the dairy sector accounts for only about 16 percent of all corn fed to livestock.

In all but three of the past twenty years, hogs consumed a larger percentage of total corn fed than any other type of livestock. For the three years when the hog share declined below that of beef cattle, the reversal is attributable to an increase in beef cattle production rather than a marked decline in hog numbers.

These corn consumption levels reflect livestock production patterns from which their demand is derived. In this respect, two characteristics of the domestic U.S. livestock sector are salient, the short-run elasticity of supply and the longer-run production cycles, particularly in the beef and hog subsectors. In the short run, within a year or six months, livestock numbers are fixed and output can be increased only by feeding animals to heavier weights or by slaughtering members of the breeding herd; consequently, response to current own or input price is not great (although flexibility varies among sectors). In the longer run, expansion of future output can be achieved by adding to the breeding herd. The breeding to market phase for hogs takes about two years, while for cattle the elapsed time may be three to four years. Derived corn demand in the short run, then, will depend upon production flexibility in feeding, as well as the number of animals available for slaughter. In the longer run, feed demand for corn will be determined by overall production levels, which were influenced by prices expected several periods earlier.

Cyclical phases in hog and cattle numbers arise due to a rather complex interaction between economic forces and biological constraints. These cycles run eight to ten years from peak to peak in the beef cattle sector and about three to four years for hogs. The absolute level of peak production has changed from cycle to cycle, although relative intracycle relationships have been more or less constant. Consequently, derived corn demand is influenced by the magnitude and timing of the buildup and liquidation in any given cycle.

The price responses implied by these production characteristics are made within the context of specialized livestock enterprises. As long as grain supplies and prices were stable, large-scale operations were further encouraged. However, fluctuation in either input or output prices, as occurred in the 1970s, poses problems for producers. Gustafson explains,

> (This) volatility in grain prices makes formulation of long run plans extremely difficult for the livestock sector. Producers find themselves in a position in which they have little protection against sudden falls in the prices of their livestock and sharply increasing grain prices, particularly during periods of large livestock inventories.
>
> (p. 128)

Consequently, livestock producers in the face of price uncertainty may restrict supplies to limit their risk in times of pronounced instability.

Overall livestock numbers have shown a secular increase since World War II. Each peak of the cattle cycle has brought new production and per capita consumption records. Broiler production has increased tremendously, although pork not as much. Table B-1 provides per capita consumption data for beef, pork, poultry and dairy products. Beef

Table B-1. US per capita consumption of livestock products (in pounds).

	Beef a/	Pork a/	All Dairy b/	All Poultry a/
1960	64.3	60.3	384	34.4
	65.8	57.6	377	37.7
	66.2	59.1	376	37.2
	69.9	61.1	374	38.0
	73.9	60.9	374	39.9
1965	73.6	54.7	373	41.1
	77.1	54.3	371	43.8
	78.8	59.8	362	45.3
	81.2	61.4	364	45.0
	82.0	60.6	360	47.0
1970	84.1	62.0	355	48.9
	83.6	68.2	355	49.1
	85.9	62.9	357	51.3
	81.1	57.6	352	49.6
	86.4	62.2	346	50.4
1975	88.9	51.2	349	49.6
	95.7	54.6	352	52.9
	93.2	56.7	349	54.5
	88.8	56.5	346	57.2
1979	79.6	64.6	342	62.0

a/ retail cut equivalent

b/ total retail product weight

Source: USDA, 1981b, pp. 4,6,7.

consumption increased steadily through the 1960s, peaked in mid 1970s, and fell in 1979 to its lowest level in 12 years. Pork consumption has averaged about 60 pounds per capita annually since 1960. The six-fold multiplication of the broiler population is reflected in the doubling of per capita consumption of poultry meat. Consumption of dairy products has decreased slightly over the period, a pattern consistent with the decline in milk cow numbers and attendant increase in their productive efficiency.

The proportion of total domestic U.S. corn disappearance represented by seed and food consumption has remained constant over the years since 1960. Seed use has usually accounted for less than one half of one percent of domestic disappearance and food use for about ten percent. Food uses include breakfast foods, cornmeal and grits, and wet process products, this last category responsible for about two thirds of annual food corn consumption. Wet process.(milling) products include corn starch, corn syrup, crude corn oil and steepwater concentrates (from which such medical supplies as intravenous glucose solutions are made) (Chicago Board of Trade, p. 120).

Demand for corn to be fermented and distilled into ethyl alcohol (ethanol) had traditionally arisen from whiskey producers in Pennsylvania, Maryland, and Kentucky, where lime deposits are sufficiently rich to supply the desired water qualities. However, a new demand for corn has arisen derived from the production of liquid fuel in the form of ethanol. Ethanol's greatest potential as a supplement to national energy supplies is an octane enhancer when mixed with unleaded gasoline as gasohol. Without the original federal subsidies, the viability of the U.S. ethanol industry depends on the relative prices of corn and petroleum.

Over the past decade, an increasingly large amount of corn has been traded internationally. Total trade was 30 MMT during the 1970/71 crop year, had increased to 69 MMT in 1978/79, and was 80 MMT in 1979/80 (USDA 1980b, p. 13). Major corn producers are listed in Table B-2, which can be compared to Table B-3, which gives the major world corn importers and exporters. Several major producers, notably Eastern Europe, the People's Republic of China (PRO, and Brazil consume practically all their corn output domestically. On the other hand, South Africa and Argentina export significant amounts of their domestic corn production, averaging 35 and 55 percent, respectively. The U.S. annually exports about a third of its corn crop, which has usually accounted for about 75 percent of all corn traded internationally.

Those factors which influence a nation's demand for corn imports can be used to aggregate countries into import blocks. These blocks are formed based on similarities in importing behavior which can be attributed to characteristics of a nation's income level and growth rate, its livestock feeding regimen and its trade policies. First, as per capita income grows, the composition of foods demanded changes. Foodgrains, which usually display low or even negative income elasticity, diminish in importance, while items like livestock products (which use feedgrain as an input), with high, positive income elasticities, become an increasingly large part of food expenditures. Second, the type of grains which can be grown domestically influences their utilization in providing energy to

Table B-2. Major world corn producers (MMT).

Country/Region	1978/79	1979/80	1980/81
United States	184.6	201.7	168.9
PRC	55.9	60.9	57.0
Eastern Europe	27.7	34.3	30.1
Brazil	16.3	20.2	21.6
European Community	16.3	17.4	16.6
Mexico	10.2	9.2	10.2
Argentina	9.0	6.4	12.3
South Africa	8.2	10.6	11.0
Soviet Union	9.0	8.4	9.7
Canada	4.0	5.0	5.5
Thailand	3.0	3.3	3.2
All others	46.7	44.9	47.7
World	390.9	421.5	393.8

Source: USDA OASIS Data Base

Table B-3. Major world corn importers and exporters (MMT).

Country/Region	1978/79	1979/80	1980/81
Importers			
European Community	17.2	15.8	15.7
Japan	10.9	11.9	13.9
Soviet Union	9.6	14.5	11.4
Eastern Europe	5.5	6.8	8.1
Spain	4.3	4.4	4.5
Mexico	0.6	3.9	4.8
Taiwan	2.6	2.4	2.6
South Korea	2.9	2.3	2.7
All others	15.4	16.6	18.1
World	69.0	78.6	81.8
Exporters			
United States	54.2	61.8	64.8
Argentina	6.0	3.5	8.9
South Africa	2.3	3.7	3.7
Thailand	2.1	2.2	2.1
All others	6.4	7.3	6.4
World	71.0	78.5	85.9

Source: USDA OASIS Data Base

livestock. Consequently, import demand for corn depends not only on livestock numbers and on domestic corn production but also on the production of any other important substitute grains (such as wheat and barley). Third, a nation's agricultural trade policies, which are most often linked to domestic economic and political circumstances, can act to insulate the home market from events in the world market.

Nations which import significant amounts of corn can be aggregated into four groups, based on a consideration of the historical path of their imports and the structural determinants of that path, as discussed above. Table B-4 displays the groupings along with their 1979/80 import levels, both in absolute amount and as a relative share of world imports. Together, all groups account for 84 percent of all imports of corn, a percentage which is relatively constant *over* the past two decades, although the relative importance of the various groups has changed.

Group I consists mainly of middle income countries. Japan and Israel are the most affluent of the group; Mexico, Malaysia, South Korea, Taiwan and Egypt are included because their increasing affluence implies a strong derived demand for corn through meat consumption. As for domestic production, only Mexico and Egypt grow feedgrains in significant quantities. In terms of trade policy, Taiwan, South Korea, and Mexico have internal support programs for corn production, which usually require the existence of import controls. State trading agencies in South Korea and Mexico administer corn trade in response to planning goals. However, to the extent that these goals reflected increased consumption of livestock products in an improved diet, imports may not be unduly.

Corn is often grown in rotation with soybeans because of the legume's nitrogen contribution to the soil (Pierre, Aldrich, and Martin, p. 14). Relative prices of the two crops influence farmer's planting decisions along with rotational needs. The extensive use of both corn and soybeans (in the form of high protein meal) in livestock production enhances the importances of their relationship relative to the feed concentrate market.

In 1979/80, corn area harvested for grain was 29.5 million hectares (73 million acres), higher than any year since 1960/61 when about 30 million hectares were harvested. In between these extremes, there appears to have been two types of behavior. In the 1960s, area harvested fluctuated between about 22 and 26 million hectares (55 and 65 million acres). The next decade saw the beginning of a more noticeable upward trend, although this period was ushered in by the sharp decline of the 1970/71 corn blight. The blight had severe effects; 27 million hectares were planted but only 23 million harvested. Average yield dropped to 4.54 MT per hectare (72.4 bushels per acre), compared with 5.29 in 1969/70 and 5.53 in 1971/72 (USDA 1980a, p. 30). The broader behavior pattern of corn acreage can be explained by government support programs, market conditions, and weather.

The sharp decline in area planted from 1960/61 to 1961/62 growing seasons appears primarily attributable to a change in the government feedgrain support program in the face of large reserves and low market prices. Under this program,

Table B-4. Aggregation of major world corn importers.

Croup	1979/80 Corn Imports	Share of World Corn Imports
	(MMT)	(%)
Group I		
Mexico	3.9	5
South Korea	2.3	3
Taiwan	2.4	3
Malaysia	0.5	0.6
Israel	0.5	0.6
Egypt	0.5	0.6
Subtotal	9.6	12.8
Japan	11.9	15
Group I total	21.5	27.8
Group II		
Soviet Union	14.5	18
Eastern Europe	6.8	9
Group II total	21.3	27
Group III		
European Community	15.8	20
Group IV		
Spain	4.4	6
Portugal	2.4	3
Greece	1.2	1
Canada	1.0	1
Group IV total	9.0	11
Total All Groups	68.1	85.8
All others	10.5	14.2
World	78.6	100.0

Source: USDA OASIS Data Base

> ...cooperating producers were required to divert land from (corn and sorghum) to conserving uses as a qualification for obtaining price support loans. To induce compliance, a payment from the government was made for idling this land; it was called an acreage diversion payment.
> (Cochrane and Ryan, p. 188)

Following the institution of this program, feedgrain production was less than consumption for the first time in ten years. Stocks were reduced by about 12 MMT and market prices rose. Over the remainder of the decade there was little change in the level of overall support although the relative contributions of loan rate and direct payments fluctuated (Cochrane and Ryan, p. 199). Thus, the constancy in area planted over the 1960s appears in large part due to the constancy of government support levels as well as to the absence of any catastrophic weather or diseases.

While the corn blight inaugurated the 1970s, the following year saw the first major change in government feedgrains policy since 1961.

> As before, a government payment was authorized for cropland diverted to a conserving use, but the diversion did not require a reduction in acreage planted to any particular crop. The diverted acreage was called 'set aside.'
> (Cochrane and Ryan, p. 201)

The set aside restrictions were relaxed as the 1970s sore on, as a result reduced crops due to dry weather from 1973/74 to 1976/77, with a particular poor crop in 1974/75, coupled with buoyant export demand. No corn acreage was set aside or diverted in the 1975 through 1977/78 crops years. Two and one-half million hectares were set aside in 1978/79 and 1979/80 (USDA 1980a, p. 13). Stocks had been drawn down to very low levels in the middle part of the decade but began to climb again, although prices stayed strong enough to forestall the reintroduction of set aside rules through the end of the seventies.

Corn yields in the United States have risen from an average 2.51 MT per hectare (40 bushels per acre) at the close of World War II to 6.84 (109 bushels) in 1979/80 (USDA 1980a, p. 30). This persistent upward trend is broken significantly at two junctures. These drops, in 1970/71 and 1974/75, can be ascribed to the influence of corn blight and bad weather (drought), respectively. The general increase in yields can be attributed to genetic improvements in corn characteristics through the introduction of hybrid varieties and to improved husbandry practices. "The management tends to reduce the environmental stresses, while hybrids are developed that are less sensitive to adverse environmental factors that can be controlled (e.g., fertilizers, weed control, insect control, etc.)" (OTA, p. 53).

Favorable weather, as well as improved technology and husbandry, contributes to higher yields. The correlation between low yields and bad weather makes this point. Variation in corn yields can be explained well by meteorological influences. Yields in the Corn Belt appear "very sensitive to high maximum temperatures and prolonged dry periods, especially during pollenation," (Benci and Runge, p. 282),

> (B)ased on approximately seventy years of historical weather data, corn yields decreased approximately 14% for a combination of 1°C increase in average weekly maximum temperature and a 10% decrease in precipitation. Results from (their model's) predictions also indicate that from 1930-72 a trend towards favorable weather events existed which alone explains 36% of yield variability.
>
> (p. 282)

Although corn accounts for over 80 percent of all feedgrain disappearance, only about 55 percent of feedgrain stocks are held as corn. Indeed, compared to those of all grains, stocks for corn have been a smaller percent of available supply for the past twenty years. The stocks to use ratio for corn (and sorghum as well) has averaged about 15 percent in contrast to 47 percent for wheat, 50 percent for oats and for barley. Although affected by the same government policies as other grains, corn stocks have not overhung the market. Since 1965, private stocks have averaged about 14 percent of annual use and government stocks for only about 3 percent (in the years when stocks were held at all, being zero from 1973/74 through 1976/77).

Prior to 1977, stocks of corn were acquired by the Commodity Credit Corporation (CCC) as a consequence of the support program, the level of accumulation dependent on the relationship between the legislated loan rate and the market price. Minimal stocks were accumulated during the seventies because usually the market price stayed well above the loan rate. The Food and Agriculture Act of 1977 included a provision authorizing the institution of a farmer owned reserve (FOR) for feedgrains, similar to that mandated for wheat and rice in the same bill. The FOR represents the "first serious U.S. experience with a managed, national reserve program" (Meyers and Ryan, p. 316).

The FOR for corn sets up a system which makes stock accumulation and release potentially more sensitive to price movements. In addition to the nine month nonrecourse loans available to eligible farmers, the FOR provides three-year loans with an annual storage subsidy approximately equal to commercial storage costs in the major corn producing states (Meyers and Ryan, p. 316). This FOR corn is then subject to a set of redemption rules dependent on the relationship between market price and a series of specified price levels. At the lowest level is the loan rate, which still acts to put a floor under market price. The release level, at which reserve grain may be redeemed, and the call level above that, at which it must be redeemed, are set at fixed percentages above the annual loan rate. The Secretary of Agriculture has some discretionary authority over the terms under which grain may be placed in the FOR (such as waiving interest payments on storage subsidies, as after the Soviet embargo); these may be used to provide farmers with further incentive or disincentive to store corn.

The FOR has been in place, then, since 1977. Meyers and Ryan identify its main objectives as price stabilization within a broad range and increased reliability of U.S. export and domestic supplies. In an evaluation of FOR operation over its first three years, they find that, for wheat and corn,

> ...the elimination of the FOR results in a higher price variance, lower total stocks, lower reserve levels, and higher free stocks. Effects on production over this period were relatively small, but the changes in stock levels were substantial. Without the FOR, grain stocks as a percentage of utilization in 1980/81 would approach the levels experienced in 1973/74 for corn and 1974/75 for wheat, and all reserves would be exhausted.
>
> (p. 321)

To increase price stability for livestock producers, the call and release levels for corn have been set in a more narrow band than that for wheat. While this causes more frequent changes in the status for FOR corn, which irritates corn producers who would like to see the call price abolished, it represents the first time the grains/livestock linkage has been incorporated.

If the FOR has been judged fairly effective at price stabilization, it would seem less successful as an adequate supply assurance mechanism. The goal for total corn carryover was set at about 38 MMT (Meyers and Ryan, p. 316). In 1980/81, stocks were drawn down to 26 MMT and would have been lower had the FOR not absorbed much of the embargoed corn the previous year. While stocks are expected to reach the 38 MMT level in 1981/82, after a bumper harvest, it is not clear that the FOR can consistently assure this minimum level.

The 1981 farm bill extended the FOR provision through 1985, establishing a lower limit for the feedgrain reserve of 25 MMT (1 billion bushels). Otherwise, the basic operating rules remain essentially the same as at the FOR's inception. The Secretary has the discretion to set both the release and the call levels, and, when price has reached these levels, to "increase the rate of interest on loans that have been made and design other methods to encourage the orderly marketing of wheat and feedgrains" (Johnson, Rizzl, Short, and Fulton, p. 18).

Over the past decade, the U.S. held an average 55 percent of total world corn ending stocks. Since the U.S. produces about the same proportion of all world corn each year, this mean level is not disproportionate. U.S. stocks, while of modest size relative to supply, have been much more variable than those of the rest of the world. U.S. stocks in the 1970s had a standard deviation of 10 MMT, which represents 50 percent of their mean level of 20 MMT. In contrast, total corn stocks abroad over the same period averaged 15 MMT and showed a standard deviation of 1.5 MMT, about ten percent of the mean. This discrepancy arose as U.S. stocks were drawn down in response to world shocks and the U.S. became the residual supplier. As noted earlier, government stocks were depleted at mid-decade.

As is the case within the U.S., coarse grain stocks are not as large as those of wheat, a foodgrain, where size is measured by the average ratio of stocks to supply. The figure for world coarse grains was 11 percent and for wheat 21 percent, averaged over the 1970s. The historical level of stocks of coarse grains was not sufficient to prevent large gyrations in the price of corn, the only feedgrain traded in appreciable quantities internationally. Since feedgrain stocks worldwide are relatively small, and since the U.S. is the residual supplier in the event of a shortfall, the ability of stocks to buffer shocks in the future will depend on the levels held by the U.S. A 25 MMT minimum on the feedgrain FOR, in the absence of expansion of commercial holdings, probably means that the stocks to use ratio over the 1980s will not be significantly higher than it was in the 1970s. Should market shocks recur, price instability may thus again be the result in the absence of an adequate buffer reserve.

Methodological Considerations

Modeling Yield Response. To gain perspective on existing knowledge about yield response, earlier studies were reviewed and compared with respect to the selection of explanatory variables, estimated coefficients, and units of observation (Table B-5). This paper cannot explore all aspects of the studies; instead, focuses on the definition of the appropriate level of aggregation for the geographical area under study. Aggregation bias is an important concern in analyzing response to weather modification.

The studies cited in Table B-5 display little consistency in level of aggregation of the empirical investigations. (Compare notations under last column, "unit of study.") The definition of the geographical area from which the data are drawn is not the same across studies, but ranges along a continuum from the national aggregate to the individual farm. At the highest level of aggregation, investigations involve variables calculated as U.S. national average (e.g., Menz and Pardy, 1983). At the next level are regional aggregates, such as the Great Plains or Corn Belt, or subsets of states within those regions, (e.g., Thompson, 1969, 1970). State level data represents the next tier (e.g., Changnon and Neill, 1967). Crop reporting districts on a sub-state basis were used by Huff and Neill (1982). At the lowest level of aggregation are studies by county (Nelson and Dale, 1978a, b) and then individual farm data (Swanson and Nyankori, 1979). Are results of the studies, in terms of their explanation of the relative importance of technology and weather in affecting yield behavior over time, invariant with respect to level of aggregation?

The studies' results do differ, especially with respect to the identify of important explanatory variables (Table B-5). The empirical estimates of response coefficients across studies vary as well in the relative importance of variables. Both types of differences may be attributable to differences in level of aggregation. Before introduction of a systematic statistical framework for dealing with possible biases which may arise because of aggregation, illustrations of these effects are offered.

Very different pictures of yield behavior often emerge when the results of studies are compared. For example, the work of Menz and Pardy (1983) at the national aggregate level suggests that corn yields did not reach a plateau over the 1970s. In contrast, the farm level study of

Table B-5. Selected research on the effects of technology arid weather on U.S. crop yields.

	Technology				Weather[1]											
	Fertilizer		Time Trend		Precipitation					Temperature				Area	Corn	Unit of
	lin.	N-lin.	lin.	N-lin.	PP	MP	JP	JYP	AP	MT	JT	JYT	AT	Pltd.	Price	Obser.
Hendricks-Scholl[a]							x	x	x		x	x	x			b
Changnon-Neill			x		x[s]		x	x	x	x	x	x	x			c
Nicholson	x				x						x	x				d
Thompson, 1969			x		x*			x*			x*	x*	x*			e
Thompson, 1970			x		x*			x*			x*	x*	x*			e
Huff-Changnon			x[f]		x*		x*	x*	x*		x*	x*	x*			c
Houck-Gallagher	x												x[t]	x	x	g
Butell-Naive	x		x					x						x		g
Nelson-Dale, 1978a	x		x[h]		x*		x*	x*	x*		x*	x*	x*			i
Nelson-Dale, 1978b[j]	x		x[h]		x*		x*	x*	x*		x*	x*	x*			i
Swanson-Nyankori			x	x[k]	x*	x	x*	x*	x*		x*	x*	x*			l
Huff-Neill			x	x[m]	x		x	x	x		x	x	x			n
Pope-Heady	x[p]		x[q]	x	x			x*	x*		x*	x*	x*			r
Menz-Pardey		x	x	x[k]				x								g

Explanation of Symbols

1. Weather variables: PP: Preseason precipitation (September-April)' MP: May precipication; JP: June precipitation; JYP: July precipitation; AP: August precipitation; MT: May temperature; JT: June temperature'; JYT: July temperature; AT: August temperature.

* Indicates that both linear and quadratic forms were used.

a. Temperature-rainfall interactions were included for each month, and also weekly weather data were ;used in the same manner.
b. Region consists of states Ohio, Indiana, and Ohio, period 1890-1939.
c. Regions consist of counties in Illinois.
d. Region consists of Eastern Washington and Northern Idaho.
e. Five state region, the states are Illinois, Indiana, Iowa, Missouri, and Ohio.
f. Interactions of temperature and precipitation with technology for the months of June, July, and August were used.
g. National level.
h. a linear time trend (T) was used in three different forms: 1. T increased by one each year from the beginning of ;the period through 1960, after it became constant, 2. T was zero through 1960, began with a one in 1961, and increased each year by one, and 3. T was squre of the second form.
i. County level in Indiana.
j. Four different models were employed by using the variations of independent variables.
k. Indicates that t^2 and T were used.
1. Single farm, Piatt County, Illinois.
m. Linear and quadradic, and linear and cubic time trend forms were used.
n. Analyses were performed for eahc crop reporting districts in each state, then combined to determine average relationships for larger areas such as a state or groups of states.
p. In corn yield model, nitrogen-linear time trend interactions were used.
q. In addition to linear time trend (t), which was increased by one from 1950 to 1980, the following forms were also used: 1. t was increased by one each year unitl 1968, then t = 18; 2. $t = (t)^2$ until 1968, the was $(18)^2$; 3. t = 0 until 1968, then increased by one until 1980.
r. State level, states: Illinois, Indiana, Ohio, Iowa and Missouri.
s. Average rainfall over growing season.
t. USDA weather index.

Swanson and Nyankori (1979) indicated no such leveling off. These differences may be attributable directly to the level of aggregation. From the national perspective, yields may appear to have leveled off over the 1970s as acreage planted and harvested increased when more marginal lands were brought into production. Since yields on these parcels were lower than on the earlier base, the national average figure is reduced. In the Menz and Pardy study, the coefficient of an explanatory variable in the equation, the number of acres harvested each year, has a negative sign, which bears out the depressing effects of marginal lands on national average yields. When acreage in the unit under study remains essentially unchanged over this period, as in the Swanson and Nyankori study, yield variation is explained solely as a function of changes in technology and weather, and no leveling off is observed.

That the level of aggregation may influence the results of a study intended to describe the impact of weather and technology on crop yields is an important consideration in evaluating the effects of weather modification on yields. Weather modification as currently discussed would occur over a relatively limited geographical region. Thus, the response coefficients should pertain to that region to assess accurately effects of modification, since weather events may have differential effects from different regional perspectives.

Such regional differences have been recognized in, for example, the analysis of soil erosion potential. Several distinct geographical regions within one state may be designated as having different erosive potentials because of differences in soil and topography. Such environmental differences may then also affect general yield levels, such that, for example corn yields in east central Illinois are on average higher than those in more northerly areas, although the weather and technology may be relatively uniform. Consequently, a study should seek to account for these types of structural differences in order to isolate the effect of technology and weather on crop yields.

In the majority of the studies which use multi-state or state level data, no allowance is made for differences in response coefficients which may arise because of differences in resource endowment (e.g., soil quality) and economic structure (e.g., farm size) across and within geographical regions. Man-made political boundaries do not necessarily provide an adequate means of aggregating data since they do not necessarily coincide with changes in agronomic and economic conditions relevant to variation in crop yields. Historically, most data are collected by government agencies which usually operate within state boundaries. However, the U.S. Department of Agriculture had defined Crop Reporting Districts (CRD) which correspond more closely to desirable agronomic boundaries than do traditional political units. Typically, each state has nine such districts; data on crop yields and acreages and on weather and economic variables are generally available for each district. Thus, CRD data represent a more useful aggregation unit for studying the effects of weather modification.

Use of CRD data still assumes that response coefficients are uniform over farms within the district. While this assumption is probably not strictly correct, disaggregation to farm level is costly and may not ultimately increase the amount of useful information available to the researcher. With this limitation, it seems reasonable to suppose that response coefficients might differ among these districts. Thompson 1969, 1970) recognized that such differences might exist on an inter-state basis, but, as argued, state units may still mask important intra-state variations. Huff and Neill (1982) used CRD data for their study, but their method of aggregation may be improved.

To account for inter-district differences arising out of agronomic and economic environmental variation, a systematic statistical framework for analysis may be based on the analysis of variance, implemented in regression analysis through the use of binary (dummy or zero-one) variables. This approach attempts to measure differences among regional aggregates without explicitly identifying the factors which lie at the root of the differences. In yield response studies the identification of the genesis of such underlying differences is less important than accounting for their existence. A "hierarchy" of model specifications can be constructed under varying degrees of similarity across regional units. The existence of these differences may then be tested to determine their significance in some statistical sense, and so should be allowed for in the modeling effort. At present, inter-regional differences are assumed constant across time, although the framework may be easily adapted to compensate for variation over years as well as across regions.

To facilitate empirical investigation, models of inter-regional or cross-sectional (as opposed to time series) variation may be defined from the most restrictive hypothesis about response coefficients to the least. The general statistical model for this procedure may be written as:

$$Y_{it} = \beta_{0it} + \sum_{k=1}^{k} \beta_{kit}\, x_{kit} + e_{it} \qquad (1)$$

where i = 1,.., N refers to a cross-sectional unit and t = 1,..., T refers to a given time period. Thus, Y_{it} is the value of the dependent variable (crop yield) for cross section unit (CRD) i at time t and x_{kit} is the value of the kth explanatory variable (technology, weather, etc.) for unit i at time t. The stochastic error term e_{it} is initially assumed to have mean zero and constant variance and be independent across units (i.e., $E(e_i e_j') = \sigma^2_{ij} I$, = 0 for $i \neq j$). The β_{kit} are unknown response coefficients; in the most general case, they may be different for different units i at different times t; here only differences over i are considered and so the t subscript may be dropped. Using this model, the hierarchy may be defined as below.

I. Response coefficients do not differ over units:

$$Y_i = \beta_0 + \sum_{k=1}^{k} \beta_k\, x_{ki} + e_i. \qquad (2)$$

II. There are differences in the level of response (intercept) over units but not among the (slope) coefficients associated with the individual explanatory variables:

$$Y_i = \beta_{0i} + \sum_{k=1}^{K} \beta_k x_{ki} + e_i. \qquad (3)$$

III. Both intercept and slope coefficients differ over time, and the disturbances (e_i) associated with different units are correlated at a given point in time but not over time:

$$Y_i = \beta_{0i} + \sum_{k=1}^{K} \beta_{ki} x_{ki} + e_i \qquad (4)$$

where the variance of the disturbance now reflects the correlation across units

$$(E(e_i e_j') = \sigma^2 \quad ij \neq 0 \text{ for } i \neq j).$$

IV. Both slopes and intercepts differ across units, with no relations among contemporaneous errors:

$$Y_i = \beta_{0i} + \sum_{k=1}^{K} \beta_{ki} x_{ki} + e_i. \qquad (5)$$

These models may be applied to test hypothesis about the nature and extent of possible differences among units.

In applying these models, the null hypothesis may be taken to be the model of no cross-sectional differences (model I) and the alternative may be formulated as any one of models II, III, or IV. In Thompson's studies, model II was taken as the maintained hypothesis, implying differences in overall yield levels across units (states in his formulation). However, the validity of that assumption may be tested statistically by comparing the explanatory power of model I to that of model II using a standard F test (involving the ratio of the sums of squared error from each model). Model III suggests that certain random factors (perhaps events in the macroeconomy) may affect all units and that taking into account this similarity will improve the estimates of the individual response coefficients. This model may be taken as the alternative hypothesis and compared to model I, again using a F test. Model IV implies differences in both level (intercept) and response (slope) coefficients across units, with no relation through the error terms.

In one of II, III, or IV represent the true model, then application of model I to the pooled data will result in biased estimates of the response coefficients. The direction and magnitude of the bias will often be difficult to determine a priori. Models II, III, and IV account for the existence of various differences among response coefficients by region through the use of binary variables. In general, in each region a binary variable is defined to be one for observations on that region and zero for observations on all other regions. A more detailed description of this technique is given in standard statistical and econometric texts (see, for example, Johnston (1984)).

This procedure may be applied to sensible aggregates of data containing more than one CRD. To determine candidates for grouping, CRD boundaries may be compared to soil map delineations. Regions with similar soils and topography may exhibit fairly homogeneous yield response to changes in weather and technology. This approach can be useful in building aggregates because it provides a statistical basis for determining appropriate groupings. Huff and Neill's (1982)s aggregation scheme was similar, although apparently it did not allow for aggregation of CRD's across state boundaries and did not draw on soil similarities. Moreover, it had no systematic framework for judging the validity of the resultant groupings.

To isolate the effect of changes in technology and weather on crop yields in a particular region, an empirical study should control for differences in yields among regions which are not directly attributable to changes in technology and weather. Estimates of response coefficients may be biased if such control is not incorporated in the estimation design. Since the response coefficients are ultimately of interest in considering the impact of weather modification, high quality estimates are desirable. Approaching the problem in the framework of hypothesis testing will help avoid imposing untenable assumptions on the data that may ultimately bias the results.

The Econometric Representation. The methodology proposed here addresses several of these issue through a modeling effort which links consumption and production. This approach permits an effective assessment of the temporal impacts of weather modification, and classification of the interactions that exist between changing weather, production, prices and the value of the commodity.

An econometric model, developed to examine the livestock and feed-grain sectors of U.S. agriculture, assumes that the value of additional production depends on the interaction of supply and demand. Specific variables are included to analyze the influence of climate-related factors on feed production, range productivity and livestock numbers. Prices at various stages of the marketing system, determined by the interaction of supply and demand, then feed back into the production and marketing sectors of the industries and are reflected in subsequent production decisions.

The feed-livestock industries consist of a complex set of relations that involve biological and economic time lags, differences in the location of productions, and changes in product characteristics. The supply and demand for feedgrains interact to establish their price. Similarly, the supply of livestock and the wholesale demand for meat determine prices of livestock and meat. The relations between output prices (livestock prices) and input prices (feedgrain prices) for the producer constitute the line between the two sectors influencing feedgrain and livestock production and consumption.

The econometric model explains the production and prices of corn and livestock, as well as consumption of U.S. corn domestically and in the export market. Specifically, the livestock and corn markets are linked through derived demand relationships. The model is annual in period, except for the hog production sector, which is semiannual, and is estimated over 1961-62 to 1982-83. Beef cattle, hog, and broiler production are described in a series of recursive equations. Current livestock product prices are determined by the demand at the wholesale level. The feed demand for corn is derived from current livestock production levels. The demand for corn on the world market is composed a set of demand estimates for groups of importers, aggregated according to similarity of their input behavior. The U.S. is assumed to be the only world market supplier in which significant consumption/production adjustment to changes in world conditions are possible; corn exports by other countries are exogenous. The aggregate U.S. supply of corn is assumed to be the summation of the production from each crop reporting district. Equilibrium corn price is determined endogenously when the market clears and so demand and supply are equal.

The basic empirical model is dynamic, nonlinear (in variables) and contains 53 equations, of which 35 are behavioral equations and 18 are identities. Four aggregated equations explain domestic U.S. corn production: area planted, area harvested; yield, and an identity for production, (i.e., area harvested times yield). These four equations are to be estimated for each year, 1951-82, for each corp reporting district for the 9 major corn producing states, thereby adding 36 equations to the basic specification. Corn produced outside the major states will be modeled at the aggregated level.

The nature of the model permits an assessment of the gains to crop producers and indirectly to consumers. Successful weather modification is, in effect, an output-increasing technology. Crop production is performed in an economic environment which approximates a perfectly competitive industry. At the aggregate level, therefore, increases in output because of successful weather modification can result in a lowering of the market price for the commodity produced. Given that demand for agricultural sector output is largely unresponsive to price changes, this results in a reduction of total revenue to feedgrain producers.

This analysis assumes that weather modification techniques are effective in all producing regions and will be adopted uniformly. In all likelihood this is not true, especially where international production is involved. Probably, a more reasonable assumption is that crop producers can be divided into at least two categories: those in areas where weather modification is successful; and those in areas without weather modification. The economic impacts on the crop producer will differ between the two categories.

The individual producer in a region with weather modification has more output to sell, but since the price received is determined by aggregate market conditions, it is slightly lower than if the weather modification does not exist. More specifically, under fairly robust assumptions, in the area with successful weather modification production will reduce price less than the reduction in per unit costs (Edwards and Freebairn, 1984). The larger the percent of the crop influenced by the weather modification, the greater the decline in price. Thus, within the context of this study, farmers in a localized producing area, e.g., a crop reporting district, region or even a state, should gain from the introduction of weather modification in their area.

Producers in a region without weather modification also face the somewhat lower price. With no additional output increase from effective weather modification, these producers are worse off from development of an effective weather modification technology. Consumers of the final products (i.e., meats and derivatives of corn) will be better off because of the resulting lower prices. In terms of the market, this benefit can be measured as a reduction in expenditures at the wholesale level of the meat product sector.

The system's relations can be influenced by economic, governmental, technological, and weather related phenomena. Linking the corn supply response sector to the demand for corn permits a dynamic assessment of the benefits of successful weather modification, ceteris paribus. Simulation of alternative weather modification scenarios provides estimates of the impact of additional corn production on feed prices, corn consumption, livestock production, and prices. Specifically, the effects of each weather scenario can be found by calculating the changes in revenues accruing to producers and consumers in wholesale expenditures for meat between a base simulation (with "normal" weather) and simulations with modified weather.

Data

Data in numerous variables have been collected for use in this research. The variables in Table B-6 were obtained for the period 1960-82. These are generally related to the aggregate demand markets for corn and the aggregate supply and demand markets for livestock commodities and their products. In addition, data as yields, acreage, and production have been collected by crop reporting districts for the corn producing states for the period 1950-83. This information was obtained through crop reporting services in each state. Weather information (monthly temperature and precipitation among other variables) by reporting states was obtained from the National Climatic Data Center (NCDC) Documentation on the tape is included in the Appendix.

Progress

The research is progressing at a rather nice pace. Several important tasks have been accomplished. First, the econometric model, except for

Table B-6. The model in implicit form.

Variable definitions	
Exogenous	
CGPRDII	coarse grain production Group II (MMT)
CGPRDIII	coarse grain production Group III (MMT)
CHOCAV	corn fed per hog, average (MT)
CIMPROW	corn imports by the rest of the world (MMT)
CIMPSU	corn imports by the Soviet Union (MMT)
CLFSLUS	calf slaughter (million head)
COASAUST	corn area set aside US (million hectares)
COLVSUS	corn red to other livestock US (MMT)
COPLDT	corn loan rate US ($/MT)
COUXTROW	corn exports by the rest of the world (MMT)
DLIQ	dummy for cattle cycle (1974/75 to 1978/79 = 1)
DPIUSPC	disposable personal income per capita US ($1000)
D68, etc.	dummy for year indicated
HGAVDWT	hog average dressed weight (lbs)
LVSTKII	livestock production Group II (million pounds)
LVSTKIII	livestock production Group III (million pounds)
NFBAVDWT	nonfed beef average dressed weight (lbs)
POPUS	population US (millions)
PPIUS	producers prices paid index US (1967 = 100)
PP7PZ	fertilizer price index US (1967 = 100)
SOYPUSDT	soybean price US ($/MT)
TIME	time, linear trend (1961/62 = 1, ...)
WLDCPI	world consumer price index (1970 = 100)

Table B-6. The model in implicit form (continued),

Variable definitions	
Endogenous	
BFCOWINV	beef cow inventory January 1 (million head)
BGPFUS1	barrow and gilt price, average December to May ($/100 lbs)
BGPFUS2	barrow and gilt price, average June to November($/100 lbs)
BGSLUS1	barrow and gilt slaughter, December to May (million head)
BGSLUS2	barrow and gilt slaughter, June to November (million head)
BRCONPC	broiler consumption per capita (pounds)
BRPRDUS	broiler production, liveweight (billion lbs)
CBEEFUS	corn fed to beef cattle (million metric tons (MMT))
CDAIRUS	corn fed to dairy cattle (MMT)
CFOODUS	corn used for food, seed, and industry (MMT)
CHOGSUS1	corn fed to hogs, December to May (MMT)
CH0GSUS2	corn fed to hogs, June to November (MMT)
CIMPI	total corn imports by Group I (MMT)
CIMPII	total corn imports by Group II (MMT)
CIMPIII	total corn imports by Group III (MMT)
CIMPIV	total corn imports by Group IV (MMT)
CLFCROP	calf crop (million head)
CLFDLOSS	calf death loss (million head)
CLVSTKUS	corn fed to all US livestock (MMT)
COAHGUS	corn area harvested (million hectares)
COAPLUS	corn area planted (million hectares)
COPFUSDT	corn price, season average to farmers ($/MT)
COUXTUS	corn exports by US (MMT)
COWSLUS	cow slaughter (million head)
CPOLTUS	corn fed to poultry (MMT)
CPRDUS	corn production US (MMT)
CSTKTUS	total corn stocks US (MMT)
CYLDGUS	corn yield US (MT/hectare)
FBAVLWT	fed beef average liveweight (lbs)

Table B-6. The model in implicit form (continued),

Variable definitions	
FBCONPC	fed beef consumption per capita (lbs)
FBCPUS	fed beef cattle price ($/100 lbs)
FBPRDUS	fed beef production (million lbs)
FBSLUS	fed beef slaughter (million head)
FCAVLWT	feeder cattle average liveweight (100 lbs)
FCPKCUS	feeder cattle price ($/100 lbs)
GADD1	gilts added, December to May (million head)
GADD2	gilts added, June to November (million head)
HFADD	heifers added (million head)
HGBINV2	hog breeding inventory, June 1 (million head)
NETCROP	net calf crop (feeder cattle supply) (million head)
NFBCONPC	nonfed beef consumption per capita (lbs)
NFBPRDUS	nonfed beef production (million lbs)
NFBPUS	nonfed beef price ($/100 lbs)
PCROP1	pig crop, December to May (million head)
PCROP2	pig crop, June to November (million head)
PKCONPC	pork consumption per capita (annual) (lbs)
PKCONPC1	pork consumption per capita, December to May (lbs)
PKCONPC2	pork consumption per capita, June to November (lbs)
POPFMUS	broiler price to farmers ($/100 lbs)
SOWFAR1	sows farrowing, December to May (million head)
SOWFAR2	sows farrowing, June to November (million head)
SOWSLUS1	sows slaughtered, December to May (million head)
SOWSLUS2	sows slaughtered, June Co November (million head)

the disaggregated supply response sector has been estimated and validated over the sample period. Preliminary assessment of the model suggests that it is sufficiently representative of the corn-livestock complex for weather modification analysis. Currently, we are in the process of writing this section for the final report.

Second, a paper has been published in the April 1985 Journal of Weather Modification, "Potential Benefits to Agriculture of Augmenting Precipitation." This paper documents the approach to be used in the analysis of weather modification.

Third, a paper, "A Methodological Consideration for Assessing the Potential Benefits of Weather Modification in Illinois Agriculture," was presented at the 17th Conference on Agricultural and Forest Meteorology sponsored by the American Meteorological Society in Scottsdale, Arizona in May. An extended abstract also will appear in the proceedings.

Fourth, a manuscript, "The Distribution of Benefits From Technology When Input quality Varies" has been submitted to the American Journal of Agricultural Economics for publication. This paper uses data generated for this research project and attempts to isolate the impact of weather-normalized technology on the distribution of gains to producers. Fifth, a manuscript is in progress on the impact of applied vs basic technology on producer and consumer gains. The analogy between the applied technology and weather modification is straightforward. Sixth, the crop yield, production and acreage data are computerized and ready for analysis.

A potential impediment to finishing the first year's tasks on schedule is the weather data. It took much longer to get the NCDC data than expected and, unfortunately, the data is not in the appropriate form for direct and easy utilization. Our Research Associate and the Department's computer programmer presently are working on this task.

Tasks to be accomplished in the immediate future are:

1) Estimation of the CRD supply response and yield relationships.

2) Combining these response relationships with the validated econometric model.

3) Identifying the benefits of alternative modification scenarios.

4) Examining the interaction between technology, weather and yields over time and across regions with similar agronomic characteristics.

Summary

Substantive data assembly and econometric work have been completed. Supply response relationships are to be combined with the corn-livestock model for direct assessment of the benefits of weather modification.

REFERENCES

Benci, J. F., and E. C. A. Runge, 1977: Modelling Corn Production - Yield Sensitivity to Temperature and Precipitation. The Agrometeorology of the Maize (Corn) Crop, World Meteorological Organization, Geneva, pp. 282-287.

Butell, R. and J. J. Naive, 1978: Factors Affecting Corn Yields. Feed Situation. Washington, D. C, U.S. Dept.

Chicago Board of Trade, 1979: Grains: Production, Processing and Marketing, Chicago.

Cochrane, W. W., and M. E. Ryan, 1976: American Farm Policy 1948-1973. North Central Pub. Co., St. Paul, MN.

Cooter, W. S., 1984: An Analysis of the Impact of Climate on the Oklahoma Economy. Oklahoma Climatological Survey, Norman, The Economic Impact of Climate Vol. XIX, p. 219.

Changnon, S. A., and J. C. Neill, 1967: Areal variations in corn-weather relations in Illinois. Trans. Illinois Acad. Sci., 60(2):221-230.

Changnon, S. A., R. J. Davis, B. C. Farhar, J. E. Haas, J. L. Ivens, M. V. Jones, D. A. Klein, D. Mann, G. M. Morgan, S. T. Sonkia, E. R. Swanson, C. R. Taylor, and P. G. van Blokland, 1979: Hail Suppression: Impacts and Issues. Illinois State Water Survey Contract Rpt. 184, 427 pp.

Crittendon, A., 1981: A Breed Apart: Building a Better Cow. New York Times, March 22, pp. F6-7.

Edwards, G. W., and J. W. Breebairn, 1984: The gains from research into tradable commodities. Am. J. Agr. Econ., 66:41-49.

Gustafson, R. A., 1977: Livestock-grain interdependence: implications for policy. Agr. - Food Pol. Rev., ERS AFPR-1, pp. 119-129.

Hendricks, W. A., and J. C. Scholl, 1943: The Joint Effects of Temperature and Precipitation on Corn Yields. North Carolina Ag. Expt. Sta., Tech. Bull. 74.

Houck, J. P., and P. W. Gallagher, 1976: The price resposiveness of U.S. corn yields. Am. J. Agr. Econ., 58:731-734.

Huff, F. A., and S. A. Changnon, 1972: Evaluation of potential effects of weather modification on agriculture in Illinois. J. Appl. Meteor., 11:376-384.

Huff, F. A., and J. C. Neill, 1982: Effects of natural climatic fluctuations on the temporal and spatial variations in crop yields. J. Appl. Meteor., 21:540-550.

Johnson, J. R. W. Rizzi, S. D. Short, and R. T. Fulton, 1982: Provisions of the Agriculture and Food Act of 1981. USDA ERS Staff Rep. No. AGES811228.

Johnston, J., 1984: Econmetric Methods. New York: McGraw Hill.
Kansas Agricultural Experiment Station, 1978: A Study of the Effects of Altering the Precipitation Pattern on the Economy and Environment of Kansas. Final Report to Kansas Water Resources Board, Manhattan, 211 pp.

Menz, K. M., and P. Pardey, 1983: Technology and U.S. corn yields: plateaus and price responsiveness. Am. J. Agr. Econ., 65:558-562.

Meyers, W. H., and M. E. Ryan, 1981: The farmer-owned reserve: how is the experiment working? Amer. J. Agr. Econ., 63:316-323.

Nelson, W. L., and R. F. Dale, 1978a: Effects of trend or technology variables and record period on prediction of corn yields with weather variables. J. Appl. Meteor., 17:926-933.

Nelson, W. L., and R. F. Dale, 1978b: A methodology for testing the accuracy of yield predictions from weather-yield regression models for corn. Agrono. J., 70:734-740.

Nicholson, E. L., 1969: Impact of weather and technology on net return estimates. Agric. Econ. Res., 21:19-22.

Office of Technology Assessment, 1980: Energy from Biological Processes Volume II Technical and Environmental Analyses. Washington, D.C.

Pierre, W. H., S. A. Aldrich, and W. P. Martin, 1966: Advances in Corn Production: Principles and Practices. Ames: Iowa State University Press.

Pope, C. A. III, and E. O. Heady, 1982: The Effects of Technological Progress and Weather on Corn Belt Crop Yields. The Center for Agricultural and Rural Development, CARD Report 113T, Ames, Iowa.

Sonka, S. T., 1979: Economics of Weather Modification: A Review. Illinois State Water Survey Rpt. of Investigation 89, Urbana, IL.

South Dakota State University, 1972: Effects on Additional Precipitation on Agricultural Production, The Environment, The Economy, and Human Society in South Dakota. Special Study Team, Agric. Exp. Sta. S. D. State Univ., Brookings, 117 pp.

Swanson, E. R., and J. C. Nyankori, 1979: Influence of weather and technology on corn and soybean yield trends,. Agric. Meteor., 20: 327-342.

Thompson, L. M., 1969: Weather and technology in the production of corn in the U.S. corn belt. Agron. J., 61:453-456.

Thompson, L. M., 1970: Weather and technology in the production of soybeans in the central United States. Agron. J., 62:232-236.

United States Department of Agriculture, 1980a: Agricultural Statistics 1980. Washington, D.C.

United States Department of Agriculture, 1981: Livestock and Meat Situation Supplement for 1980. SRS AMS Stat. Bull. No. 522, September.

United States Department of Agriculture: OASIS Data Base.

2. Precipitation Augmentation Effects on Microscale of Agriculture

Steven E. Hollinger

Introduction

The impacts of weather on agriculture are felt by all segments of the economy. Producers of raw agricultural products are the first to feel impacts of drought and other weather events that affect crop yields and livestock production. The effects felt by the producer are reduced yield, when the weather impacts are negative, and the impact of changing prices for agriculture inputs or outputs. Ultimately the consumer feels the impacts through increased food costs. Agribusinesses feel the effects by the producers inability to purchase more goods or even pay his bills when crops fail or in cases of extreme surplus, reduced prices received by the producer.

Precipitation augmentation through cloud seeding may provide a means of leveling out some of the yield and price changes by the timely generation of rainfall during short term droughts. The benefit realized by various producers in the area of increased rainfall or adjoining areas will not all by equal. For example in one area the receipt of rain at a given time may result in an increase in production while in an adjoining area the same rainfall may result in no yield increase. In the case where no yield increase is realized the producer may actually experience a reduction in his net income due to the increased yields in the adjoining area causing a decrease in the price received by the producers for the commodity because of a larger national supply of the commodity.

To adequately evaluate the benefit of any precipitation augmentation, the effects must be evaluated on the microscale and the macroscale levels. The microscale effects can be defined as those weather effects that are felt on a given crop in a given field. The effects in this case would be expressed as an increase (decrease) in yield, and the producer would experience a corresponding increase (decrease) in revenue. The macroscale effects can be defined as those effects that affect the national grain supply and the prices paid by and received by the producers. This report will discuss methods of evaluating the effects of precipitation augmentation on the agricultural microscale.

Theory and Methods

Traditional methods of modeling crop responses to weather have involved the use of statistical regression. For large areas these methods have a value because the main goal is to determine the total production over a large area for use in grain trading and policy decision making. To develop these models thirty or more years of weather and yield data are needed for each area being modeled to develop a good relationship between weather and crop yields. Because of the extensive data needed it is not practical to develop statistical models at the farm or field level.

One of the biggest problems of the statistical models is their site specificity. This means that a model developed on a given site will often fail to give reliable results if it is used on a different site that has different soil conditions and/or different management practices are used.

Because of these problems, deterministic models have been developed to evaluate the effects of weather on field or farm size areas. These models are generally composed of numerous submodels that describe the various physical, chemical and biological processes that are impacted by the weather. The big advantage to this approach is that the same model can be used on many different sites.

For optimum evaluation of weather effects on small tracts it is necessary that the models evaluate the entire soil-plant-weather-management system. This involves including not only weather information but also the effects of management practices on the agricultural production system.

A diagram showing some of the broad categories that need to be included are shown in Figure B-1. Notice that the process is not a simple one since the end result (crop yield and production) have an effect on management decisions through the economic and political constraints applied by financial institutions and government policy. Because of this the same weather in different years may have a profoundly different impact on the producer in a given year and subsequent years. In a system where man is not involved in making decisions about the crop, the weather would have the same effect from year to year given a constant soil environment and identical pest populations. It is the assumption that forms the basis for deterministic modeling of crop yields. In this work, the weather effects on the soil and plants will be considered. The impacts of the management interactions will be examined with the assumption that the producer is not constrained by economics in any given field, i.e., he is striving for optimum production.

A simple schematic diagram of the weather-soil-plant-management system is shown in Figure B-2. The important weather variables considered are precipitation, evaporation, solar radiation, and temperature. In this project precipitation is the weather variable of greatest interest as we are trying to determine the effect of increased precipitation on crop yield. Although not addressed in this study, at some point, the question of how precipitation enhancement might affect crop yields through modifications of evaporation, solar radiation and temperature should be examined. This is especially true in the case of evaporation and solar radiation as they impact soil moisture, and soil temperature. Temperature modification would become important whenever very high temperatures are being experienced. For example, if the ambient temperature could be reduced by several degrees during silking when the anticipated temperature would exceed 36 C a benefit might be observed.

Important management practices that need to be evaluated include tillage practices, fertilization, planting date, plant population, and variety. Currently, the models respond only to plant population, planting date and hybrid maturity. Future work must include other important management decisions such as tillage practices and fertilization.

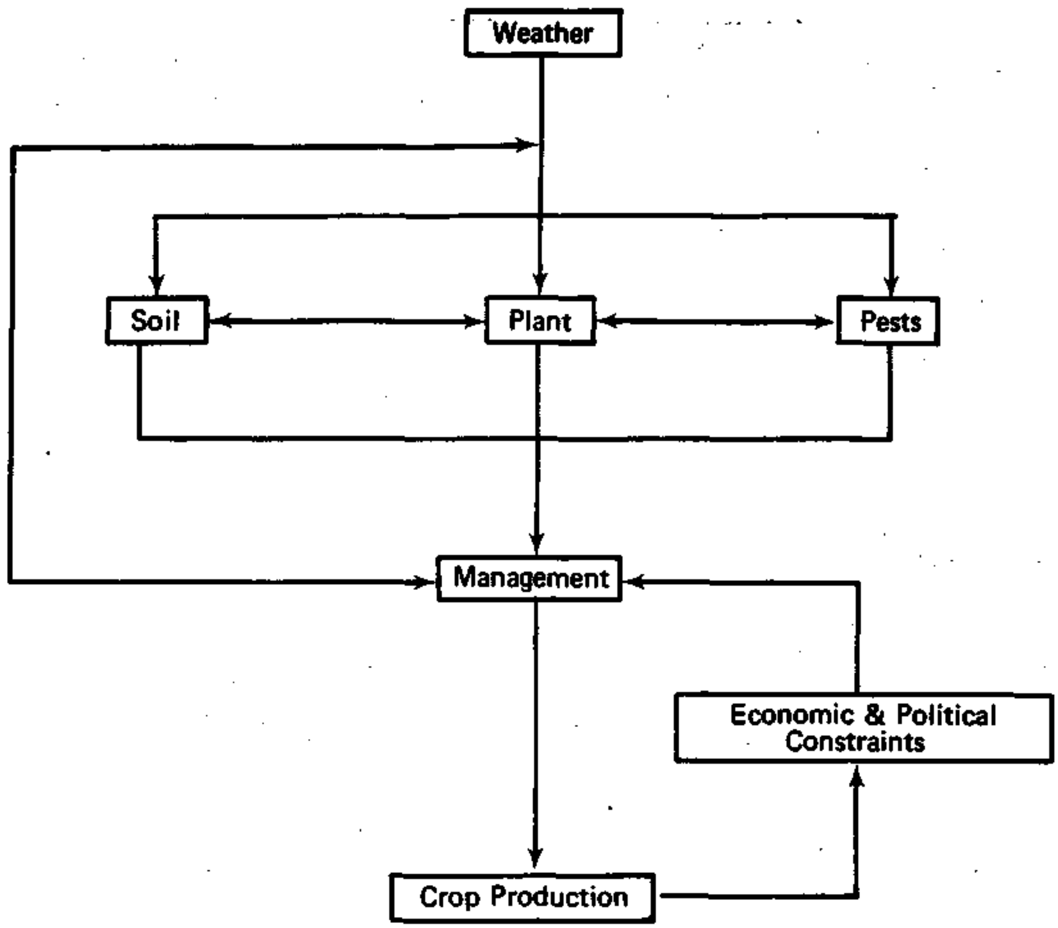


Figure B-1. Simple diagram of an agricultural production system.

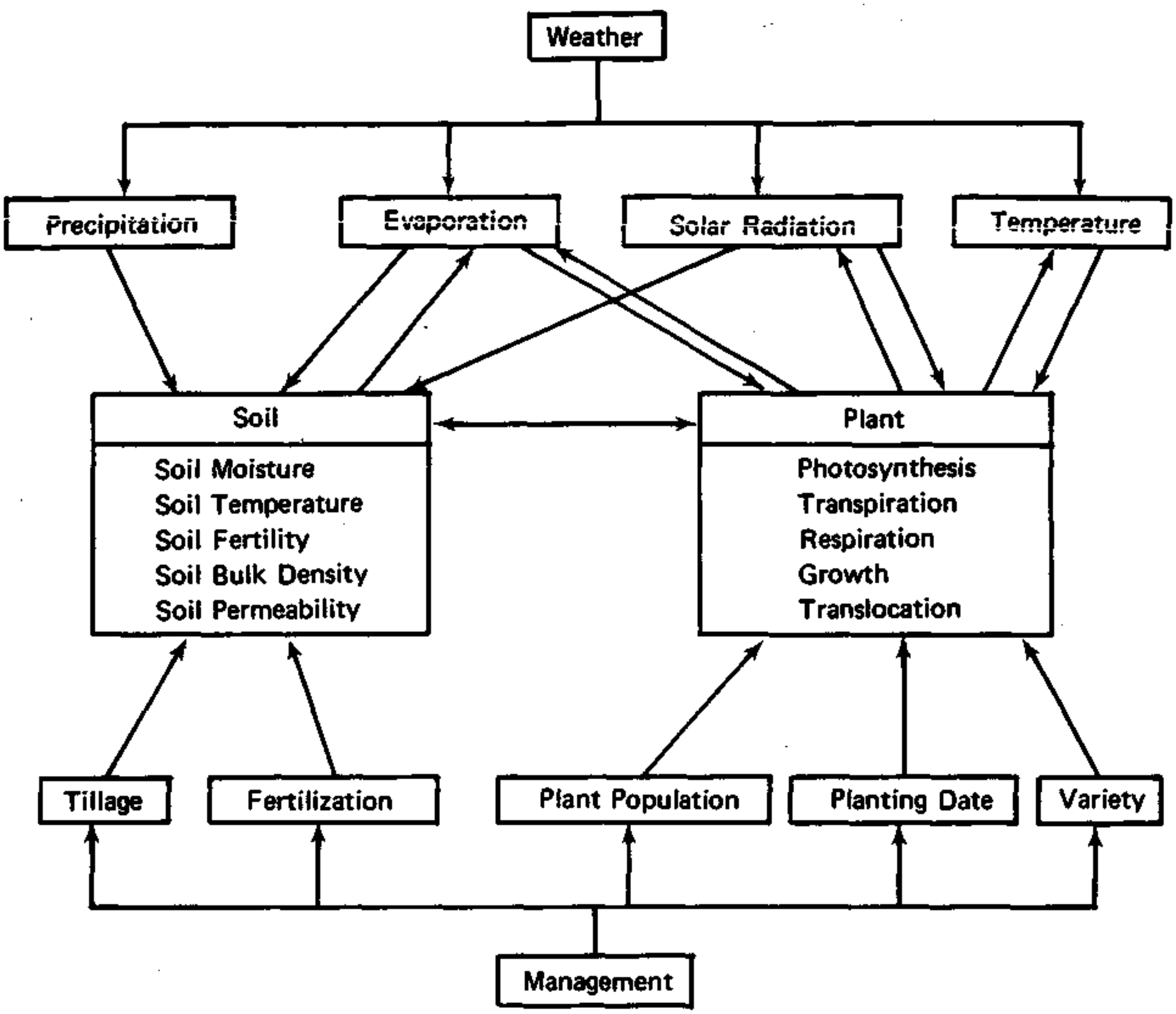


Figure B-2, Soil and plant factors affected by weather and mangement.

Evaluating weather-tillage practice interactions is important because of the impact on soil bulk density, soil permeability, and ultimately soil moisture and temperature. From standpoint of the plant the soil moisture and soil temperature are the items of interest. Both of these variables are dependent upon each other, soil bulk density permeability, precipitation, and evaporation. The timing of tillage practices has a major impact on these soil variables. For example, tillage under less than optimum soil moisture conditions will result in an increased soil bulk density which in turn will reduce the amount of plant available water in the soil and increase the resistance of the soil to root growth and expansion.

In the deterministic model currently available, soil moisture is estimated as a function of the soil water holding capacity, precipitation and evaporation. The model does allow for the presence of a shallow water table and artificial drainage with field tile. The soil bulk density and thus water holding capacity is assumed to be constant throughout the year because the model does not evaluate the effects of tillage on soil bulk density.

The area of weather-soil fertility interactions is vitally important in a study such as this. Traditional methods of studying soil fertility do not include the effects of weather on soil fertility or response of crops to different fertilizer rates under different weather conditions. The crop model does not include soil fertility effects on plant growth or the effects of weather on soil fertility. An example of how weather can impact the response of corn to anhydrous nitrogen fertilizer will be presented later.

The other three management practices shown in Figure B-2, plant population, planting date and variety are direct inputs to the crop model. The main function of plant population is to initialize phytomass so the model can simulate the crop growth. Planting date and variety selection serve to fix the length of time available for the crop to grow. In the real world variety selection has a greater effect on yield response to weather than just fixing length of growing season. Some of these effects are drought hardiness and physiological rates. In the crop model physiological rates of photosynthesis, respiration, translocation of soluble carbohydrates and other plant substances, and growth do not vary relative to variety. In most cases, varying this information over a large area is not practical because the information is not readily available nor constant from field to field. The best one can do is estimate a typical variety for a given area and assume it is constant for that given area.

Model Description and Example Runs

Many deterministic models have been developed to simulate the effects of weather on crop yields. These models have varying degrees of complexity. The more complex models require more computer time to run a simulation of one site-year. A site-year is defined as the results of running the model on a given geographic location with one year of weather.

The model used to demonstrate the validity of the approach described above is an adaptation of Corn-Crops (Reetz, 1976). This model is a physiologically based model that simulates the effect of weather on photosynthesis, transpiration, respiration, translocation and growth. Photosysthesis is assumed to occur only in the leaves. For most purposes this is a valid assumption, as little photosysthesis will occur in the stem region of corn. Transpiration is also assumed to occur only from the leaves. The other biological processes (respiration, growth, and translocation) are simulated for each plant compartment (leaves, stems, ears, and roots). This procedure of simulating the corn growth allows testing the model against field data collected throughout the year as well as the final yield.

Description of Simulations. Simulations were run on 14 years of weather data (1970-1983) collected at the National Weather Service Climatological Station at the Morrow plots on the University of Illinois campus at Urbana, Illinois. The soils and agronomic data bases described a typical Champaign County, Illinois site. It is not possible to exactly characterize a typical site due to the simplifications that exist in all models. The assumptions contained in the model used here consist of three kinds - those associated with the crops and soil models and those made relative to the model inputs.

The first assumption relative to the soil moisture model is that the site being modeled is perfectly flat (slope = 0%). Therefore, all precipitation must percolate through the soil profile and there is no surface runoff. Second it is assumed that each soil layer is filled before water can percolate into the layer below. Further, if the precipitation, received exceeds the amount of water required to completely fill the soil profile, the excess is immediately drained below the root zone and is not available for use by the plant. Thus there is no water ponding or reduced soil aeration due to excess water. The depth from which water is withdrawn from the soil profile by the crop roots is a function of plant age and varies with time.

The crop model assumes that soil fertility and plant nutrients are not limiting. A corn monoculture is assumed and there are no soil compaction layers in the top 1.05 m of soil. Carbohydrates are partitioned into a root compartment, but roots are not distributed through the soil profile. Therefore soil water withdrawal is accomplished by empirical rooting depth estimates in the soil moisture model. Root competition for nutrients and moisture are not accounted for with the crop model.

The one assumption about the model inputs is planting occurs regardless of soil moisture status on the day of planting. Thus if the soil is at field capacity on the day the crop is to be planted, it is assumed to be planted even though in actual practice it would not have been planted.

Data Bases Used. The three data bases used in conducting the experiment, were a soil data base, an agronomic data base, and a weather data base. The weather data were obtained from Champaign County, Illinois, and the soil data base and agronomic data base are characteristic of conditions and practices in that area.

The soil data base contained the soil water characteristics. In this experiment a Drummer soil (fine silty mixed mesic. Typic Hoplaquolls) that is poorly drained with tile drainage at a depth of 1.05 m was assumed.

The soil profile was divided into ten 0.15 m layers with seven layers above the drainage tile and three below. Soil water holding capacity and other soil characteristics were obtained from the Soil Survey of Champaign County (USDA-SCS, 1982). The 0.3 bar and 15 bar water holding capacities were obtained from the relationship developed by Rawls et al. (1982).

The agronomic data base contained soil moisture and crop information for each of the 14 years used. Most of the agronomic practices can be changed or controlled by the producer. Included are the planting dates, maturity rating for each of the hybrids, plant population, and initial soil moisture in each of the 10 soil layers. The five planting dates in the data base are April 20, May 5, May 15, May 25, and June 10. The maturity rating for the varieties are expressed in Celsius growing degree days. For the short season variety, the growing degree days required to reach maturity was 1276, the medium season variety 1454, and for the full season variety 1494.

The plant populations were 49400, 59280, and 79040 plants/Ha (20000, 24000, 32000 plants/ac). It was assumed that no plants were lost during emergence or post emergence therefore harvest and planting populations are equal.

The soil moisture was initialized each year on the second day that pan evaporation information was available. This date varied from April 1 to April 23. The initialization value was the percent of soil water potentially available to the plant in each soil layer, and was determined using winter precipitation to estimate the degree to which the profile was recharged. Only 5 of the 14 years were not saturated at the start of the evaporation record. These years are 1971, 1972, 1977, 1980, and 1981.

The final item included in the agronomic data base was the depth to the water table on the date of soil initialization. If the soil moisture in the eighth soil layer was equal to 100% of the plant available water than it was assumed that the water table was at the drainage tile depth of 1.05 m.

The weather data base included 14 years of weather (1970-1983) collected at the Morrow Plots climate station on the University of Illinois campus in Urbana, IL. The weather variables included in the data set are daily maximum and minimum temperature, precipitation, evaporation, and solar radiation. The temperature and precipitation data were used as recorded in the weather records except for the frost date in 1974. On October 2, 1984, all the stations within 100 km of Urbana reported a freeze with minimum temperatures below -1.1 C due to a polar air mass moving into the region. The Urbana station did not report temperatures below 0 C on that date. Since this was a general freeze and effectively killed the crop that year, the minimum temperature was changed to reflect the general cold temperatures of that night.

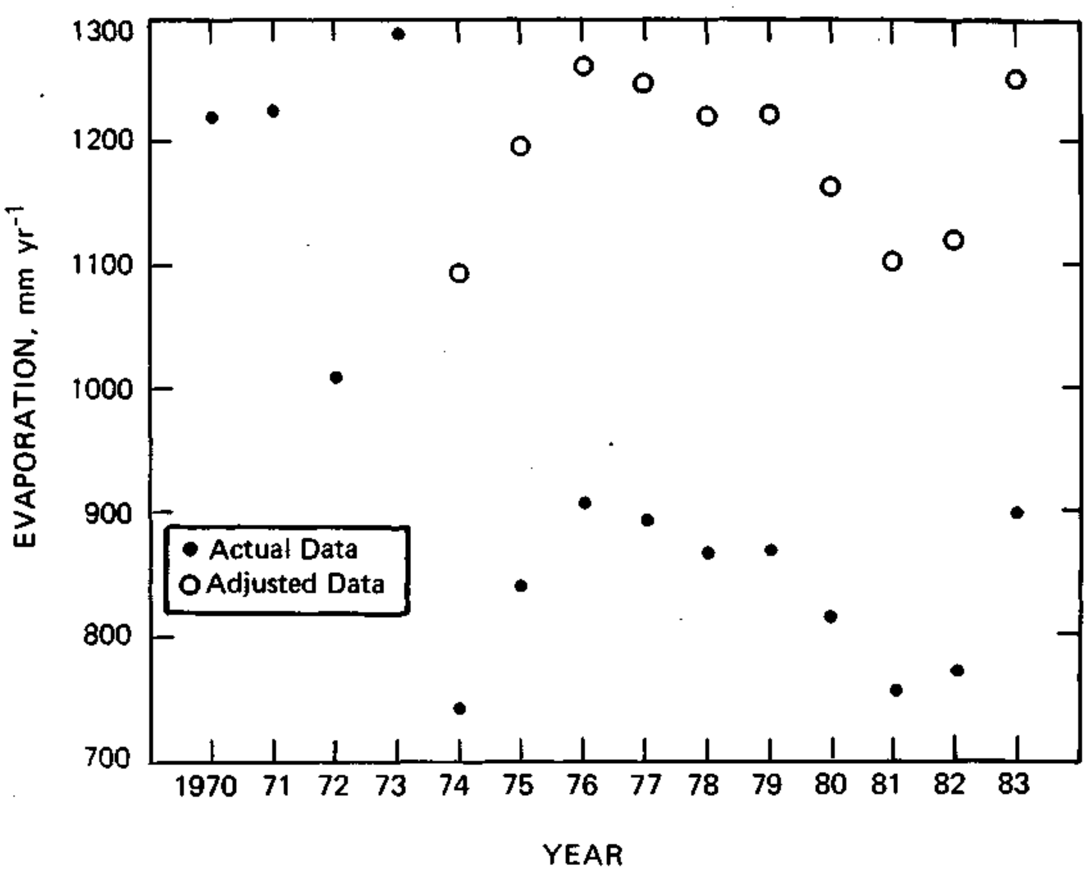


Figure B-3. Total annual evaporation, (•) is that observed at the station, (0) is the adjusted.

Evaporation data were examined for missing data and correlation with time. When data were missing in the original record, the evaporation was estimated by using the mean evaporation of the day before and the day after the missing data, or by substituting pan evaporation from other days that had comparable temperature, wind, and humidity.

A correlation was run with each weather variable and year to represent time. A significant negative correlation between evaporation and time was found. The negative correlation was due to the growth of an evergreen hedge within 6 meters of the evaporation pan. The hedge was established in 1973 to enclose the Morrow Plots and has reduced the wind exposure of the evaporation pan to easterly winds. Today the top of the hedge is above the evaporation pan. To determine how best to correct for the trend in the data, yearly evaporation was plotted against time (Figure B-3). The plot reveals a discontinuity occurring between 1973 and 1984. When regression equations were fit to the 1970-1973 data and then to the 1974-1983 data, the respective slopes of the equations were not significantly different from zero. Therefore, the 1974-1983 data were adjusted by adding the difference between the mean 1970-73 evaporation and the mean 1974-1983 evaporation. Daily evaporation values were calculated by equation 1,

$$E_{ci} = E_{oi} + E_m/215 \qquad (1)$$

where E_{ci} is the corrected daily evaporation, E_{oi} is the observed daily evaporation, E_m is the difference between the mean yearly evaporation of 1970-1973 and 1974-1983, and 215 is the mean number of days that evaporation data were available each year.

Solar radiation data were available from pyronometer readings at the Illinois State Water Survey for 1982-1983, 1/2 km north of the site where the rest of the weather data were collected. Reliable data for Urbana, for the period from 1970-1981 were not available. Therefore radiation was obtained using 1970-1983 radiation measurements from West Lafayette, Indiana, (145 km northeast of Urbana). The West Lafayette data was collected using a pyronometer and corrected to the Champaign County site using a regression of the 1982-1983 Urbana data on the West Lafayette 1982-1983 data. The correction factor was (Eq. 2).

$$Y_u = 71.31496 + 0.96830\ Y_L \qquad (2)$$

where Y is the estimated Urbana radiation, and Y_L is the measured West Lafayette radiation.

Because of the uncertainties in the weather data (mentioned above) and the assumptions in the models and the agronomic and soil data bases, the model should not be expected to duplicate the Champaign County yields reported by the USDA. However, one should expect the yields to be of the same relative magnitude, and the rank ordering of the yields should be approximately the same. For this study, the variation in yield relative to weather and management are more important than absolute yields.

Slmulatlon Results

To determine if the yields from the model represent the real world, the model results were compared to the USDA yield estimates for Champaign County (Table B-7). The model estimates are the overall mean of the planting date, population, and variety treatments for each year. The overall mean for the 14 years is underestimated by 2.4% by the model. As occurs with most models, the model yield variation between years is less than occurs in the actual data. The result of less variation is that the model will under predict yields in very good years and over predict yields in very bad years.

Comparing the rank of the model yields and USDA yields reveals that 11 of the 14 years have ranks that differ by 2 places or less. This would indicate that the model does an acceptable job of evaluating the effects of weather on corn yields.

Management-weather-yield interactions were evaluated by a multifactor analysis of variance (ANOVA) assuming all the factors in the ANOVA are random. Year was used as a dummy variable for the weather. This is valid since the year is used by the crop model to select a weather data set. In the ANOVA, the important interactions are the year and management factor interactions. In this case the management factors are date of planting (D), population (P), and variety (V). If the year-management two and three way interactions are significant then the model results demonstrate enough sensitivity to evaluate the response of different management practices to precipitation enhancement, and thus the microscale response of crops to weather.

The results of the ANOVA are presented in Table B-8. All the two and three way year management interactions are significant except for the year-population-variety interaction. It is probable that this three way interaction should be significant but the current model is not designed to handle it.

Nitrogen Fertilizer-Weather Interaction

The results of the model runs reported above do not consider the effects of weather interactions with nitrogen fertilizer application. To demonstrate these interactions data from a multi-year anhydrous fertilizer experiment conducted on the Agronomy farm at Urbana were analyzed to determine the impact of weather on nitrogen fertilization and what weather period or periods were important.

Materials and Methods. Nine years of yield data were collected from 1975 to 1983. Only 1976, 1977, 1979, 1980, 1981, and 1983 data (Table B-9) were used in this study since they represent a monoculture where corn follows corn. In 1975, 1978, and 1982, corn followed soybeans. These three years were omitted as there is a significantly different response to nitrogen fertilization when corn follows soybeans than when corn follows corn (Nafziger *et al*., 1984).

Table B-7. Comparison of model runs to USDA yield estimates in Champaign County, 1970-1983.

	Yield (mg/Ha)			
Year	Model Estimate	Rank	USDA Estimate	Rank
1970	6.67	11	5.97	11
1971	7.57	6	7.73	8
1972	7.74	4	8.11	6
1973	7.48	8	7.73	9
1974	6.65	12	5.91	12
1975	7.63	5	8.55	4
1976	8.95	1	8.04	7
1977	6.86	10	7.48	10
1978	7.24	9	8.36	5
1979	8.46	2	9.12	2
1980	6.36	13	5.16	14
1981	7.50	7	8.61	3
1982	8.21	3	9.24	1
1983	5.84	14	5.72	13
Mean	7.37		7.55	
Sd	±0.85		±1.33	

Table B-8. ANOVA for model results testing for significance of management-weather interactions. The 4 way interaction term is assumed to be the error term and is used to test the main effects and interactions for significance. All factors are assumed to be random.

Factor	Degrees of Freedom	Sum of Square	Mean Square	F
Year (Y)	13	418.47	32.190	4598.57*
Date of Planting (D)	4	740.23	185.058	26436.86*
YD	52	72.37	1.392	198.85*
Population (P)	2	224.29	112.145	16020.71*
YD	26	2.83	0.109	15.57*
DP	8	0.30	0.038	5.48*
YDP	104	3.99	0.038	5.48*
Variety (V)	2	294.46	147.230	21032.86*
YV	26	12.23	0.470	67.14*
DV	8	1.67	0.209	29.86*
PV	4	3.06	0.765	109.29*
YDV	104	11.27.	0.108	15.43*
YPV	52	0.34	0.007	1.00
DPV	16	0.48	0.030	4.29*
YDPV	208	1.49	0.007	
TOTAL	629	1787.49	2.842	

*Significant at 0.001 level

Table B-9. Ammonia treatment levels for each year with the corresponding yields.

	Nitrogen Rate (kg/Ha)							
Year	0	67	112	134	168	225	269	337
				Yield Kg/Ha				
1976	4653	8802		13643			14146**	
1977	4715	8299		9620			10311**	
1979	9179		11066		11254	11694**		11631
1980	4150		3709		2829	4464**		2766
1981	5910		10814		11883**	11066		11003
1983	3835		7922		8299	8991**		

Yield data were obtained from plots which had received varying rates of spring applied nitrogen (N) as anhydrous ammonia. , The studies were conducted on a naturally poorly drained Drummer silty clay loam (Typic Haplaquoll). In 1981 and 1983 the experimental plots were located in an area of the field that had been tiled so the soil would be classified as moderately well drained.

Weather data for the 9 years were obtained from the Urbana climate station at the Morrow Plots on the University of Illinois campus, Urbana, Illinois. The station is located approximately 2 km north the experimental plots. Maximum and minimum daily temperatures, daily rainfall and daily pan evaporation were recorded.

In addition to these variables, the ratio of precipitation to evaporation (P/E) was used as a moisture availability index. This ratio has been used to classify climate (Thornthwaite, 1948). In this case it is used to quantify the potential for drought during each growth period. The weather data were summarized by dates which typify normal corn growth stages (Table B-10). The growth stages represent planting, emergency, vegetative growth, silking and pollination, and grain fill.

Evaluation of the corn yield response to nitrogen was accomplished by calculating a relative yield index (Y_{Ij})

$$Y_{Ij} = Y_{ij}/Y_{xj} \qquad (1)$$

where Y_{ij} is the yield at the ith level of nitrogen fertilization in the jth year, and Y_{xj} is the maximum yield observed in the study in the jth year. Y_{Ij} was related to the level of nitrogen fertilization with the model

$$Y_{Ij} = \alpha_j \ (N+1)^{\beta_j} \ \mu_j \qquad (2)$$

where α_j is the fraction of the maximum yield expected with no nitrogen fertilizer, N is the level of nitrogen fertilization in kg/ha, β_j is the yield increase with each addition of N fertilizer, and μ_j is an error term. Each years data were fit to (2) using a ln-ln transformation and linear regression model.

$$Y'_{Ij} = a_j + b_j N' + e_j \qquad (3)$$

where

$$a_j = \ln \alpha_j$$
$$b_j = \beta_j$$
$$Y'_{Ij} = \ln Y_{Ij}$$
$$N' = \ln (N+1)$$
$$e_j = \ln \mu_j.$$

The α's and β's for the 6 years are presented in Table B-11 along with the coefficient of variation of the linear model determined on the transformed variables. With the exception of 1980, the transformed model

Table B-10. Calendar periods used to examine weather relationships and associated crop growth events.

Period From	To	Growth Description
4-1	5-15	Fertilizer application and early planting
5-16	6-10	Planting and emergence
6-11	7-15	Vegetative growth
7-16	7-31	Tasseling and silking
8-12	9-30	Grain fill and maturation
4-1	9-30	Entire growing season

Table B-11. Calculated α's and β's for each years response to nitrogen treatment. The correlation coefficient is included as a measure of variation explained.

Year	α	β	r	r^2
1976	0.319	0.199	0.972	0.945
1977	0.456	0.141	0.9.98	0.996
1979	0.784	0.042	0.994	0.988
1980	0.942	-0.042	-0.462	0.213
1981	0.505	0.117	0.978	0.956
1983	0.426	0.153	0.999	0.998

explained more than 90% of the variation in yield due to the nitrogen treatments in a given year. The 1980 data were included because the poor fit was due to drought along with high temperatures. These weather events need to be considered when evaluating the effects of weather on fertilizer response.

The a in (2) is the fraction of maximum yield expected if no nitrogen fertilizer is applied. The percent yield increase (I) due to optimum nitrogen fertilization can be determined by

$$I = 100-\alpha. \qquad (4)$$

B in (2) is a measure of the rate of yield increase with each additional unit of fertilizer applied. When g is less than zero, each increment of fertilizer will cause a yield decrease, if 8=0 there is no response, and when B > 0 each increment of fertilizer results in a yield increase. Normally B ranges from slightly less than 0 to about 0.2.

The expected fraction of yield increase (E_y) for any level of nitrogen application over zero nitrogen is given by

$$E_y = \alpha\ [(N+1)^{\beta}\ -1] \qquad (5)$$

Weather-Nitrogen Response Relationship. The relationship of a and 6 to both precipitation and precipitation evaporation ratios was evaluated for various growth stages (Figures B-4 and B-5). Of these, the strongest correlation between weather and crop response to N was obtained with the use of precipitation to evaporation ratios during the June 11 to July 15 period. This corresponds to rapid vegetative growth and is generally considered to be the stage of growth just before the most rapid nitrogen uptake by the plant (Jones and Houston, 1914; Hanway, 1962; Mengel and Barber, 1974; Russelle et al., 1983). It also relates to the June-July weather period found to have the greatest significance by Asghari and Hanson (1984a, 1984b) in evaluating nitrogen and climate interactions. The summary of the weather and weather indices for this period are shown in Table B-12.

The best polynomial fit of P/E with a and B are shown in Figure B-5b. Extrapolation of the curves above P/E values of 1.107 or below P/E values of 0.228 is invalid because it violates the definition of the yield response index (i.e., Y_I cannot be greater than 1.000).

The coefficients for the α and β models

$$\left[\begin{matrix}\alpha\\ \beta\end{matrix}\right] = b_0 + b_1\ (P/E) + b_2\ (P/E)^2 \qquad (6)$$

are given in Table B-13 along with their significance level, the multiple correlation coefficients, and the error mean square. All the coefficients are significantly different from zero at the *5%* level.

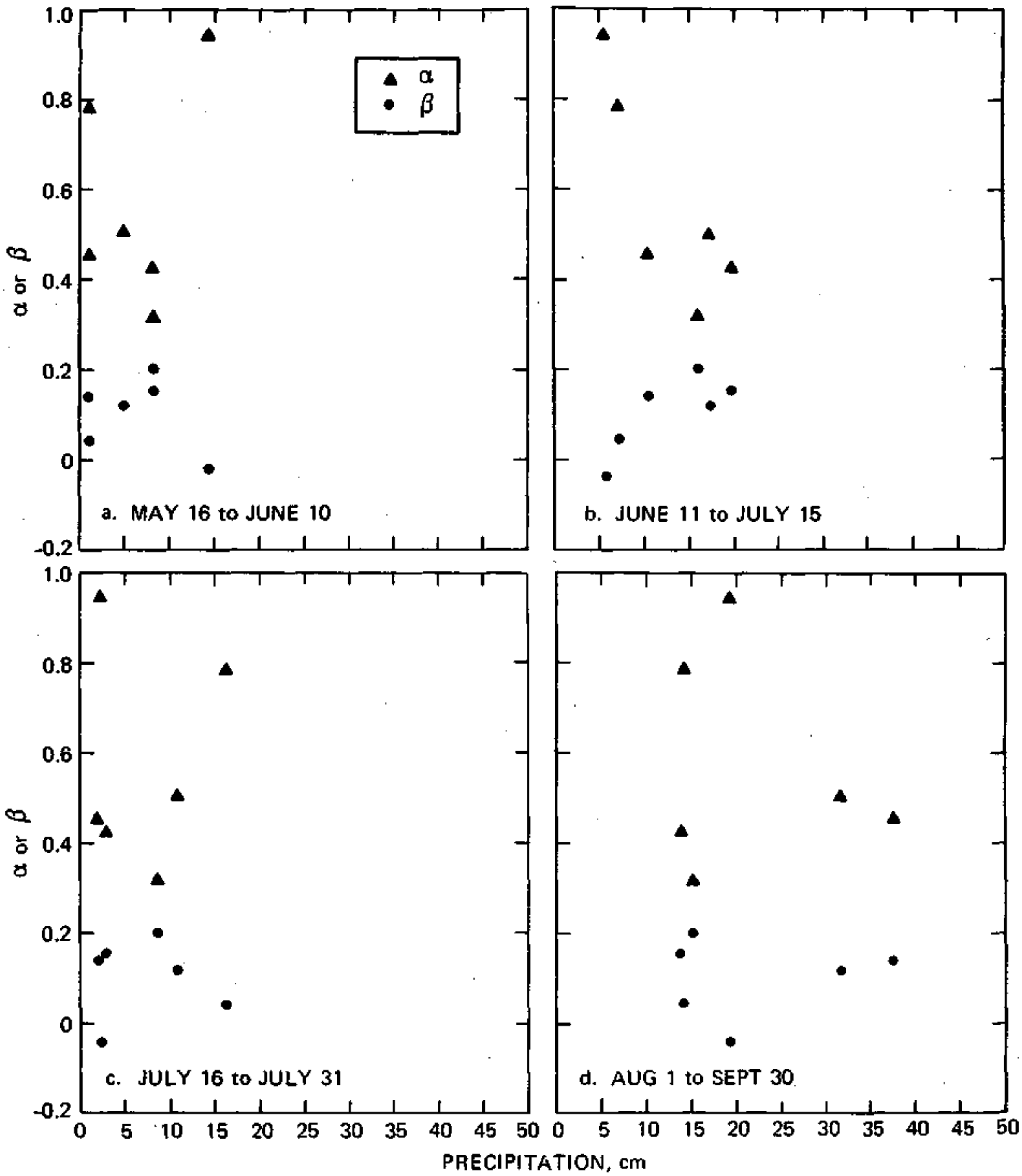


Figure B-4. Plot of α and β is a function of precipitation of the period of May 16 to June 10 (a), June 11 to July 15 (b), July 16 to July 31 (c), and August to September 30 (d).

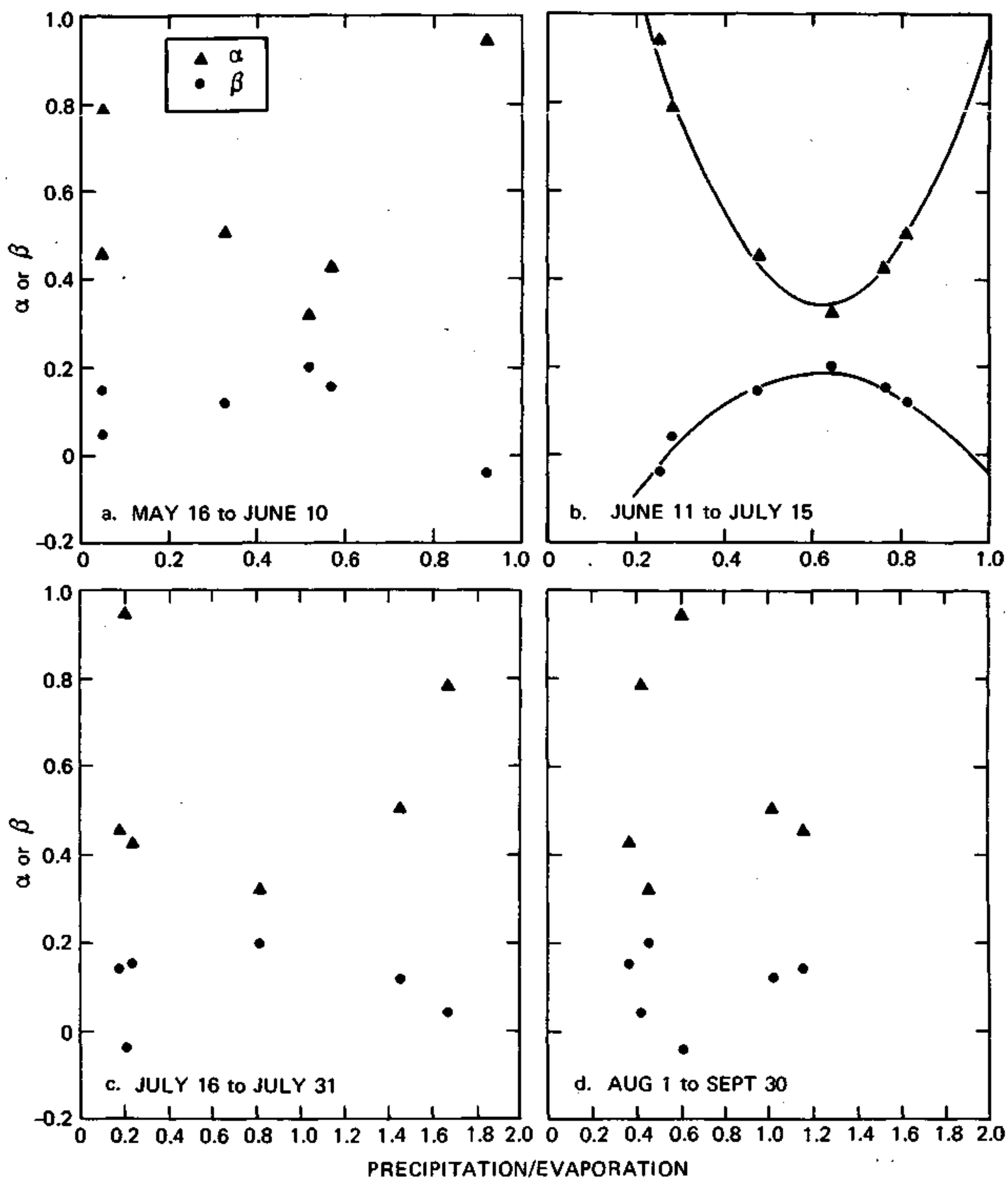


Figure B-5. Plot of α and β against the P/E ratio for the periods of May 16 to June 10 (a), June 11 to July 15 (b), July 16 to July 31 (c), and August 1 to September 30 (d).

Table B-12. Summary of weather and indices for the June 11 to July 15 growth period for each year.

Year	PPN[a] cm	EVAP[b] cm	Tx[c] C	Tn[d] C	Ta[e]	(P/E)[f]
1976	16.21	25.15	28.6	16.7	22.6	0.645
1977	10.59	22.00	29.5	18.0	23.8	0.481
1979	7.26	25.45	28.6	15.9	22.2	0.285
1980	5.77	22.73	29.8	16.9	23.3	0.254
1981	17.32	21.29	28.8	18.4	23.6	0.813
1983	19.81	25.93	30.3	18.9	24.6	0.764

[a]PPN = Precipitation
[b]Evap = Evaporation
[c]Tx = Mean maximum air temperature
[d]Tn = Mean minimum air temperature
[c]Ta = Mean air temperature
[f]P/E = Precipitation/Evaporation

Table B-13. Coefficients for the β and β models with significance level, R^2 and mean square error.

	Model	
	α	β
b_0	1.980*	-0.422**
b_1	-5.266*	1.987**
b_2	4.231*	-1.621**
MSE	0.001	0.0006
R^2	0.987	0.954

* Significant at 1% level
**Significant at 5% level

Expected yield indices were calculated using

$$Y_E = \alpha(N+1)^\beta \qquad (7)$$

where α and β were calculated from (6) using observed P/E for each year.

The actual yield indices obtained from the experimental data are compared to those obtained from the model in Table B-14. The mean error in yield was 8.4% with the greatest error occurring in 1980. when a drought occurred during the June 11-July 15 period. This is also the year where the ln-ln transformation failed to fit the experimental data well (Table B-11). In this case the model underpredicts the actual response to nitrogen application.

The strong relationship of a and B to P/E reflects the effect of drought and excess moisture on nitrogen fertilizer efficiency. When P/E is less than 0.6, water becomes limiting and the crop is unable to utilize the available nitrogen. At the other end of the spectrum, when P/E is greater than 0.6 then water is not limiting but as P/E continues to increase, soil moisture rises and a faster rate of nitrification will occur (Sabey, 1969; Parker and Larson, 1962; Miller and Johnson, 1964). The increased rate of conversion of NH^+_4 to NO^-_3 accompanied by excess moisture would increase the potential for nitrate leaching.

The rate of denitrification is also strongly affected by soil moisture. Focht and Verstraete (1977) reported that denitrification stopped when soil moisture potential dropped below -1/3 bar. This would be the more probable case when P/E is less than 0.6 and the probability of soil moisture potential being less than -1/3 bar would increase as P/E continued to decrease. When P/E exceeds the optimum (> 0.6) there is a greater probability that poor soil aeration will cause an increase in the denitrification rate. Wesseling and Van Wijk (1957) found that oxygen diffusion in the soil becomes critical at about 85% water saturation of the total pore space. In wet period, there is a greater probability that soil water saturation would be at or above the 85% value for a significant period of time and increased denitrification could be expected to occur.

When drier than optimum conditions occur, nitrogen losses from leaching and denitrification would be expected to decrease. This would result in more nitrogen being available for future growth stages. The residual nitrogen is not likely to help the growing crop except to the extent it might decrease the effects of drought and improve water use efficiency. However, the increased soil nitrogen would not overcome the negative effects of drought or heat stress during silking and grainfill.

Applications to Weather Modification. The test of the effectiveness of the above nitrogen fertilizer weather interaction can be demonstrated by adjusting the results of the crop model runs using the average nitrogen application rate for Champaign County for each of the years used to run the crop model. The rate of nitrogen application was determined using the record of fertilizer sales from January to June, and the acres of corn planted each year. The yields estimated by the model were then adjusted

Table B-14. Predicted yield indices compared to the actual yield indices.

	Nitrogen Applied (Kg/Ha)																			
	0		67		112		134		168		225		269		337					
Year	Io[a]	Ic[b]	Io	Ic	Io	Ic	Io	Ic	Io	Ic	Io	Ic	Io	Ic	Io	Ic	USE	RMSE	Error
1976	0.329	0.344	0.622	0.754			0.964	0.857					1.0	0.974			0.0074	0.086	8.6Z
1977	0.457	0.426	0.805	0.833			0.933	0.929					1.0	1.038			0.0008	0.028	2.8Z
1979	0.784	0.822			0.946	0.874			0.962	0.879	1.0	0.882			0.995	0.887	0.0078	0.088	8.8Z
1980	0.930	0.917			0.831	0.826			0.633	0.819	1.0	0.814			0.620	0.807	0.0209	0.144.	14.4X
1981	0.497	0.497			0.910	0.885			1.0	0.929	0.931	0.963			0.926	1.011	0.0028	0.053!	5.3Z
1983	0.427	0.427			0.881	0.872			0.923	0.926	1.0	0.968					0.0003	0.017	1.7%
MSE		0.0005		0.0091		0.0015		0.0057		0.0116		0.0126		0.0011		0.0180	0.0071		
RMSE		0.022		0.095		0.038		0.076		0.108		0.112		0.033		0.134		0.084	
Error*		2.2%		9.5%		3.8%		7.6%		10.8%		11.2%		3.3%		13.4%			8.4Z

[a]Io = observed yield index

[b]Ic = yield index calculated from α and β derived from the weather model

by assuming the model was developed with a nitrogen fertilizer rate of 160 kg/ha and adjusting the yields to the nitrogen actually applied with the efficiency (β) expected with the weather that occurred from June 10 to July 15.

Table B-15 shows the results of the above adjustment and how it compares to the county yields estimated by the USDA. Except for 1976 and 1978 the nitrogen adjustment improves the yield estimates. The errors associated with 1976 and 1978 are problems with the model used to make the initial yield estimates. The exact cause of the problem is not known at this time but it is suspected to be associated with the temperature functions in the corn model.

Summary

The above nitrogen-weather interaction function could be used very effectively in determining the value of additional rainfall due to weather modification during the June 10 to July 15 period. With this relationship and others yet to be developed intelligent decisions could be made relative to when and if weather modification should be attempted. When used in conjunction with the crop model, it should be possible to determine how much each weather modification event has profited the producer in a given area. It is important to remember that the results of microscale modeling give the benefit to the producer in terms of increased yield. To determine his true economic return or benefit, it is necessary to evaluate the aggregation of all the fields up to a national level and then use macroscale economic models to evaluate the economic impact on the agriculture community.

Table B-15. Effect of adjusting model yields using the nitrogen fertilizer-weather relationship on rank order of yields by year in Champaign County, Illinois.

Rank Order	
USDA Estimate	Nitrogen Adjusted Model Estimate
82	76
79	82
81	79
75	81
78	75
72	72
76	71
71	78
73	73
77	77
70	74
74	70
83	80
80	83

REFERENCES

Asghari, M., and R. G. Hanson, 1984a: Nitrogen, climate and previous crop effect on corn yield and grain N. Agron. J., 76:536-542.

Asghari, M., and R. G. Hanson, 1984b: Climate, management, and N effect on corn leaf N, yield and grain N. Agron. J., 911-916.

Focht, D. D., and W. Verstraete, 1977: Biochemical ecology of nitrification and denitrification. Ann. Rev. Microbiol. Ecol., 1:135-214.

Hanway, J. J., 1962: Corn growth and composition in relation to soil fertility: II. Uptake of N, P, and K and their distribution in different plant parts during the growing season. Agron. J., 54: 217-222.

Jones, W. J., Jr., and H. A. Huston, 1914: Ccmpsoition of Maize at Various Stages of its Growth. Purdue Univ. Agric. Exp. Sta. Bull. 175.

Mengel, D. B., and S. A. Barber, 1974: Rate of nutrient uptake per unit of corn root under field conditions. Agron. J., 66:399-402.

Miller, R. D., and D. D. Johnson, 1964: The effect of soil moisture tension on carbon dioxide evolution, nitrification and nitrogen mineralization. Soil Sci. Soc. Amer. Proc, 28:644-647.

Nafziger, E. D., R. L. Mulvaney, D. L. Mulvaney, and L. E. Paul, 1984: Effect of previous crop on the response of corn to fertilizer nitrogen. J. of Fert. Iss., 16:136-138.

Parker, D. T., and W. E. Larson, 1962: Nitrification as affected by temperature and moisture content of mulched soil. Soil Sci. Soc. Amer. Proc, 26:238-242.

Rawls, W. J., D. L. Brakensick, and K. E. Saxton, 1982: Estimation of soil water properties. Transactions of the ASAE, 25:1316-1320, 1328.

Reetz, H. F., Jr., 1976: CORN CROPS! A Physiology-Based simulation of the Corn Crop. Ph.D. Thesis, August 1976, Purdue University, West Lafayette, Indiana.

Russelle, M. P., R. D. Hauck, and R. A. Olson, 1983: Nitrogen accumulation rates of irrigated maize. Argon. J., 75:593-598.

Sabey, B. R., 1969: Influence of soil moisture tension on nitrate accumulation in soils. Soil Sci. Soc. Amer. Proc., 33:263-266.

Thornthwaite, C. W., 1948: An approach toward a national classification of climate. Geographical Review, 38:55-94.

USDA-SCS,. 1982: Soil Survey of Champaign County, Illinois.

Wesseling, J., and W. R. van Wijk, 1957: Land Drainage in Relation to Soils and Crops. I. Soil Physical Conditions in Relation to Drain Depth. In: Luthin, L. N. (ed.), Drainage of Agricultural Lands, pp. 461—504. American Society of Agronomy, Madison.

3. Study of Weather and Crops in 1978-1983

Sharon Gould-Stewart

Objectives and Scope

A study of crop and weather conditions during 1978-83 was undertaken to define the sensitivity of crops to weather under current technology (farm practices). The 1978-83 period was studied in detail because these were years of similar agricultural technology and also years with a wide range of rain and temperature conditions in Illinois and with a large variation in crop yields. Another objective was to examine, in a qualitative way, whether the positive and negative weather influences in recent years were similar to those defined in earlier years (Huff and Changnon, 1979).

The crop and climate data used in this study are from Illinois. Crop data used includes acreage, production, yield, and phenological information for corn and soybeans. Climate data includes daily temperatures, daily rainfall, and computed quantities such as cumulative rainfall and cumulative heat index. Study of the 6-year period was made, both as a comparison among the years of interest, and as a comparison with the earlier climatic record.

Data

Crop data for the six years (1978-83) were obtained from the Illinois Cooperative Crop Reporting Service (ICCRS). Yield, acreage, and production figures for all Illinois counties were taken from the Illinois Agricultural Statistics Annual Summary for 1980-1984. Estimates of crop phenology for the 9 Crop Reporting Districts were from work sheets kindly provided by the ICCRS.

Yield estimates are in units of bushels per acre, to the nearest tenth of a bushel. Acreage estimates are in bushels, to the half-thousand acres. Production estimates are in bushels, to the nearest hundred bushels. Estimates of plant phenology are made for six stages of development: planting, silking, dough, denting, maturity, and harvest. Estimates of percentage of the total crop at each state are made weekly. For each year, the date at which 50% of the plants in the crop reporting district attained each stage was linearly interpolated between weekly estimates. The day number of this interpolated date was the data used for phenology statistics.

Daily precipitation data for 78 stations were archived at the Water Survey. This preliminary study used 33 of those stations, chosen for completeness of record for the 1978-83 period. There were only 6 observations missing in the entire 6-year, 33-station sample. The 33 stations are in 32 counties and all 9 Crop Reporting Districts, as shown in Figure B-6. The sample will be expanded by going to the printed records and filling late data. Six stations with complete precipitation records were used to develop a climatology of daily precipitation. The methods used to create the climatology are discussed in the next section.

Daily minimum and maximum temperature data are also archived at the Water Survey. Presently, temperature records are available for nine stations, six of which are stations with 83-year precipitation records. The scope of this study will be expanded soon to a complete study of temperatures over the state as soon as the temperature data comes on line.

Methods of Analysis

Precipitation data character files were made into unformatted files for speed of calculations. The files were checked for missing data and non-numeric characters. Non-numeric characters indicate either a punching error or an accumulated value, and were translated to numbers when they appeared.

Six stations with precipitation records beginning in 1901 or earlier had missing data that could be filled in from printed records, late reports or from the original observer records at the Water Survey. For these six stations, a climatology of daily rainfall was made for the 83-year record 1901-1983. The climatology of daily rainfall was filtered using a 25-day Hanning window, which has a frequency response similar to a 18-day running mean. The filtered, or smoothed, frequency was used as a basis of comparison when plotting the cumulative rainfall for individual growing seasons in 1980-83, an example of which is shown in Figure B-7.

Four years is not a long enough sample for making a reliable climatology. Six years is the minimum acceptable sample size for climatological purposes. The six years 1978-1983 have reasonably similar levels of agricultural technology. Where climatological values or anomalies are required for statistical purposes, the 6-year, 1978-1983, sample was used.

For comparison with the 1978-1983 crop data, a 6-year climatology of daily precipitation was made for 33 stations with complete records or records with fewer than 5 observations missing in the 6 year period. Anomaly time-series for each station were made using its 6-year climatology. These anomaly time-series were used to make the composites for comparing crop years.

Temperature data for the six stations discussed above were used to calculate cumulative heat units, and an example is shown in Figure B-8. A heat unit is defined here as a standard growing degree unit base 50°F, except that the upper limit is removed. A standard growing degree unit (GDU) is GDU = T_{MAX}-T_{MIN}/2 - 50°F, TMAX $\leq$ 86°F. A heat unit is defined as HU = T_{MAX}-T_{MIN}/2 - 50°F. This definition allowed indexing of high temperatures.

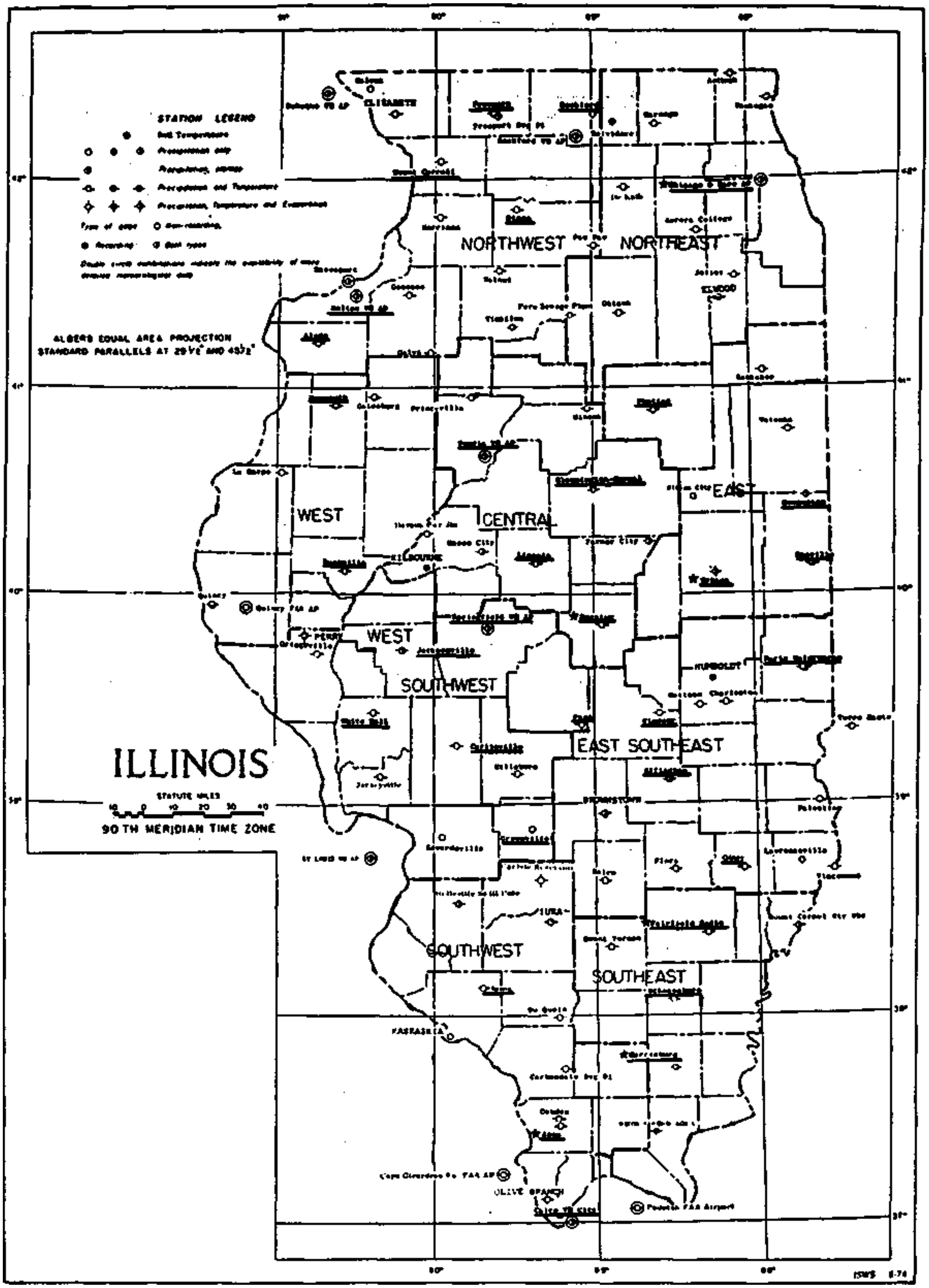


Figure B-6. Location of rainfall stations archived at the State Water Survey. Underlined station names indicate that the station was used in the present study. ★ indicates stations with a complete 83-year record for precipitation and temperature.

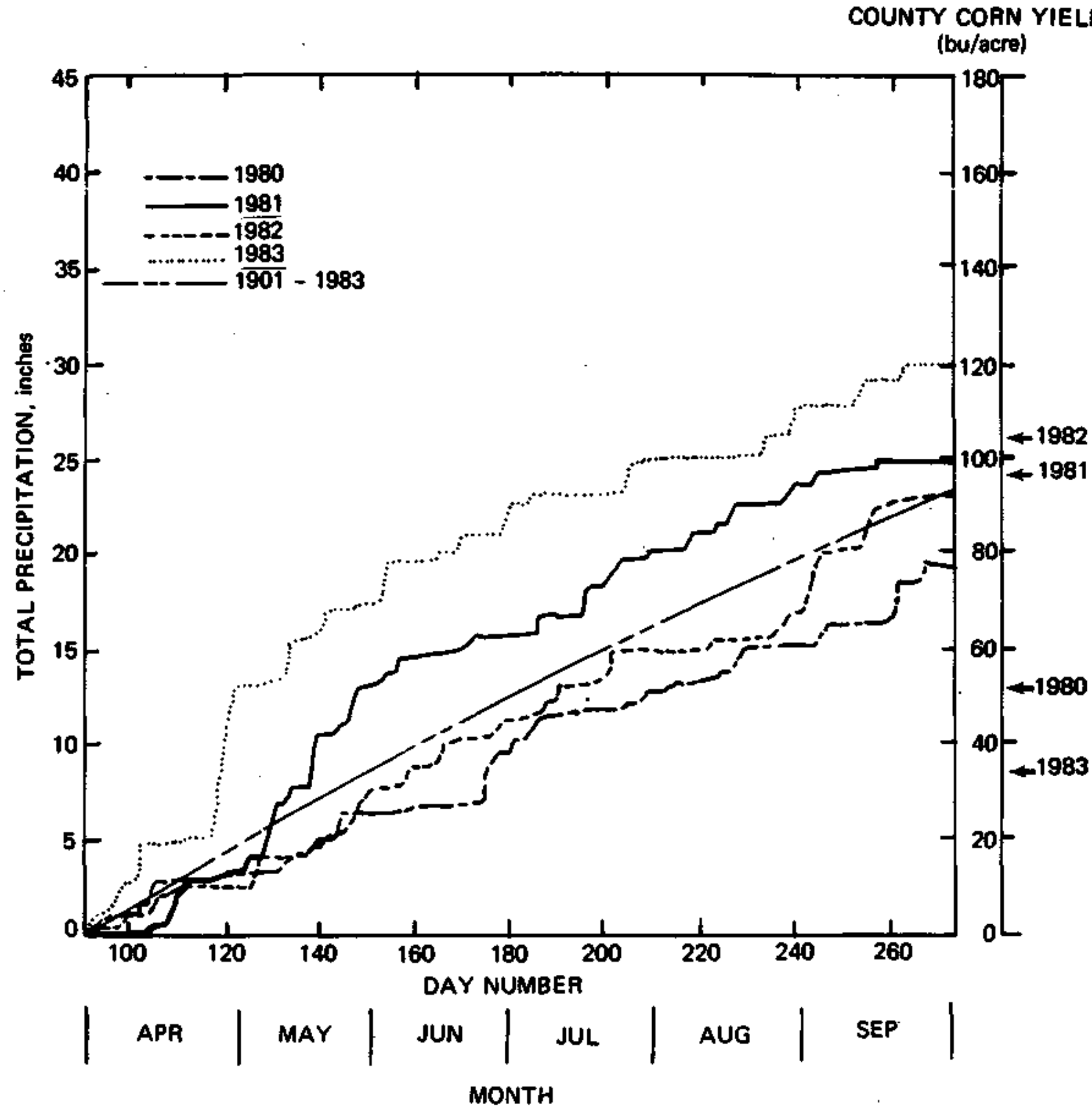


Figure B-7. Cumulative rainfall for growing season, April through September, 1980-83, at Fairfield, in southeastern Illinois. Units are inches of rain.

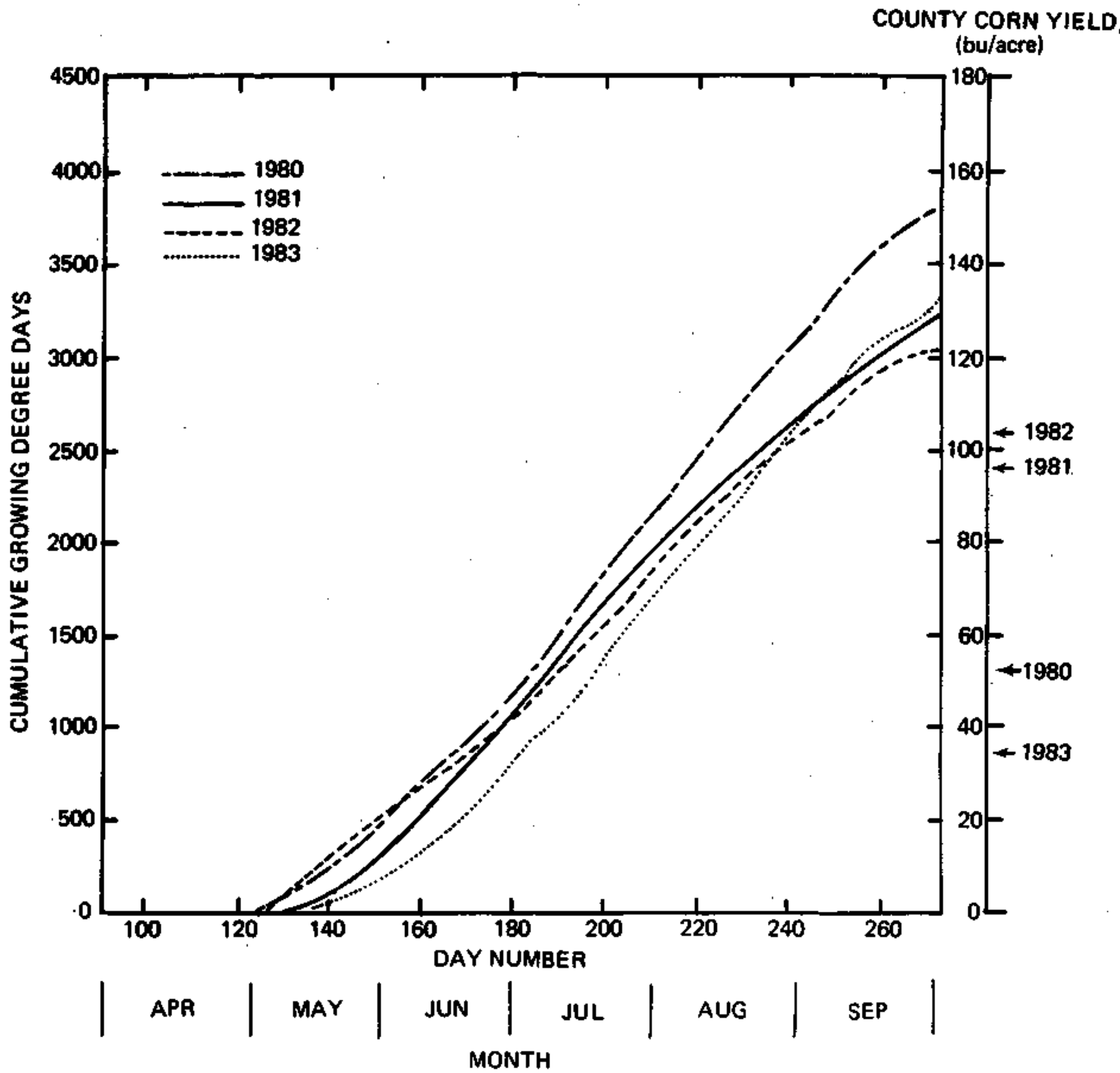


Figure B-8. Cumulative heat units for growing season, planting through September, 1980-83, at Fairfield, in south-eastern Illinois. Units are degrees Fahrenheit.

Analysis of crop data for 1978-1983 was performed on annual yields for corn. For each county, mean corn yields for the 6-year period were calculated and an anomaly series constructed. The anomaly series was normalized by dividing by the mean for that station, so that counties with widely differing 6-year means could be compared. For each station, the normalized yield anomalies were ranked. Years in which the crop yield anomaly was at least one standard deviation (SD) above the mean were ranked as "good." Station-years in which the corn anomaly was between one SD above and one SD below the mean were ranked as "normal" years. Station-years in which the corn yield anomaly was more than one SD below the mean were ranked as "bad" years. The resulting rankings are shown in Table B-16.

Composite cumulative rainfall anomaly series were constructed using the rainfall anomaly series of station-years ranked in the "good", "normal", and "bad" categories.

Ranking and compositing of station-years for each phenological stage was carried out in a similar fashion. For phenological stages the date representative of plant development in the crop reporting district is taken to be the date that 50% of the acreage is estimated to have attained that stage. The 50% date was linearly interpolated for 1978-1983 for each stage and crop reporting district from weekly estimates provided by the Crop Reporting Service, and the Julian day of the interpolated date was used to compute anomalies from the 6-year means. Station-years were ranked into "early", "normal", and "late" for each phenological stage using the regime described above for ranking normalized crop yield anomalies. Composite cumulative rainfall anomaly series were constructed using the rainfall anomaly studies of station-years falling into the three categories.

Description of Growing Season and Weather

The years 1978 to 1983 consist of two cold-dry years (1978 and 1980), two cool-wet years (1979 and 1982), and two years with near normal average annual temperatures and above normal annual rainfall (1981 and 1983). However, 1981 had consistent seasonal deviations from normal, and 1983 had highly variable and extreme month-to-month deviations from normal.

The corn yield of the cool-dry years was normal (near 6-year average) for 1978 and normal to bad for 1980. The cool-wet years, 1979 and 1982, had corn yields in the normal and good categories. The year with normal temperatures and above average precipitation, 1981, had most counties with good corn yields and some with normal yields. The year with highly variable and extreme weather conditions, 1983, had many bad corn yields, as shown in Table B-17. Cumulative rainfall anomaly plots for the composite of the 33 rainfall stations are shown in Figure B-9.

The discussion of individual years' weather and crop development patterns for 1978-1983 is summarized in Table B-18.

Table B-16. Weather station list and rank of corn yield[1].

Standard deviation is: 0.2298239

	County	1978	1979	1980	1981	1982	1983
Aledo	Mercer	0	0	0	0	0	0
Dixon	Lee	0	0	0	0	0	0
Freeport	Stephenson	0	0	0	0	0	-1
Moline	Rock Island	0	0	0	0	0	-1
Mt. Carroll	Carroll	0	0	0	0	0	0
Rockford	Winnebago	0	0	0	0	0	-1
Chicago	Cook	0	0	0	0	0	0
Monmouth	Warren	0	0	0	0	0	-1
Rushville	Schuyler	0	0	0	1	1	-1
Bloomington	McLean	0	0	-1	0	0	-1
Decatur	Macon	0	0	-1	0	0	-1
Lincoln	Logan	0	0	-1	0	0	0
Peoria	Peoria	0	0	0	0	1	-1
Danville	Vermilion	0	0	-1	0	0	0
Hoopeston	Vermilion	0	0	-1	0	0	0
Pontiac	Livingston	0	0	-1	0	1	-1
Urbana	Champaign	0	0	-1	0	0	-1
Carlinville	Macoupin	0	1	0	0		-1
Greenville	Bond	0	0	-1	1	0	-1
Jacksonville	Morgan	0	0	0	0	1	-1
Pana	Christian	0	0	0	0	0	-1
Springfield	Sangamon	0	0	0	0	0	-1
White Hall	Greene	0	1	-1	0	0	-1
						0	
Effingham	Effingham	0	1	0	0	0	-1
Olney	Richland	0	1	-1	0	1	-1
Paris	Edgar	0	0	-1	0	0	-1
Windsor	Shelby	0	0	0	0	0	0
Anna	Union	0	1	-1	1		-1
Cairo	Alexander	0	1	-1	0		-1
Sparta	Randolph	0	0	-1	0		-1
Fairfield	Wayne	0	1	-1	0		-1
Harrisburg	Saline	-1	1	-1	0		0
McLeansboro	Hamilton	0	1	0	1		-1

[1]Key of yields: -1 Bad corn yield
0 Normal corn yield
1 Good corn yield

Table B-17. Ranking of corn yield; 1978-1983.

Year	Category of Station Years: Bad	Normal	Good	Sample Size
1978	1	32	0	33
1979	0	24	9	33
1980	16	17	0	33
1981	0	29	4	33
1982	0	22	11	33
1983	24	9	0	33
Total for 6 Years	41	133	24	198

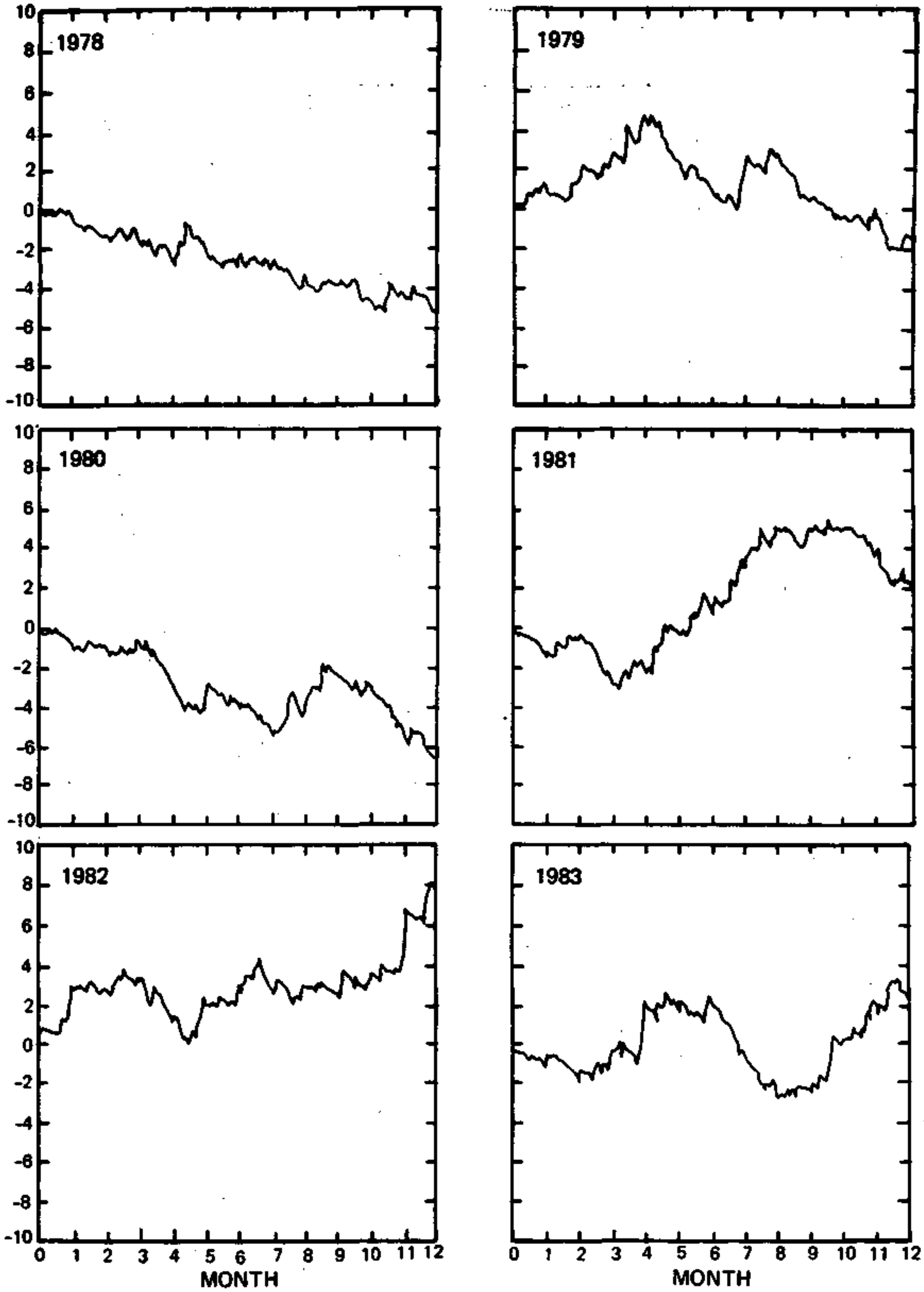


Figure B-9. Composite cumulative rainfall anomaly for individual years 1978-83 for 33 Illinois stations. Deviation is from 6-year mean. Units are inches of rainfall.

Table B-18. Summary of weather and corn development 1978-83.

	1978		1979		1980	
General Weather	Cool, dry		Cool, wet		Cool, dry	
Growing Season Weather	Cool, dry		Cool, wet		Warm, dry	
Corn Yield Rank	Normal		Normal to Good		Normal to Bad	
Weather	Temp.	Precip.	Temp.	Precip.	Temp.	Precip.
Jan	-	-	C	+	N	D
Feb	Cold	-	C	Normal	C	D
Mar	-	-	+	+	C	N
Apr	-	-	-	+	-	-
May	-	+	-	-	N	-
Jun	-	Dry	+	-	-	N
Jul	-	+	+	Wet	Hot	N
Aug	-	-	-	W	H	-
Sep	+	-	N	D	+	W
Oct	-	-	-	-	-	N
Nov	+	+	N	+	N	-
Dec	-	+	+	+	N	N
Winter J-F-M	Record March Snowfall		Record January Snowfall Heavy February Snow			
Spring A-M-J	Planting: b. late April complete mid-June		Rain slows field work Planting: b. late complete early, mid-May		Planting b: raid-April complete end of May	
Summer J-A-S	Development: Slow due to cool temperatures		Very little moisture stress Maturation: slow due to cool temperatures		S & Central: heat causes development & pollina-ation problems North: cool & wet	
Fall O-N-D	Harvest: Ahead of schedule Complete: mid-November		Harvest: Excellent conditions warm dry weather		Harvest: Excellent conditions Yield poor due to heat in July-August	
Sample Mean Yield	106 bu/acre		125 bu/acre		87 bu/acre	
Standard Deviation	SD = 1 3		SD =15		SD = 22	

Table B-18, cont'd. Summary of weather and corn development 1978-83.

	1981		1982		1983	
General Weather	Normal T, wet		Slightly cool, wet		Highly variable	
Growing Season Weather	Cool, wet		Cool, wet		Early A-M-J cool, wet Late J-A-S warm, dry	
Corn Yield Rank	Good to Normal		Normal to Good		Bad	
Weather	Temp.	Precip.	Temp.	Precip.	Temp.	Precip.
Jan	N	D	C	W	+	D
Feb	N	N	C	+	H	D
Mar	N	D	N	+	+	D
Apr	+	+	C	N	-	W
May	-	W	H	N	-	W
Jun	N	W	C	N	N	W
Jul	-	W	N	W	H	D
Aug	-	W	C	N	H	D
Sep	-	W	C	N	N	W
Oct	-	N	N	N	N	W
Nov	+	N	+	W	+	W
Dec	-	N	H	W	C	W
Winter J-F-M	Drought: Southern half of State		Record # of severe winter storms in Jan. Record snow depth for Feb.			
Spring A-M-J	Plant: b. late April delayed by May T-storms Complete: mid-June		Planting: b. late April complete early: late May		Planting: delayed by cool T, heavy April-May precip. Complete: mid-June	
Summer J-A-S	Development: excellent wx. Maturation: late due to cool T		Development: Ahead of normal		Development: Parched by high T, low precip. Damages corn Muturation: Accelerated due to hot August Very bad for crop	
Fall O-N-D	Harvest: late due to late planting, cool growing season Complete: late Nov.		Harvest: Excellent cond. war, dry Complete by mid-November		Harvest: b. on schedule Complete: early Nov.	
Sample Mean Yield	125 bu/acre		129 bu/acre		73 bu/acre	
Standard Deviation	SD = 18		SD = 15		SD = 22	

1978. Statewide average annual rainfall for 1978 was 1.96 inches below normal, and temperatures statewide averaged 2.8°F below normal. Early 1978 had significant snowfall, the runoff from the spring thaw slowed early spring field work. Corn planting began in late April in cool, dry conditions. Scattered heavy rain in May slowed planting, and planting was completed in mid-June, much later than normal. Cool temperatures persisted through August, causing the corn crop to develop at a slower than normal pace. Growing season precipitation was below normal with the exception of the end of July which had timely heavy rains in the north and central regions.

A warming trend developed in September, leveled in October, and returned in November, producing a warm fall. Harvest progressed ahead of normal and was completed by mid-November. Corn yields were generally above expected levels. The quality of the grain was good, with moisture content lower than in immediately previous years. In the context of 1978-1983, 1978 was a year with an average yield. The average corn yield for the state was 111 bushels per acre.

1979. Statewide, annual precipitation was 0.96 inch above normal in 1979, and temperatures averaged 2.6°F below normal. Heavy snowfall in early 1979, coupled with heavy spring rains, caused widespread flooding in March. These wet conditions hindered field work through April and early May. Planting, though it began late, finished ahead of normal due to dry conditions in mid-May. Dry conditions persisted through October, except in the south where heavy rainfall in July and August caused some flooding. The corn did not suffer moisture stress during the summer dry period due to adequate soil moisture from the wet spring, and the lower temperatures than normal, especially in July and August. The cool temperatures caused the corn to mature slower than normal.

Mild dry fall conditions minimized harvest losses and disease problems. The cool-dry summer and excellent harvest conditions combined so that the 1979 corn crop set new records for yield and production. The average corn yield for the state was 128 bushels per acre. The years 1977, 1978, and 1979 had growing season conditions without much stress and were typical of many years in the 1963-1976 period.

1980. Illinois was very dry and somewhat cool in 1980. Temperatures statewide were 0.8°F below normal for the year, and statewide precipitation averaged 5.76 inches below normal.

Conditions were dry and cold in early 1980. March brought normal precipitation amounts to the central part of the state. Planting began in mid-April, at normal dates. Good spring weather allowed planting to be finished in late May, ahead of normal. The northern third of the state had normal summer temperatures and adequate rainfall, making for a good corn crop. However, the southern two-thirds of the state had extremely hot and dry weather during pollination causing problems in corn development. Rainfall in the northern two-thirds of the state was above normal in August and September while the extreme south remained dry. The period October through December was dry, minimizing harvest losses. The good fall weather could not compensate for the crop development problems in the July-August dry period, and the southern 7 crop reporting districts had their poorest yields since 1974. Yields in the northwest, northeast, and west crop districts were generally at the 1978 levels. The average corn yield for the state was 93 bushels per acre.

1981. The weather in 1981 was generally wet with near normal temperatures. Precipitation was 13% (or about 5 inches) above the statewide average. Temperatures averaged a bit above normal in the cool months and a bit below normal in the warm summer months.

Early 1981 was dry and unseasonably warm, allowing spring field work to be completed early, by mid-May. Corn planting began in the last week of April under dry soil conditions. Frequent heavy rains, particularly in the south and central regions in April and May, delayed completion of planting there until mid-June.

The growing season had adequate rainfall and mild temperatures, allowing excellent crop development. Heavy rains caused some flooding in May, August, and September, mostly in the northern two-thirds of the state, causing local reductions in yields. Harvest conditions were optimal. Warm and dry weather aided late maturation and a delayed harvest. Harvest was completed at the end of November.

Corn yields were good to normal in the context of the 1978-1983 period; generally at or slightly below the record 1979 levels. The average corn yield for the state was 129 bushels per acre.

1982. Illinois in 1982 was generally wet with temperatures slightly cooler than normal. Early 1982 had heavy rainfall and snowfalls, setting snow depth records in February and April. However, planting began on schedule, progressed rapidly, and was completed early (in mid-May), due to excellent spring weather.

Growing season weather was good, with normal to cool temperatures and adequate precipitation. Development of the corn crop ran ahead of normal. July had above normal precipitation over the state, and August was also above normal. Precipitation dropped below normal in September and stayed slightly low through November, providing excellent harvest conditions with the harvest completed in mid-November.

The corn crop was normal to excellent over the state, setting new yield records. The average corn yield for the state was 134 bushels per acre.

1983. The weather in 1983 was remarkable for extremes in deviation from normal. Temperatures averaged over the state for the year were near normal, but it was the result of wide deviations cancelling each other. Precipitation was generally greater than normal, but with very dry periods interspersed with extremely wet periods.

Early 1983 was mild with precipitation lower than normal and temperatures running normal to slightly warm. Planting was delayed by heavy precipitation in April and May. Temperatures were cool in the planting season. Corn planting lagged behind the normal pace, beginning in late April and ending in mid-June.

The summer growing season was a reversal of planting season conditions. Temperatures were above normal and precipitation below normal. Emergence was aided by rains very early in the growing season, in June. However, at the critical pollination stage, the weather turned hot and dry. July and August were 3.5°F and 6°F above normal, respectively. The continued hot-dry weather caused widespread crop damage and accelerated corn maturation.

The fall continued warm and dry. Harvest began on schedule in mid-September, progressed rapidly, and finished ahead of normal.

Yields were low everywhere in Illinois with southern counties having lowest yields. Far northern counties fared the best, with even the best yields just below 1978 levels. The average corn yield for the state was 79 bushels per acre.

Results

The evolution of each of the six growing seasons was unique, but important similarities existed in the years of similar crop yield. The composite integrated rainfall anomaly of bad, normal and good corn yield years (based on the 33 stations and the 6 years studied) is shown in Figure B-10. A positive slope to the rainfall curve indicates greater than normal rainfall, negative slope indicates a rainfall deficit, zero slope indicates normal rainfall. Years of bad corn yield from (in 1980 and 1983) had a rainfall deficit in January and February, in late April, and again in July and August. They typically had near-normal rainfall amounts in May and September and from mid-October to mid-November. They also had greater than normal rainfall in mid-March to mid-April, in early May, and again in mid-October.

Years with good crop yields had greater than normal rainfall in February, and from May through July. They had near-normal rainfall in March-April and from mid-July through October, and a rainfall deficit in late April and early October (good for planting and harvesting).

The above description implies that in recent years (with current farm practices) a deficit of precipitation in winter, in late April, and in July and August is bad for corn yields. Also, greater-than-normal rainfall in the spring (planting) and in mid-October, the middle of harvest, are bad for corn yields.

Greater-than-normal rainfall in winter and again from May through July are beneficial to the crop. A deficit of rainfall in late April and early October seem to enhance corn yield.

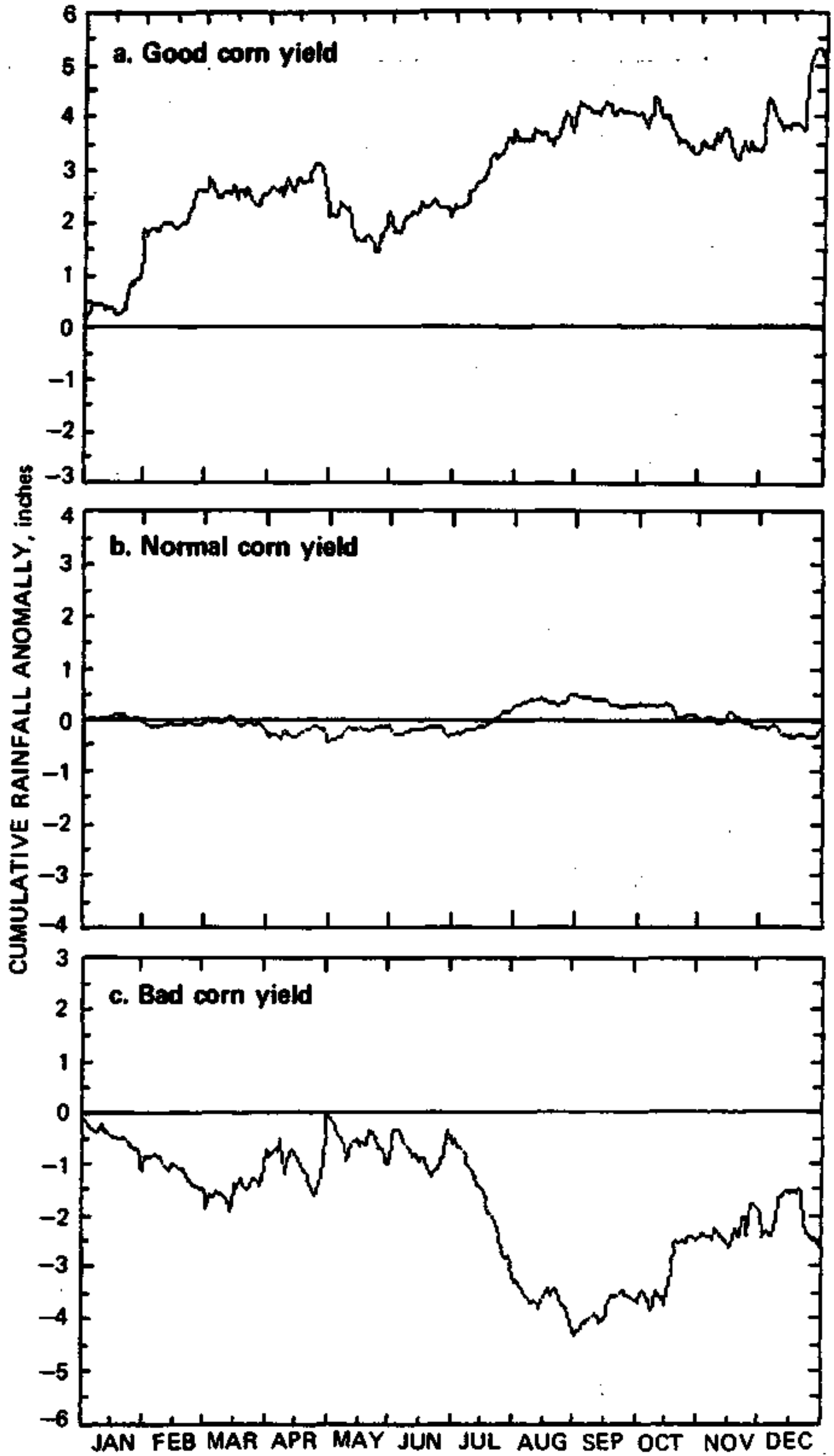


Figure B-10. Composite integrated rainfall anomaly for station-years in good, normal, and bad corn yield categories.

Due to limited sample of years, no definite conclusions about the significance of rainfall in these periods can be made. However, these findings agree well with earlier studies based on weather and crop yields from 1940-70 (Huff and Changnon, 1979).

Composites of integrated rainfall anomaly for early, normal and late planting, Figure B-11, show that excess rain in May delays planting while early planting occurs in years with rainfall deficits in April and the first half of May. The composites of rainfall anomaly for early and late harvest, Figure B-12, indicate that late harvest years had excess rainfall in late June through mid-July and that early harvest years had deficit rainfall in July. The early harvest composite is heavily skewed by 1983 when harvest was early to try to salvage the crop and cut losses.

Conclusions

These preliminary results show that there is a strong dependence of crop development and crop yield on rainfall in narrow (weekly) time periods. The sensitivity of crop yield to winter rainfall is probably due to its effect on soil moisture. Adequate soil moisture promotes emergence and plant development.

The sensitivity of crop yield to July and August rainfall is due to the fact that the corn plants are in a critical pollination and grain development stage at that time, which ideally requires rainfall in small but frequent events.

The sensitivity of crop yield to fall rainfall stems from the need for dry field conditions at harvest-time both get equipment into the fields and to avoid damage and disease problems which come with rainy fall weather.

This study is being extended to include a full-scale study of the sensitivity of crops to growing season temperatures, and development of a heat-and-moisture-stress index.

REFERENCES

Huff, F. A., and S. A. Changnon, 1979: Review of the Societal, Environmental and Legal Aspects of Precipitation Modification In January. PACE Contract Report 203, Illinois State Water Survey, Urbana, 79 pp.

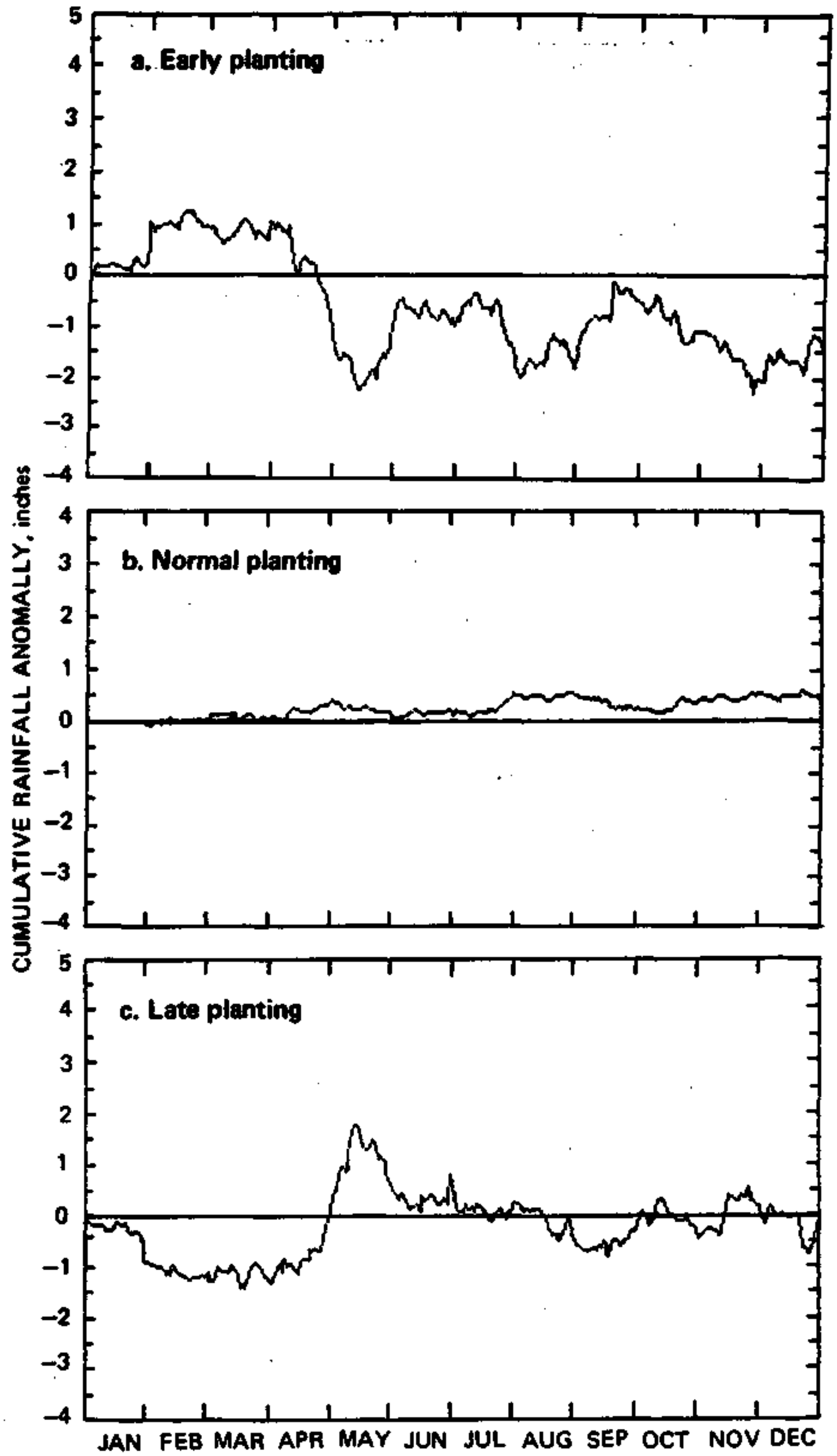


Figure B-11. Composite integrated rainfall anomaly for station-years in early, normal, and late planting categories.

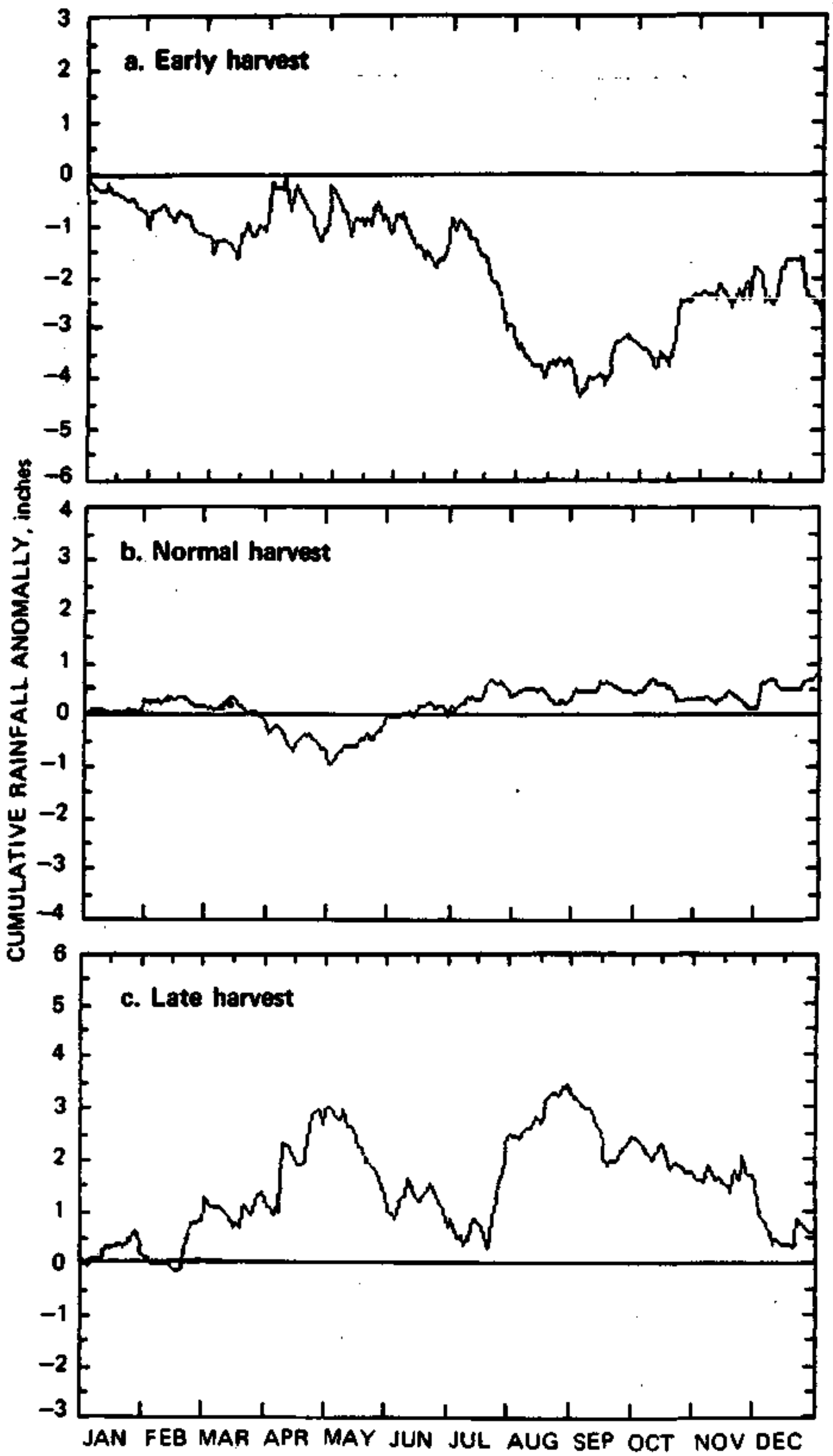


Figure B-12. Composite integrated rainfall anomaly for station-years in early, normal, and late harvest categories.

4. Water Supply Assessments

Stanley A. Changnon, Kris Singh, and Floyd A. Huff

Introduction

Further studies of how altered summer precipitation could affect water supplies involved four activities. Huff (1973) had examined for general possible benefits of added precipitation, in all seasons, to Illinois surface water supplies using rainfall-runoff relationships.

In the past year, we installed soil moisture measurement tubes at 4 sites (in potential field study areas) and we initiated bi-weekly measurements. These data are desired as input in future detailed hydrologic modeling attempting to account for added water.

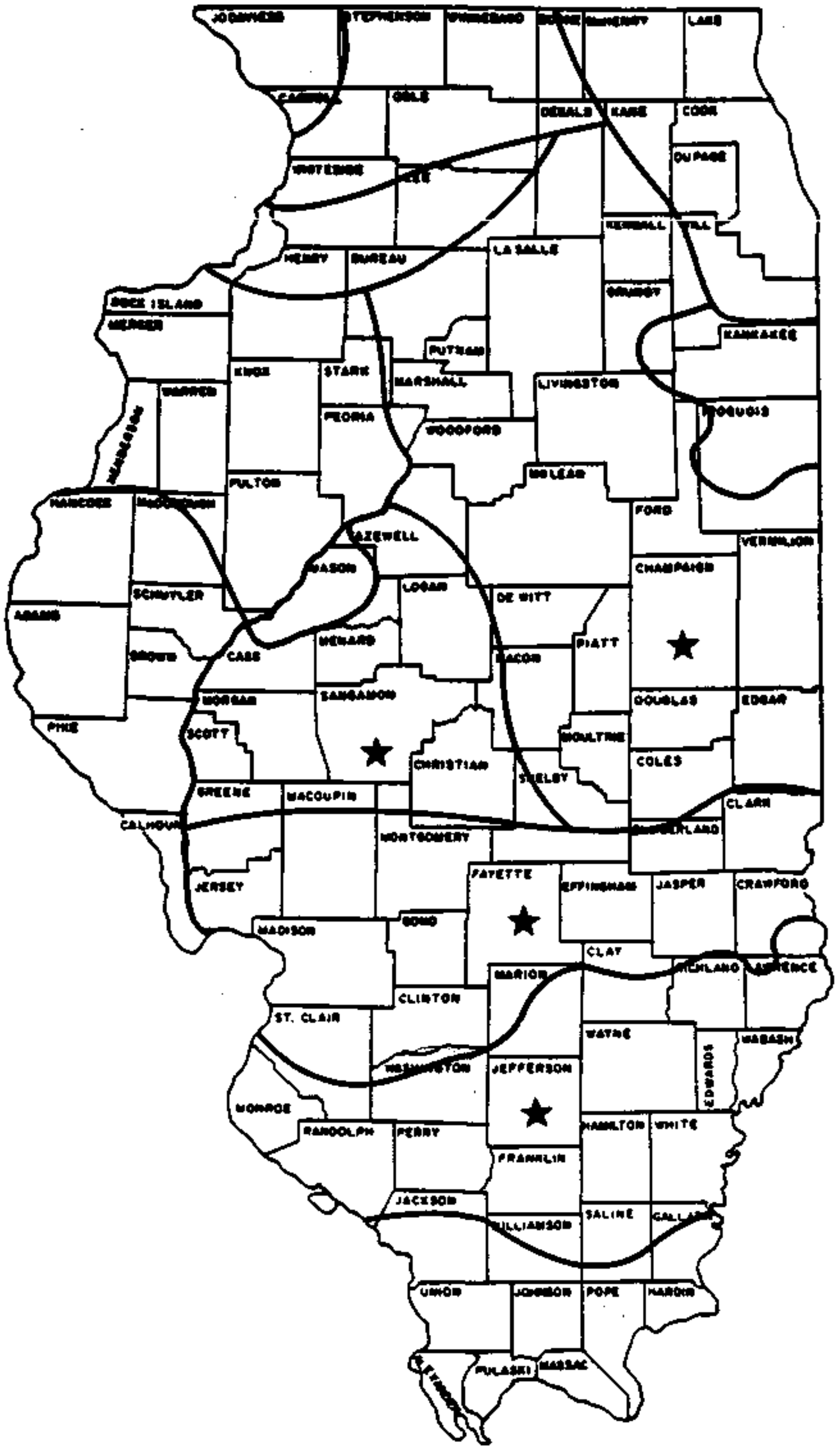
Second was planning for development of a basin model adequate for discerning effects of added summer rainfall.

Third was an assessment of efforts to hydrologically assess the distribution of water from increased rainfall in the Israeli cloud seeding projects. This effort helped plan the modeling effort for PACE. A fourth effort concerned analysis of heavy rainstorms and their possible influence on the outcome of PACE.

Soil Moisture Measurements

When this new period PACE investigations was launched in April 1984, we decided to pursue detailed basin modeling to define how and where added summer rainfall affected the hydrologic cycle. A prime question we could not answer with existing data concerned soil moisture, the immediate receptor, along with runoff, of rainfall. The modeling effort would need soil moisture data as input and to help calibrate it.

Past research had shown that areas in southern and central Illinois were where a PACE field (area) experiment should be conducted, and where added rainfall would be most beneficial for crop production. Hence we chose, with input from soil scientists, four sites in representative soils of the southern and central sections. These sites are shown on Figure B-13 which depicts the major different regions which have distinctive responses to drought due to soil and topographic factors. These stations were established in April 1984 with tubes driven to 80 inch depths and raingages were installed. A neutron probe was purchased, and after calibration, measurements began in April 1983. Table B-19 presents the history of the 1984 measurements at two of the four sites, Springfield and Bluford sites. Data collection will be pursued until the end of PACE to develop the rainfall-soil moisture relationships.



PACE SOIL MOISTURE SITES AND DIFFERENT REGIONS FOR DROUGHT

Figure B-13.

Table B-19. Soil-moisture values for different depths at two of the four sites.

a. Lake and Major Weservoir Summary

b. Peak River Stages, past month

c. Mean River Flows, past month

Soil Moisture for ICM Site at Brownstown (Cisne)

Layer Depth	0-6 in.		0-20 in.		0-40 in.		40-80 in.	
Mn/Dy/Yr	(in)	%PAM	(in)	%PAM	(in)	%PAM	(in)	%PAM
06/27/84	1.74	n/a	6.40	n/a	15.94	n/a	17.87	n/a
07/16/84	999.0	n/a	999.0	n/a	999.0	n/a	999.0	n/a
07/30/84	.47	n/a	2.06	n/a	9.84	n/a	17.56	n/a
08/16/84	.47	n/a	2.06	n/a	9.38	n/a	1.7.41	n/a
08/30/84	999.0	n/a	999.0	n/a	999.0	n/a	999.0	n/a
09/12/84	1.46	n/a	3.54	n/a	10.55	n/a	16.78	n/a
09/26/84	2.18	n/a	7.91	n/a	16.32	n/a	17.13	n/a
01/02/85	999.0	n/a	999.0	n/a	999.0	n/a	999.0	n/a
01/31/85	999.0	n/a	999.0	n/a	999.0	n/a	999.0	n/a
02/27/85	999.0	n/a	999.0	n/a	999.0	n/a	999.0	n/a
03/26/85	2.35	81.8	8.19	87.6	18.03	97.6	17.91	104.2
04/15/85	2.54	94.8	9.46	111.1	19.53	111.4	17.92	104.3
04/30/85	1.83	45.3	6.67	59.6	16.39	82.4	17.76	102.9
05/15/85	2.10	63.9	7.32	71.6	16.97	87.7	17.74	102.7
05/28/85	1.62	30.6	6.10	49.1	15.71	76.2	17.67	102.0
06/12/85	2.14	67.2	7.94	83.1	17.72	94.7	17.79	103.2

Sail Moisture for ICN Site at Salem (Bluford Silt-loam)

Layer Depth	O-6 in.		0-20 in.		0-40 in.		40-80 in.	
Mn/Dy/Yr	(in)	%PAM	(in)	%PAM	(in)	%PAM	(in)	%PAM
04/19/84	2.21	n/a	7.89	n/a	17.24	n/a	17.44	n/a
04/30/84	2.25	n/a	8.07	n/a	17.56	n/a	1.7.73	n/a
05/22/84	2.09	n/a	7.53	n/a	16.50	n/a	17.60	n/a
06/05/84	1.81	n/a	7.01	n/a	15.92	n/a	1.7.41	n/a
06/19/84	1.67	n/a	6.65	n/a	15.30	n/a	17.47	n/a
06/27/84	1.67	n/a	6.65	n/a	15.30	n/a	17.47	n/a
07/17/84	.78	n/a	4.04	n/a	11.97	n/a	16.69	n/a
07/30/84	.53	n/a	3.3.6	n/a	10.45	n/a	1.6.55	n/a
08/14/84	1.27	n/a	5.26	n/a	12.81	n/a	16.77	n/a
08/29/84	.92	n/a	4.30	n/a	11.47	n/a	16.46	n/a
09/13/84	1.77	n/a	6.70	n/a	14.01	n/a	16.52	n/a
09/27/84	2.1.6	n/a	7.83	n/a.	16.83	n/a	1.7.35	n/a
11/28/84	999.0	n/a	999.0	n/a	999.0	n/a	999.0	n/a
01/04/85	2.34	n/a	8.26	n/a	17.80	n/a	1.7.74	n/a
01/28/85	999.0	n/a	999.0	n/a	999.0	n/a	999.0	n/a
02/26/85	999.0	n/a	999.0	n/a	999.0	n/a	999.0	n/a

Basin Modeling

The long-term goal of the Precipitation Augmentation for Crop Experiment (PACE) is to learn whether agriculturally useful increases in summer convective rainfall can be produced in the Midwest. An essential part of this program is to identify and quantify the effects of altered rainfall on agricultural production and water resources. Basin or watershed models are used to predict or forecast watershed response to precipitation. In order to understand the effect of precipitation augmentation on agriculture and fresh-water resources, it is necessary to understand the effect of such a change on infiltration, soil moisture, baseflow, and runoff. The effects of change in agricultural practices (such as row cropping versus contour farming, and ploughing versus no-till) on the various processes and parameters involved need to be analyzed.

After study, we decided that a model appropriate for PACE studies should have the following attributes:

1. A lumped parameter model with the area segmented into small segments or subwatersheds, each segment with relatively similar physical characteristics, to approach the concept of a distributed model.

2. Continuous operation (instead of discrete operation as for flood models).

3. Capability to use small time intervals (say, hourly) during storm events and long intervals (say, daily) after such an event. This will achieve better infiltration and soil moisture accounting and take less computer time.

4. Rainfall hydrology will be modeled, however, snowmelt hydrology may be included to make the model versatile and to extend its use for precipitation augmentation for other purposes such as water supply as well as to provide increased precipitation during April and May if the soil moisture deficits are excessive.

5. Other climatic parameters including temperature and potential evaporation.

6. Physical data needed will include soil and infiltration characteristics, layered-soil profile for soil moisture accounting, land use, soil cover, and appropriate USLE parameters.

7. Soil moisture accounting — include data and relations developed from 4 stations.

8. Submodels to consider interception, infiltration, evapotranspiration, soil moisture, subsurface flow, snow accumulation and snowmelt, overland flow, channel routing, etc.

9. Modeling capability to extend to 100-1000 sq mi area.

10. Tradeoffs between model complexity, calibration, and data requirements and not adequate representation of watershed will govern the structure of the model.

11. Model should be able to provide information for analyzing the effects of precipitation augmentation on the following:

    a. Agriculture

    b. Soil moisture

    c. Drought and low flows

    d. Protected and instream flows

    e. Increased flooding, if any

    f. Water withdrawals from streams

    g. Recreation—streams and reservoirs

12. The model should have self-optimizing capability for parameters to avoid numerous trial-and-error solutions.

The developed model will undergo extensive testing and calibration to that it can adequately represent the changes in soil moisture and streamflow for different precipitation and temperature conditions over a number of years. Its use in the PACE project will also help in answering some of the following questions.

1. How much increase in runoff and soil moisture occurs from different levels of precipitation augmentation for different rain periods, using stochastic as well as deterministic mode?

2. Can an operational procedure be developed for decision making as to whether advance on the basis of soil moisture and predicted effect of increased precipitation on soil moisture and runoff? The intent is to maximize benefits and minimize damages.

3. What level of storm precipitation can be ignored as far as precipitation augmentation is concerned? Economic analyses will be helpful.

4. What kinds of field measurements are needed to verify predicted effects of precipitation augmentation? These will also serve a useful purpose in decision making regarding precipitation augmentation for the next storm. This will lead to a satisfactory monitoring network design.

The kinds of models under consideration are listed below.

1. ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation): distributed type, discrete operation, models rainfall hydrology, less than 40 sq mi area, baseflow and soil moisture simulated crudely, event model, Purdue University.

2. BSAM (Basin Simulation Assessment Model): lumped type, continuous operation, models rainfall and snowmelt hydrology, medium to large basins, monthly time increments, no channel routing, statistical description of rainfall-runoff, Utah State University.

3. BURP2 (hydrologic impact of cutting in forested areas on annual or seasonal basis): distributed type, continuous operation, infiltration ignored, no routing of rainfall excess, U.S. Forest Service.

4. CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems): lumped typed, continuous operation, daily data, models both rainfall and snowmelt hydrology, limited to small agricultural watersheds 1-40 acres, U.S. Department of Agriculture.

5. HEC1 (HEC1-Flood hydrograph package): lumped type, discrete operation, models both rainfall and snowmelt hydrology, evaporation-infiltration not modeled, needs extensive calibration, uses unit hydrograph for generating runoff, U.S. Army Corps of Engineers.

6. HSPF (Hydrologic Simulation Program FORTRAN): lumped type, continuous operation, variable time steps, models soil moisture and evapotranspiration, channel routing, area may be variable size, empirical relationships require calibration, Hydrocomp Inc.

7. PSRM (Penn State Urban Runoff Model): distributed type, discrete operation, models rainfall hydrology, many elements not modeled, high runoff events, Pennsylvania State University.

8. PSU-IV (Penn State University): transfer function type, discrete operation, statistical flood peak relations, regionalized to Pennsylvania watersheds, Pennsylvania State University.

9. SSMAM (Sacramento Soil Moisture Accounting Model): lumped type, continuous operation, daily data, models rainfall hydrology, California-Nevada River Forecast Center, 60-1200 sq mi, does not route streamflow, runoff distributed according to unit hydrograph.

10. SCS TR-20, specifically related to flood hydrographs: hourly data, lumped type, discrete operation, considers infiltration through curve numbers, no temperature and evapotranspiration data considered, Soil Conservation Service.

11. SSARR (Streamflow Synthesis and Reservoir Regulation): lumped type, continuous operation, daily data, uses soil moisture index calibration of fitted parameters, no self-optimizing capability, U.S. Army Corps of Engineers.

12. STORM, for storm and combined sewer management: lumped type, continuous operation, hourly data, models both rainfall and snowmelt hydrology, catchment storage accounting, single urban catchment, no routing of flows, Hydrologic Engineering Center.

13. SWMM (Storm Water Management Model): distributed type, discrete operation, subhourly data, no snowmelt considered, does not directly include evapotranspiration and soil moisture accounting, event model, U.S. Environmental Protection Agency.

14. TVA Daily Streamflow Simulation Model: lumped type, continuous operation, rainfall hydrology, evapotranspiration not modeled, interflow and infiltration not determined directly, Tennessee Valley Authority.

15. USDA Hydrograph Laboratory Watershed Model: lumped type, continuous operation, variable time steps, models both rainfall and snowmelt hydrology, intended for small agriculture watersheds, USDA Hydrograph Laboratory.

16. NWSRFS (National Weather Service River Forecast System model): modular design, data (hourly precipitation, daily climatologic data, snow, etc.), models and techniques used (areal distribution of precipitation, mean areal temperature, potential evaporation, snow accumulation and ablation, soil moisture accounting, channel routing).

Useful information, algorithms, techniques can be obtained from numbers 6, 9, 11, 15, and 16; these can be modified, improved, and augmented to develop a suitable model for PACE and other purposes.

Assessment of Hydrological Studies of Summer Rainfall Modification: Israel

Introduction. Efforts to detect and define the change in the water resources related to a rain enhancement program are essential. All reasonable ways to measure the added water must be considered, including indications in the most affected portions of the hydrologic cycle and shifts in crop yields. Expected summer rain increases of 10 to 20% in Illinois will be realized largely in evaporation, transpiration, soil moisture, and shallow groundwater.

An assessment of the hydrologic studies of rain increases in Israel was accomplished to aid in the design and pursuance of similar studies in Illinois. This assessment included study of the methodology and techniques used for determining the effects of rain enhancement on some of the local hydrological components; and preparation of recommendations of any changes or new activities which should be undertaken by the rain enhancement or hydrological evaluation projects. Two documents ("Effects of Cloud Seeding on Water Resources, Second Interim Report", and "Changes in Springflow Following Rainfall Enhancement") were reviewed; and conferences were held with the authors of these documents.

Review of the two hydrologic studies and discussions with the authors did not provide compelling evidence of an increase, no change, or a decrease in water in selected springflows or streamflow sites. In essence, the results of the Israeli studies collectively reveal how highly complex the hydrologic cycle is in Israel, and that major unknowns, and hence problems, exist in detecting the added water from rain enhancement. The use of historical (premodification) relationships in a hydrologic evaluation appears questionable, as will be explained. The uncertainties cast great doubts about the results of these two studies, as well as the value of further pursuit of research based on a historical period relationships.

Results. The study of Harpaz and associates (Harpaz and Keller, 1984) did not provide convincing evidence that several key issues have been addressed adequately. The document presented was incomplete, confusing in several respects, lacking in key data (i.e., the basins selected for analysis are not shown on maps), and referred to supportive findings from other studies that were not referenced.

The discussions left concern over whether the selected and then adjusted data sets chosen for analysis have instrument/measurement problems of a magnitude likely to mask increases in water due to a 15% rain increase. The locales of the 21 springs and 4 streamgages chosen for this study reveal considerable potential for hydraulic interaction. They cannot be considered independent data sets with 17 of the 23 springs being closely adjacent to one another, and in most cases two or more are in the same "basin."

The approach involved by Harpaz does not provide for assessing added water flows in either wet or day periods. Since these are issues of great important in water resources, this omission appears serious. The search for a presumed relatively large percentage change in flow (spring or stream) hypothesized in Harpaz study does not consider conceptually the problem of detecting a relatively small actual increase in water in a very large number, the total flow. An illustration of this point is presented below.

Detecting Rain Increases. This is a scenario we developed involving a conceptual analysis of the seasonal distribution of water amounts in a spring near Lake Kinneret (Galilee). It is based on one of the three springs chosen by Harpaz in his analysis. The average seasonal conditions are as follows:

1. Average rainfall = 400 mm (1951-1980 mean at the site of the springs).

2. Average evapotranspiration = 75% of the average seasonal rainfall (derived from local experts).

3. Springflow from an aquifer area = 30 km^2 (from Harpaz).

4. Average seasonal flow = 1 million m^3 (average of the three springs in areas N_4 from Harpaz report).

The average rainfall is increased 10% by cloud seeding in area N_4, according to Israeli II Experiment findings. Hence, the accounting of the water from the rain increase is as follows:

1; 10% of the total 100 mm = 40 mm

2. Amount lost to ET = 30 mm

3. Amount in the soil and groundwater reservoirs[1] = 10 mm

4. Amount remaining, translated to springflow[1] = 30,000 m^3

First note that the rain increase in water available to underground storage and/or surface flow is an increase of 2.5%, not the 10% total rain increase. The added flow due to the rain increase (30,000 m3), when divided by the total springflow (1 million m3) is 3%.

This is a very small number. What is most critical is the appreciation, assuming the above values are reasonable, of the relatively small part of the total springflow that the rain change has caused. This reflects on the difficulty of using statistical techniques to locate changes of this magnitude, a value which is well within the measurement and instrument errors often typical in the measurement of flows.

The study of Ben-Zvi and associate (Ben-Zvi *et al*., 1984) appeared to be a more realistic approach to the problem, considering the many data uncertainties. These issues are definitively described in the paper. However, the approach also depends on the historical relationships (pre 1960) to determine the water yield in the modified period. After an extensive effort to carefully select springs for analysis, the key findings are the mixed results, plus and minus flow changes, found in the five closely adjacent springs. This alone, in an area of obviously uniform precipitation changes, is strongly indicative of the fallacy of using springflow data to verify subtle changes in waterflow. There must be leakages to unknown aquifers, flow measurement problems, and/or unknown man-made diversions such as pumpage that cannot be accounted for.

The statistical approach used was reasonable. Importantly, in analyzing some of the same springs that Harpaz studied, Ben-Zvi obtained indications of flow changes that differed, both in sign and magnitude,

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[1]This assumes no leakage to other aquifers and complete annual depletion of the spring.

from Harpaz results; a condition further revealing the sensitivity of the outcome to the analytical approach used. Importantly., the Ben-Zvi approach did allow some estimation of the magnitude of the effect of added water in wet and dry years, a highly desirable feature not apparent in the Harpaz study.

Ben-Zvi and his co-authors lean to a final assessment that suggested a rain increase was realized in the springflows. However, the mixed outcomes in closely adjacent basins, plus the problem of year-to-year carryover in groundwater flow, reveal the complexities in use of the springflow data in the target area to assess added water from rain increase.

Summary. The rainfall experimental results in Israel are considered correct and added water from the rain increases exists somewhere in the hydrologic cycle. Significant amounts of the added water are likely lost to evapotranspiration with the amount on any day, week, or longer period highly dependent on a variety of surface and climatic conditions including winds and temperature. It is important to realize that the evapotranspirative processes, or demand of nature, will be served first after rain reaches the ground. The best seasonal estimates obtained for the target area catchment, based on discussions in Israel, is that 70 to 80% of all rainfall (including the added rain), on the average, is lost through evapotranspiration. The figure seems reasonable. If it is correct, this means that roughly 25% to 30% of the added rain remains in the catchment, likely mostly in the form of shallow and/or deep groundwater, depending on the local hydrogeologic conditions.

Since the catchment area streamflow is typically only 1 to 5% of the total rainfall and largely the result of a few heavy rain days, and since the Israeli weather modification effect is minimal on heavy rain days (those greater than 20 mm), it appears unlikely that much of the streamflow from basins in the lake catchment is due to the increased rainfall. In general, it would appear that somewhere between 20% and 40% of the increased rain in the catchment areas is reaching Lake Kinneret with the best estimate of 30%.

The inability of the current hydrologic investigations to identify the added water can be explained in a number of ways. These are relevant to future activities in Illinois to identify exactly where the added water from increased rainfall is in the system. The current Israeli studies have utilized an assumption that the hydrologic (rain-runoff) relationships in the premodification period (pre 1960) are representative of those in the seeded 1960's, 1970's, and 1980's. This appears to be a highly unlikely assumption for several reasons.

- First, research with historical Israeli rainfall data has shown that in the target area, there was a poor relationship of rainfall from the decades of the 30's, 40's, and 50's with that in the various enhancement periods.

- The historical assessment approach makes it difficult to estimate (or to detect in the flow records) the effects of land use changes which have been subtle and likely continuous since about 1960 and quite possibly significant influences on the hydrologic cycle.

- Climatic changes in the rainfall and/or in the temperature and windflow (which greatly affect ET) have to be considered as confounding factors.

- The rainfall modification has been shown to alter the distribution of daily rainfall values and to make rains on days of light to moderate rainfall more spatially uniform and regionally widespread and these alter the earlier relationships.

- In the use of standard flow records (stream or springflow gages) one is searching for,a relatively low number, 30% of a 15% rain increase or 4.5%; and it seems unlikely that the man man-made diversions in the surface and groundwater systems since 1950, plus the inherent errors in flow measurements, allow one to detect realistically such changes.

Thus, it is difficult to believe that the rainfall-runoff regressions, no matter how defined (target-to-target, or control-to-target), and resting on the historical premodification data can be used to detect and/or measure the added water in the Israeli catchments. Data on the key variables of the water balance such as daily evapotranspiration and soil moisture, must be collected. Such basins representative of different basic physiographic and geologic conditions in the target area should be instrumented with devices to gather needed data over a period of years. These eventually will provide the data for ascertaining the water balance and will be useful as ground truth in sophisticated watershed models.

Exploratory testing by use of daily watershed models with simulations using daily rainfall data, altered to fit expected outcomes should be pursued. These could include the the randomized changes in rainfall, and then be compared with the non-rain change estimates in the model. Although these would not be definitive, they would be helpful in demonstrating the distribution of the water.

In summary, the study of past periods to estimate current changes in runoff involves a variety of assumptions and problems that may frustrate any attempt to quantify the rain change elsewhere in the hydrologic cycle. These reasons include 1) the lack of key data on soil moisture and evapotranspiration, 2) the possibility of systematic temporal and spatial changes in climate, 3) known changes in the rain distribution and quantity due to the modification experiment, 4) unmeasured or poorly described man-made changes in surface diversions and use, 5) instruments errors, 6) inherent instrument measurement difficulties, 7) unknown alterations in groundwater pumpage and recharge, and 8) subtle but major land use changes. Each of these are so complex it is generally very hard to quantify their effects by regression analyses. Coupled with these complexities is the fact that in Israel the rain changes in the two rain experimental periods are approximately half the total change of the operational period. Detecting such small changes in Israel where water is heavily managed appears to be an impossible task, but it may be more feasible in Illinois which has a humid climate and less water management.

Recommendations

1. The search for indications of where the additional water from

   great importance. The general recommended approach is to collect and analyze relevant data and also to search for other data sources that may be useful.

2. The historical relationships (pre seeded period) between rainfall and flow (spring and stream) need to be carefully studied to assess both temporal and spatial relationships in order to understand whether historical relationships are applicable to those during the seeded period.

3. Sophisticated daily watershed modeling involving historical data may prove useful in light of better discerning where the relatively small amounts of water from the rain increase exists and how the many intervening management factors affect these. Various simulated daily rainfall changes should be used. Conceptual modeling would also be relevant to this activity.

4. Since the rain changes of 10 to 20% are most apt to be realized in the evapotranspiration processes and soil moisture, instrumentation of several representative small basins in the target and control areas are needed, as in Illinois. These instrumented basins should typify the major physiographic units, and should be instrumented with recorders for monitoring ground water levels, anemometers, and other devices collectively able to carefully quantify the water balance. These data collection efforts should be continued for several years to obtain a sample representative of the climate, including extremely wet and dry years, heavy rains, etc. These will be eventually allow a description of the incremental effects of the added rainfall within the hydrological cycle.

Heavy Rainstorm Problems

An initial scoping analysis concerning the problem of dealing with the severe rainstorms in the PACE project was conducted. The forecasting of the occurrence of short-duration, 3~ to 6-inch rainstorm is very difficult, and impossible to achieve consistently. Using the synoptic climatology indicators, we have developed in conjunction with the "block-busters" rainstorms (6- to 15-inches in 24 hours), we can probably achieve a higher forecasting accuracy than possible with the small-area storms that can occur within a relatively wide range of convective conditions.

However, past studies reveal there will be an appreciable percentage of misses with the blockbusters types also. If these rainstorms included in the statistical evaluation of PACE, one would really overwhelm the effects of the more common storm types in the storm sample.

There are two potential problems to be addressed with respect to the extreme rain events. The first and most pressing problem at this time is how to handle these storms in the exploratory and confirmatory experiments. The second problem must be faced later when routine seeding operations are initiated in Illinois and elsewhere, assuming the PACE experiments show that seeding will produce useful rain augmentation if performed on all except the very light storms and the extremely heavy storm events (the present belief). This would involve seeding 60-70% of the Illinois storm events in July-August.

The Exploratory-Confirmatory Problem. The SWS belief is that seeding will not be significantly productive to crops if applied to very light summer rainstorms, and likely harmful if applied to heavy storms such as those producing over 1 inch (25 mm) of rain in a few hours. Our on-going agricultural and basin modeling efforts are attempting to further quantify these values.

If this is confirmed from the pre-experimental studies, it should form the basis for testing in the exploratory phase of the project. We see no justification for criticism by the statistical community for testing a hypothesis that has a lower threshold (ignore very light rains) and an upper limit (don't attempt to seed storms producing natural amounts exceeding x mm). The next question is how to handle storms outside of the lower threshold and upper limit, especially the upper limit.

If forecasting was perfect, we would just eliminate these storms by not seeding them. This can not be done, of course; this sort of thing can only be done normally in laboratory testing of hypotheses.

Some statisticians and/or certain atmospheric scientists may argue that "the exploratory-confirmatory phase should include seeding of all storms, because that is what will generally happen in practice, and, anyway we can't forecast heavy events with any real accuracy." Even if this is true, we should not include them. First, they do not help the rain augmentation in a useful manner. But most important, the very skewed distribution of these storms could easily lead to fallacious conclusions in a relatively short experimental period, such as 2-3 years. The true long-term average augmentation could be affected either way, depending upon the number occurring in the experimental period. This problem is best handled under any circumstances by adding or subtracting the effect, depending upon the long-term distribution of these events.

This leads to the question of whether we can eliminate the heavy rainstorms from our sample "after the fact" — that is, remove them from the evaluation process. As long as we state in our hypothesis prior to the start of the exploratory experiment that we are going to eliminate the very light and very heavy storms, and specifically state what the lower threshold and upper limit are to be, there is no reason why "throwing these out of the sample" would not be statistically. Legitimate — statistical aside, it is logical and reasonable to do. In fact, if stated in the hypothesis that these storms are not being considered for future seeding for the purpose of rain augmentation, then from the standpoint of statistical testing of ones hypothesis, they would have to be eliminated. Statistically (theoretically, of course) one is supposed to define what one is going to do before the experiment, and then test what one said one was going to test (and only this) in your experiment. We conclude the following:

a. severe rainstorms are not considered beneficial to modify; in fact, they are likely to be harmful.

b. we cannot consistently forecast their occurrence, so as to always avoid seeding when they happen.

c. they should not be part of our evaluation sample in the exploratory and confirmatory experiments.

d. it is logical and reasonable to eliminate them from the sample as long as we so state in our hypothesis.

e. doing the above should not introduce bias in our results, in fact, not doing it would bias our hypothesis.

The Severe Rainstorm Problem in Routine Seeding Operations. If the exploratory and confirmatory experiments of PACE should show that the original SWS hypothesis is correct — that is; useful rain augmentation can be achieved by seeding storms within a certain range of natural rainfall productivity. Very light rainfalls are not significantly useful and severe rainstorms should be avoided because of harmful effects they may cause.

The problem of the severe rainstorm arises again when and if seeding operations are then accepted and carried out on a large scale. The exploratory-confirmatory experiments would have defined (hopefully) the economic benefits to agriculture and hydrology of routine seeding operations carried out to augment the 60-70% of rain events lying between the lower threshold and the upper limit. Seeding those storms with natural rain amounts below the threshold would have no harmful effect — the only negative feature would be an increase in total seeding costs by operations in these situations where the output is negligible.

However, the severe rainstorms can cause harmful effects, such as floods and soil erosion. If these storms are seeded inadvertently, how much additional rainfall (if any) is produced, and, if so, what are the disbenefits, economic and otherwise, that should be subtracted from the benefits derived from seeded storms in the desirable range of natural productivity. That is, what is the net benefit.

Obviously, the net benefit is depending on the frequency of the undesirable rain events, the percentage of these which can be successfully forecast, and the additional precipitation produced by seeding these undesirable storms (if any).

If the severe events are not affected by seeding, there is no problem, but I do not believe we know this is true. In fact, based on our inadvertent rainfall studies in METROMEX, urban-induced factors caused increases in heavy storms (those producing over 1 inch) that were considerably larger than those produced in the more moderate storms. This suggests that unintentional seeding of the extreme events may cause a real problem — that is, a substantial disbenefit.

How do we get an answer to this problem? From the experience gained in the exploratory-confirmatory phases, plus other available knowledge, we should get a better handle on the percentage distribution of hits and misses in forecasting the severe rain events. We can then use this information to estimate the distribution of forecast errors in routine seeding operations over an extended period of time. This would have to be based on forecasts per 5-yr or 10-yr period, or some rather extended time period. The severe rainfall distribution, especially the so-called "blockbusters," is very skewed and can not be defined very well for short periods of time.

However, before integrating the forecasting errors into the benefit-disbenefit equation, the climatic distribution of the severe storm events, both the short-duration, small-area and the "blockbuster" type must be determined. For Illinois, we may have adequate information from previous studies to determine these distributions on a long-term basis. The distribution of forecasting errors, discussed above, would then be applied to these climatic distributions to obtain estimates of average disbenefits over various periods of time.

The relationship between natural rainfall amount or intensity and seeding augmentation may be better known after the exploratory-confirmatory experiments. This information, plus additional information that may be derived from the METROMEX data, will perhaps provide enlightenment on the quantitative distribution of seeding-induced rainfall in heavy storms. Estimates of this relationship are needed to use in conjunction with the climatic distribution of heavy storms and the forecast error distribution in these storms to maximize the accuracy of computations of the disbenefits that would likely occur in a long-term, routine seeding operation during July-August in Illinois and the Midwest, in general. As indicated earlier, computed disbenefits would have to be weighed against or subtracted from the computed benefits of seeding operations. This is a problem for the agriculturalist and hydrologist using his knowledge, models, etc., but the above input from the meteorologist is essential for the final agricultural-hydrologic evaluation.

REFERENCES

Ben-Zvi, A., S. Massot, and B. Anderman, 1984: Changes in springflow following rainfall enhancement. Unpublished manuscript, Tel Aviv, 22 pp.

Harpaz, Y., and P. Keller, 1984: Effects of cloud seeding on water resources. Second Interim Report: Rainfall-runoff relationship and regression analysis for estimating changes in runoff during periods of cloud seeding. Draft translation from the Hebrew version of TAHAL Publication 01/84/62, April 1984, Tel Aviv.

C. PRECIPITATION AMD CLOUD STUDIES

1. Measurement of Precipitation Particles and Rainfall

Bernice Ackerman, Arthur Jameson, and Stanley Kidder

Introduction

The natural variability of convective cloud systems presents a major obstacle to the identification of alterations induced by weather modification efforts. Since our understanding of the physical processes and their outcomes is incomplete, we must utilize statistical analyses of ensembles to detect the effects of seeding. However this does not negate severe measurement requirements, particularly since many of the hypothesized changes are expected to be fairly subtle. Accurate and representative measurements are needed to separate the "signal" from the "noise", whether experimental design requires "proof" from physical-dynamical changes in the cloud system or changes in the nature and amount of surface precipitation.

The Water Survey has been active in the research and development of techniques for precipitation measurement for many years. Our investigations have ranged from raingage network requirements to radar sensing of precipitation particles, including some of the original studies of the relationship between reflectivity and rainfall rate (Z-R).

The Z-R relationship has been widely used for rainfall measurement in all kinds of applications: weather modification experiments, research into precipitation systems, hydrologic forecasting, etc. Despite its wide usage over two to three decades, the accuracy of the radar Z-R estimates has been questioned because of inherent assumptions about the steadiness of the rain drop distributions. Errors have been estimated as being up to a factor of two for short time scales, decreasing to acceptable levels for long-period (monthly) means.

Techniques have been developed more recently for applying adjustments to the radar measurement based on "calibration" raingages, either in networks or in clusters. State Water Survey research in the late 1970's (Hildebrand et al., 1979) indicated that estimates of areal mean rainfall, based on combinations of raingages and radar as presently suggested, are no more accurate than the gage-only measurements, for gage densities $> 1/100\ km^2$. For lower gage density (e.g., 1 per 250 to 300 km^2) the gage/radar estimates may be somewhat better but still probably not good enough for weather modification purposes. Depending on the time-space means that are used for evaluation, the accuracies are probably no better than 20% and sometimes as bad as 50% to 60% for a given convective rain event.

Despite the drawback of "indirect" measurement, remote sensing techniques, such as radar, remain a necessity for weather modification, particularly in the Midwest where clouds may move at speeds of 5 to 20 mph and lines may move as rapidly as 30 mph. Thus seeded targets may move out of a surface network before the total effect of seeding has been realized. Moreover, only with such techniques can both the individual cloud and the large cloud system (including secondary or "extra-area" effects) be adequately monitored at reasonable cost. Looking to our future needs for improved measurement of precipitation, both within clouds and at the surface, the Water Survey has been investigating, in PACE, a) techniques based on satellite sensors alone and satellite-radar combinations for midwestern cloud systems, and b) multiple parameter radar techniques. (The latter investigation is largely funded by NSF, with supplemental funding from PACE.)

Radar Techniques

Although radar has been used in cloud research for 40 years, its full potential for providing microphysical information has barely been tapped. An observational study using the ISWS CHILL and the NCAR CP2 radars demonstrated the usefulness of dual-wavelength measurements to identity the location of large hail within a storm. Dual-polarization and single Doppler velocity observations recorded simultaneously with the dual-wavelength information, together provided important insights into particle growth, and the structure and evolution of the storm (Westcott, Johnson, and Jameson, 1984). Currently, simulation studies are being carried out at the Water Survey to investigate the information content of multiple polarization and multiple wavelength measurement which could enhance our understanding of the physical characteristics of convective clouds and precipitation. This investigation has two objectives: a) measurement of liquid water content and rainfall, and b) discrimination of the phase of the condensate. Results to date are summarized below; details of the study appear in Jameson, 1983, 1985a, b.

(I) Investigations into the radar measurement of rain and water content

It is technically possible to obtain multiple wavelength, multiple polarization radar measurements, although only a few existing radars have even some of the required capability. These measurements provide the following information:

(i) The ratio of the range-rate of attenuation to the reflectivity factor is a function of $\bar{D}$, the reflectivity-weighted mean drop size. By using two radars with suitable wavelengths (e.g., 10 and 3 cm), one attenuating and the other not, it is possible to obtain a measure of $\bar{D}$

(ii) The differential reflectivity from horizontal and vertical polarizations, ζ, is a function of R, the reflectivity-weighted mean drop axis ratio (a shape factor).

(iii) The circular depolarization ratio, r, and the portion of the magnitude of the circular cross-correlation function due to shape, ρ_s, provide an estimate of Σ_R^2, the variance of R.

In the case of quiescent drops or very wet melting ice, R can be estimated from ζ, $\overline{D}$ estimated from R, and Σ_D^2 derived from Σ_R^2. Using Σ_D^2 in addition to $\overline{D}$ considerably reduces the uncertainty in the estimates of the rain water content or rainfall rate in still air, when the uncertainty is caused by variability of the drop size distribution. With advanced polarization radars all of these quantities can be measured simultaneously.

In the case of active drops, drop collisions and possible subsequent oscillations are likely to influence R. In that case, the ratio of the reflectivity factor to the dual-wavelength attenuation rate, which essentially does not depend on shape, can be used to correctly transform R into $\overline{\Sigma}_D^2$, however, may not be useful since oscillations and breakup are likely to inflate σ_R^2. The influence of possible drop oscillation and of drop break-up in various rain conditions remains to be determined.

Another potentially useful quantity is the propagation differential phase shift between horizontally and vertically polarized waves which can be measured:

(i) from the argument of the cross-correlation function between sequential but alternating horizontal and vertical linear polarizations (the CHILL radar will be providing these measurements after renovation),

(ii) from the argument of the cross-correlation function between co- and cross-polarized signals.

This measurement can possibly be used to estimate rain water content from the relationship $W = C\,\Phi / (1-\mathcal{R})$, where W is the rain water content, Φ is the range rate of propagation differential phase shift, C is a constant dependent on the radar wavelength, and $\mathcal{R}$ is the <u>mass</u> weighted mean axis ratio which for quiescent drops can be estimated from R and σ_R^2.

(II) <u>Discrimination of types of precipitation particles and investigation into precipitation formation processes</u>

Discrimination between liquid and solid particles is potentially available from several different derived radar parameters.

<u>Attenuation rate</u>: Over the identical propagation path, a size distribution of water drops will produce, at a wavelength of around 3 cm, about 10 times the attenuation of solid ice particles which are distributed in size identically to the drops. However, it is difficult to estimate attenuation rates accurately using a 10 and 3 cm dual-wavelength radar except over path lengths of several kilometers. Going to shorter wavelengths might help except that, because of rapid increase in

attenuation cross-section with decreasing wavelength, it becomes increasingly likely that the transmission would be totally attenuated in relatively short penetrations. Therefore, because of the necessity to use wavelengths on the order of a few centimeters, range resolution will generally be limited to several kilometers.

Differential reflectivity (Z_{DR}): Unlike ice precipitation, drops or mostly melted ice form a highly oriented medium. Water also has a significantly larger index of refraction than ice which enhances polarization parameters. Thus whereas water will generally be associated with $Z_{DR} \gtrsim 1$ db, ice will generally be $\lesssim 0.5$ db. This dichotomy is not precise, of course, but the contrast in Z_{DR} within an updraft has been used to identify apparent wet growth in a severe hail storm during CCOPE (Westcott et al., 1984).

Linear depolarization ratio (LDR): The ratio of the cross-polarized back-scattered power to the co-polarized power is the depolarization ratio. For linear (vertical, horizontal) polarizations, LDR is a function of particle shape, the extent of particle canting and the presence of asymmetric particles. Since ice precipitation tends to exhibit greater canting than water, LDR could be greater for ice than for water. On the other hand the lower index of refraction of the ice reduces the importance of shape which in turn reduces LDR. Although it seems likely that on the whole LDR may be larger for ice than water, it will have to be confirmed by measurements. Presently in the United States only the NCAR CP-2 radar can (apparently) collect these measurements although the double antenna arrangement and 3 cm wavelength are less than ideal.

The canting parameter, Y: With advanced polarization diversity radars it is possible to measure

$$Y = |E_{HV}|^2 / |E_{HH} - E_{VV}|^2$$

where E_{tr} is the electric field vector with transmitted state of polarization (t) and received state of polarization (r) and H and V refer to horizontal and vertical polarizations, respectively. For hydrometeors of approximate oblate shapes, Y is a function only of the magnitude of hydrometeor canting. Unlike LDR, it is not affected by hydrometeor shapes. It may provide the clearest distinction between oriented (e.g., water) and more highly canted (e.g., ice) precipitation. At present, there is no American radar that can make these measurements. However West Germany is taking delivery in mid-summer, 1985, of a 5-cm advanced polarization diversity radar that has the necessary capability (the DFVLR radar).

Discriminating between different kinds of ice hydrometeors in order to shed light on the evolution of precipitation within convective storms is probably the most challenging tasks facing radar polarimetry. Although to some extent, Y may be used to distinguish between some solid hydrometeors (e.g., hail vs. graupel) more complete discrimination will probably require a) determining Y, b) using *y* to separate shape from canting effects and c) finally to form polarization parameters dependent only on hydrometeor shapes. This represents most of the extractable information from polarization measurements. Again only the DFVLR radar will be able to make the required measurements in the foreseeable future.

Satellite and Satellite-Radar Techniques

(I) Review of Existing Techniques

Satellite data have been used to estimate precipitation in several locations and for several purposes. To determine which precipitation estimation techniques using satellite data might be best for use in an Illinois weather modification program, we undertook an extensive review of existing techniques. (The review is presented in full in the Appendix).

In summary, we found that precipitation estimation schemes using satellite data can be divided into five categories:

1) cloud indexing methods in which cloud types are identified in satellite images and a climatological rain rate is assigned below the clouds;

2) life history methods in which convective clouds are monitored through their lives and precipitation is assigned to each cloud at each image time;

3) bispectral methods in which visible and infrared data are used together to locate precipitation areas;

4) cloud model methods in which a 1-D cloud model is used either to calibrate other methods or to relate satellite-observable cloud properties to precipitation rate; and

5) microwave methods in which thermally emitted radiation from precipitation is measured.

Each of these techniques has advantages and disadvantages. The cloud indexing methods could be useful for studying extra-area effects, but they use only climatological rain rates, and thus are not good for short time periods. The life history methods are designed to estimate precipitation from convective clouds (i.e., the kinds of clouds we would like to modify), but they can be computationally intensive and are not good for small clouds. The bispectral methods seem to offer a way to utilize satellite and radar data together, but the developers indicate that they are not particularly good at estimating precipitation amounts, only precipitation areas. Cloud model methods offer a way to build precipitation physics into the precipitation estimation problem, but they are subject to the inadequacies of 1-D cloud models. Microwave data are available only on polar orbiting satellites (i.e., only twice-daily observations), but they more directly sense precipitation than the other methods. In short, all of these methods are applicable to the problem, but none are applicable without modification. In particular, none of these methods was developed for. convective precipitation measurement in the Midwest.

(II) Case Study Investigations: Research and Development of Techniques

To determine which method or combination of methods is most useful in Illinois, a case study was chosen: 24 July 1979. This day was during the VIN (University of Virginia, Illinois State Water Survey, NOAA) Program—a field program conducted in Illinois to study the relationship between the low level wind field and convective activity (Ackerman et al., 1983). During this program, the CHILL radar operated in a continuous surveillance mode over and adjacent to a 5840 km^2 area containing 260 recording raingages (density 1/22 km^2) and a 27 station PAM (Portable Automated Mesonet; density 1/216 km^2). Independently, due to the threat of severe weather elsewhere, the GOES-East satellite was operated in a 15 min scan mode during much of the afternoon. These data allow us to test various precipitation estimation schemes and to compare the results with radar and raingage estimates of precipitation.

To this point, most of the effort in this portion of the project has been directed toward acquiring data and writing or implementing software to process them. The GOES data for 24 July 1979 have been acquired from the Satellite Data Services Division of the National Climatic Data Center. Software from the University of Wisconsin McIDAS System to read and navigate (position) the satellite data has been implemented on the ISWS VAX-11/750 and on the University of Illinois VAX and Image Processing (VIP) System. Digital CHILL data were converted to Universal Format tapes (Barnes, 1980). Software was developed to read Universal Format tapes on the above two computers and to display the data on a COMTAL Vision 0ne/20, which is part of the VIP System. Finally, software was written to remap the satellite data into the radar coordinates for display and analysis. (This last software utilizes a very fast algorithm which would allow real-time processing of the data to aid in the direction of a future field program.)

On 24 July 1979 the synoptic situation was as follows. A very slowly moving cold front was crossing central Iowa in response to an upper level short wave. Conditions in the eastern half of the U.S. were generally moist and unsettled. By afternoon, the Radar Summary chart showed numerous showers and thunderstorms in the Gulf air mass. Early in the day, the VIN network was in the unstable air typical of the southeastern U.S. on that day. Small to medium sized storms of the type which would be useful for seeding developed. Later, as the cold front approached, a squall line developed and heavy precipitation fell. This case offers the opportunity to test precipitation schemes in three important situations (a) when the precipitation is falling from small clouds, (b) in heavy precipitation regimes, and (c) when cloud mergers occur.

Figure C-1a shows the GOES-East visible image at 2130 GMT on 24 July 1979; Fig. C-1b is the same as C-1a except that areas where the CHILL

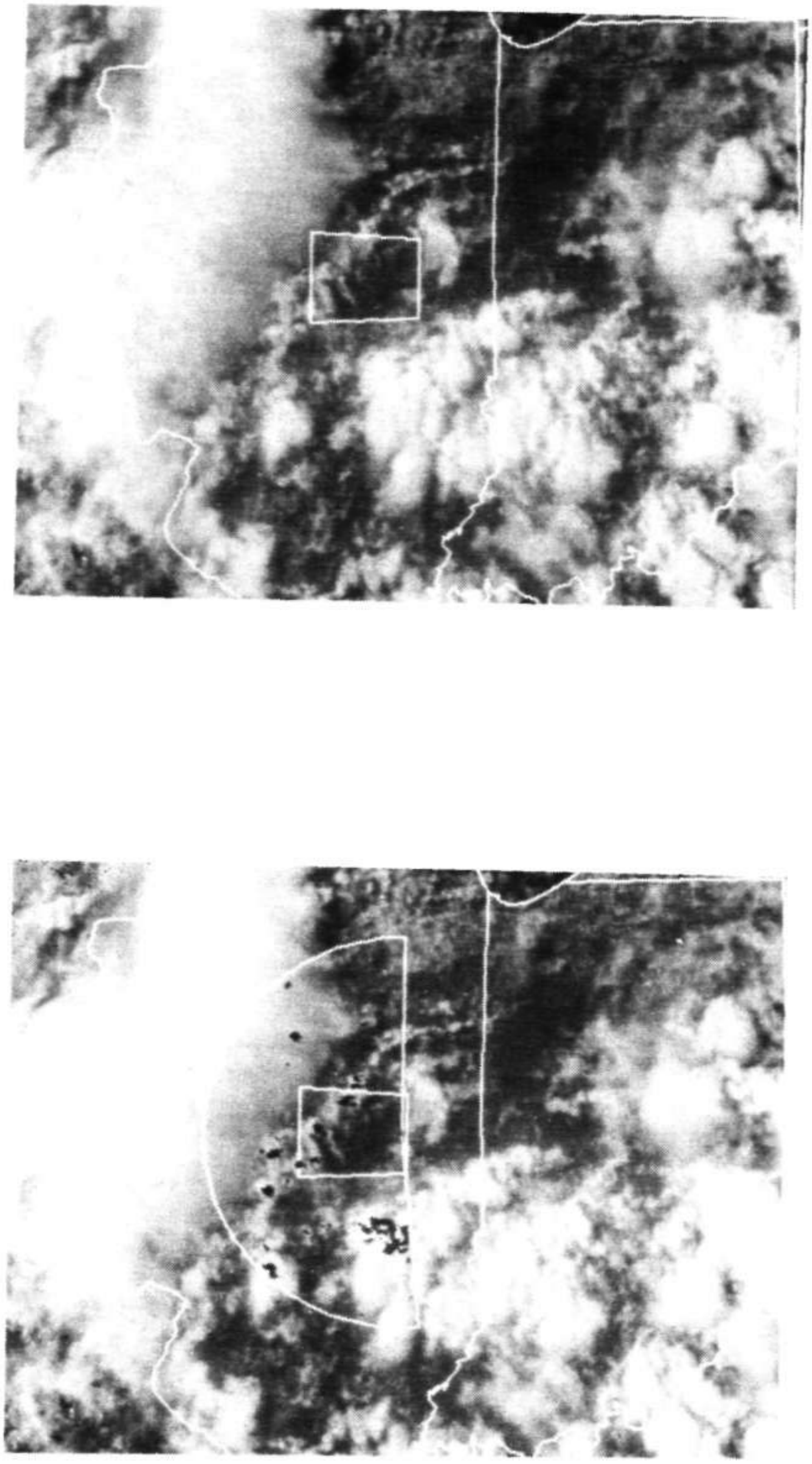

Figure C-1. (a) GOES-East visible image at 2130 GMT on 24 July 1979. (b) Same as (a) except that CHILL reflectivities of dbZ or greater are superimposed in black. The surface network is indicated by the rectangle; the area scanned by the CHILL is shown by the semi-circle.

reflectivity was 20 dbZ or greater are superimposed in black. Note that the CHILL scan pattern (a 150 km radius semicircle) did not cover the entire area shown in the image. The distance from the center of the image to the edge is about 300 km.

An interesting and important observation from Fig. C-1 is that some very small clouds produce rain. Some precipitation estimation schemes (the Griffith-Woodley (1978, 1981) technique, for example) estimate no precipitation from a cloud unless it attains an area of 2000 km^2 at some stage of its life. (Compare the 5840 km^2 area of the VIN network.) It is clear that precipitation in the early stages of a cloud's life cycle, which is important for weather modification purposes, will be under-represented by several of the existing techniques. Further, schemes which use only infrared data will have difficulty with small clouds because they will not fit the 8 km field of view of the infrared radiometer. (Unfortunately, an infrared image cannot be shown because a processing error required the infrared satellite data to be reordered.)

Work remains to be done on this portion of the project. In the next phase we will code and test some of the most promising precipitation estimation schemes and compare the results with radar and raingage estimates. The goal is to determine an optimal scheme for each type of estimation needed (e.g., detection of seeding effects, extra-area or secondary effects).

REFERENCES

Ackerman, B., R. W. Scott, and N. E. Westcott, 1983: Summary of the VIN Field Program: Summer 1979. Illinois State Water Survey, Tech. Rept. No. 1, NSF Grant ATM 78-8865, 112 pp.

Barnes, S. L., 1980: Report on a meeting to establish a common doppler radar data exchange format. Bull. Amer. Meteor. Soc, 61, 1401-1404.

Griffith, C. G., W. L. Woodley, P. G. Grube, D. W. Martin, J. Stout, and D. N. Sikdar, 1978: Rain estimation from geosynchronous satellite imagery—visible and infrared studies. Mon. Wea. Rev., 106, 1153-1171.

Griffith, C. G., J. A. Augustine, and W. L. Woodley, 1981: Satellite rain estimation in the U.S. High Plains. J. Appl. Meteor., 20, 53-56.

Hildebrand, P. H., N. Towery, and M. R. Snell, 1979: Measurement of convective mean rainfall over small areas using high-density raingages and radar. J. Appl. Meteor., 18, 1316-1326.

Jameson, A. R., 1983: Microphysical interpretation of multi-parameter radar measurements in rain. Part II: Estimation of raindrop distribution parameters by combined dual-wavelength and polarization measurements. J. Atmos. Science, 40, 1803-1813.

Jameson, A. R., 1985: Microphysical interpretation of multi-parameter radar measurements in rain. Part III. Interpretation and measurement of propagation differential phase shift between orthogonal linear polarizations. J. Atmos. Science, 42, 607-614.

Jameson, A. R., 1985: On deducing the microphysical character of precipitation from multiple-parameter radar polarization measurements. J. Climate and Appl. Meteor., 42, (in press).

Westcott, N. E., D. B. Johnson, and A. R. Jameson, 1984: Multi-parameter radar measurements of a severe convective storm in CCOPE. Preprint, 22nd Conf. Radar Meteor., Zurich, 103-107.

2. Radar Echo Climatology and Design Studies

Chin-Fei Hsu

Introduction

A major component of the current PACE project (pre-experimental phase) is to delineate the sampling unit for use in the experimental (both exploratory and confirmatory) phases. The first fundamental question relates to identification of the "individual cloud/cell units", and the second question involves identification of the sampling unit as being the individual rain period (synoptic weather system), the daily unit, or the 2-day unit. The answer to these questions involves analysis of various data available to us. Part of the answer to the second question involve an extensive review of past major randomized projects, which is described elsewhere in this report.

Scope of Study

Two study areas are identified for the echo climatology and design study. The first consists of deriving frequency distributions for single cells. This will allow us to learn more about the Illinois convective systems. The second study area focuses on analyses of "initially equivalent" echo pairs. Although considerable work has been done in Illinois and elsewhere on the characteristics of individual echoes and clusters, knowledge of the comparable behavior of two or more echoes of initially equivalent properties in time is not as adequate.

Data

Life histories of clouds and echoes from selected rain systems are being developed from recently acquired files of radar, network and satellite data. The research will yield climatologies of cloud/cell motions, durations, intensities, and volumes. As a first step to achieve this goal, the radar echo data collected by the Illinois State Water Survey HOT (Hydrometeorological Operational Tool) radar over the Chicago area (Fig. C-2) during the summer 1977-1979 CHAP project are analyzed.

The radar was located near Joliet, Illinois. It has a 21-feet diameter antenna with a 1.6 concial beam width. The radar scanned over most of Chicago and part of Lake Michigan. Minimum detectivity of reflectivity was 30 dbz, or about 220 km. The effective area in which data were collected and saved into magnetic tapes covers 16,900 sq mi (42,010 sq km). The area is represented by 64 x 64 grid points, with 2 statute mile spacing. The reflectivity was range corrected and converted to grid values by averaging neighboring bins.

The rain rate was derived from the Z-R relationship: Z = 300 exp (1.35 log(R)). These digitized and gridded rain rates were then interpreted and formed into individual cell/cloud categories for echoes at low

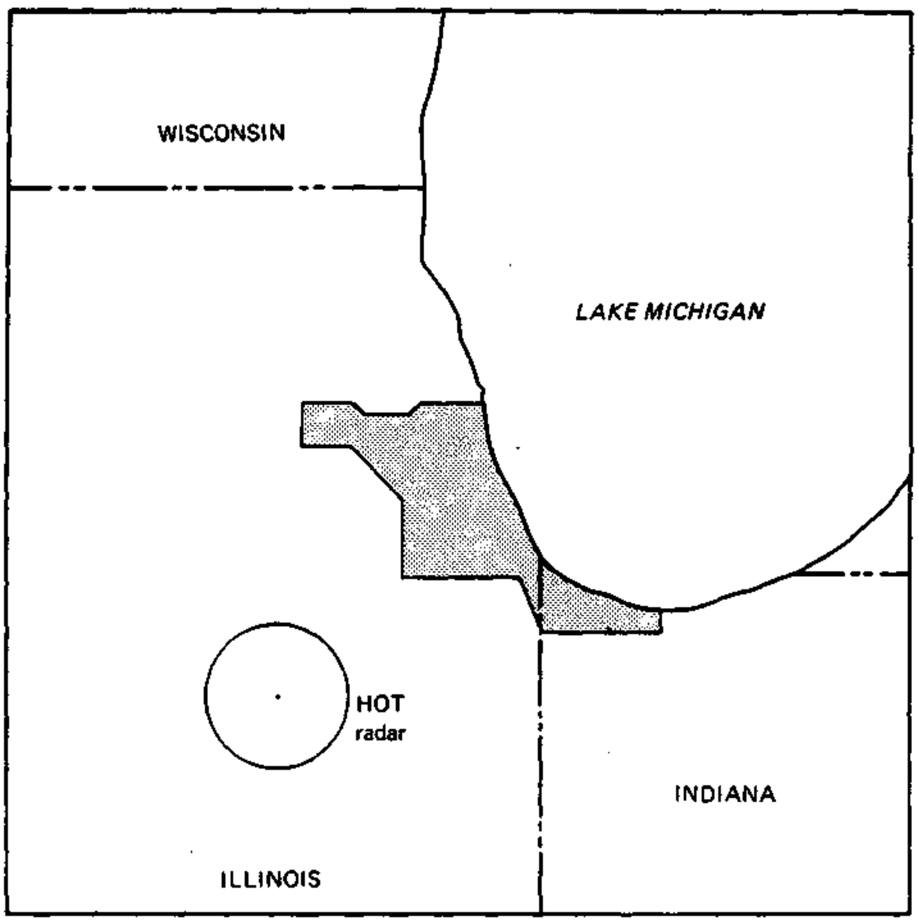

Figure C-2. HOT radar site.

level (0.75 to 5.4 degree elevation angle). The identification of a cell or echo was done subjectively and later coded into tapes. Cells were isolated and matched from scan to scan manually. The rain rate at each grid had to be at least 4 mm/hr in order to be considered. The echo was considered a "cloud" if there were 3 contiguous grid points which met the 4 mm/hr criterion. In other words, small cells often detected by a radar were excluded from the analysis. Merger and splitters were noted subjectively and coded accordingly in the data. More details of the HOT radar and data processing can be found in Changnon et al. (1982).

In all, during the 1977-1979 period, there are 86 summer rain systems thus identified, with over 3000 echoes calculated. These 86 rain systems (storms) consist of the basic data set used in this study. . A few of these storms are problem storms. They either had bad data, discontinuous echo identifier due to disrupted radar operation or computer power down, or missing data. A listing of these 86 storms and their characteristic/data problems appear in Appendix 1.

For each echo at each scan (frame), the variables in the basic data consist of an echo identifier, time echo first found, echo size (in sq mi), the grid points contained in the echo, rain rates at each grid point, displacement of the centroid between current and precious scan, time between scans, speed and direction of echo movement, ratio of current size to previous size, ratio of current average rain rate to previous one, and total rain flux from beginning to current. From these, other variables are derived for use in the design study.

Analysis of Single Echoes

For an echo to be of any use in seeding, a criterion of minimum duration (lifetime) is necessary. Echo with too short a duration is not likely to satisfy seedability criterion and does not allow enough time for aircraft operation and data collection. Currently, the criterion of minimum echo duration is set at 8 minutes, in which at least 2 scans are included. Out of the 86 storms, 14 storms were either too short or did not have any echo lasting long enough. They were excluded from any further study. Eighteen other storms did not show any usable echo data, although they lasted considerably longer. These storms are presently reserved for quality checking and are not used in the analyses; although they may provide useful echo later after appropriate recoding. From the rest "good" storms, there are 1334 echoes identified which last at least 8 minutes.

Echo parameters analyzed include time-averaged as well as peak rain rates (areal-average, total, and maximum point rr), average size (areal extent), duration, total rain volume and total rain flux. First echo (or beginning) parameters include echo size, sum of rain rate and maximum point rr. Also included in the analyses are three parameters which represent echo growth at the beginning stage, namely, the difference of echo size, sum *rr,* and maximum *rr* between the first and the second observed scans. In addition to provide information on the echo growth climatology, they are to be used in the following echo pair study as additional criteria for helping select echo pairs.

Mean and standard deviation of these echo parameters are shown in Table C-1. (In the table, "sum" refers to the sum of point rain rates, and "max" refers to the maximum of point rain rates. "Average rr" refers to the (temporal) average of (areal) rain rate average.) Duration of the echoes ranges from 8 minutes to as long as 6 hours. In average, echoes studied had a duration of 33 minutes, a area size of 80 sq miles, and total rain rate (sum-rr) of 286 mm/hour. It is interesting to note that the coefficient of variation (standard deviation/mean) of variables related to "max" is less than that related to "sum" or "size." Specific-ally, "average rr" and "average max" have the smallest variation. "Total sum of rain rates", "total rain flux", and "total size" have considerably larger variations. For first echo, the average size is 67 sq miles, the average sum-rr is 232 mm/hr. Average initial growth is 2.6 sq miles for echo size, and 3.5 mm/hr for sum-rr. These echo parameters are then fitted by various distribution functions — exponential, normal, lognormal, extreme-value 1 and 2, and Weibull — to decide the best fit. Results of the fitting of distribution is shown in Table C-1. In general, the lognormal distribution fitting is better for the variables which are totals-either sum-rr, rain flux, or size. The extreme-value distribution of type 2 fits better for variables which are either averages or peaks. The first-echo variables are also fitted better with extreme-value distri-bution. Considerable variations are found in the initial growth (differ-ence) variables, the ratio of standard deviation to mean is larger than that of other variables. The fitting to the initial growth variables was not successful (except the normal distribution) due to some unknown reason. It is not surprising that the beginning and ending times of echoes are fitted best with the normal distribution. The information of distribution of single echoes is useful in later design study for seeding.

Analysis of Initially Equivalent Echo Pairs

The 1334 single echoes derived were further analyzed to form a population of "initially equivalent pairs." The criteria of equivalence are being formed from an "operational" point of view by imitating as though echoes were encountered in a real-time seeding operation. Major components of the criteria are: (1) initial spatial separation between the echoes has to be greater than 20 km and less than 150 km, and (2) a time factor to select consecutive candidate pairs. The first criterion of proper distance is necessary to safeguard the contamination problem. The second criterion is needed to deal with potential contamination problem and operational purposes. Both criteria can be modified to suit limita-tion of available seeding equipments.

The analyses in this study used a "linear" approach in forming the echo pair population. It assumes that at any time only one echo pair is selected for treatment. When an appropriate storm is found, echoes are first identified and echo pairs are formulated at the same time. If more than one pairs are available at the same time, the initial growth echo parameters are used to select one pair with smallest difference in initial growth of maximum rain rate, size, or smr-rr (in that order). The selected pair is then followed through its life history until either one

Table C-l. Fitting Distributions To Single Echoes, CHAP 1977-79.

(Minimum individual echo duration: 8 minutes)

Total number of echo pairs = 1334

Variable(1)	Mean	Std. D.	Kolmogorov-Smirnov Statistic Exponen.	Normal	Lognormal	Extreme-Value Type 2
Begin time (hr.mn)	12.59	6.28	.202	.088	.173	.278
End time (hr:mn)	13.31	6.28	.208	.085	.164	.259
No frames	8.7	8.0	.276	.222	.118	.102
Duration (min)	32.6	33.9	.230	.233	.115	.106
Total life sum-rr (mm/hr)	4839.7	26920.6	.	.428	.080	.276
Total life rain flux	192511.6	2514355.7	.	.469	.104	.467
Total life size (sq mi)	1229.2	5373.1	.402	.411	.090	.301
Average rain rate (mm/hr)	11.0	6.9	.363	.189	.120	.094
Average size (sq mi)	79.8	173.4	.219	.347	.131	.082
Average sum-rr (mm/hr)	276.2	849.4	.299	.378	.097	.045*
Average max-rr (mm/hr)	28.6	35.6	.169	.252	.072	.048
Peak size (sq mi)	140.7	363.7	.235	.361	.103	.048
Peak sum-rr (mm/hr)	528.4	1708.3	.313	.380	.080	.029**
Peak max-rr (mm/hr)	50.1	64.2	.112	.242	.062	.038*
First echo						
size (sq mi)	67.2	177.7	.281	.377	.164	.124
sum-rr (mm/hr)	231.7	922.0	.	.405	.128	.059
max-rr (mm/hr)	25.2	35.6	.173	.278	.099	.067
Initial difference						
size (sq mi)	2.6	44.5	.	.261	.	.
sum-rr (mm/hr)	15.8	230.8	.	.287	.	.
max-rr (mm/hr)	3.3	21.1	.	.287	.	.

(1) "sum" refers to the sum of point rain rates; "max" refers to the maximum of point rain rates; "Average rr" refers to the (temporal) average of (areal) rain rate average; "initial difference" is derived by subtracting value of the second frame from that of the first frame of the same echo.

"**" means accepted at 5% level and "*" accepted at 1% level.

of the echoes dissipates, the time at that instant is defined as the ending time of the pair. The selection of next pair starts sometime after the end of active pair. At least 5 minutes is required between consecutively selected pairs.

Four scenarios were tested in formulating the pair population in this study. The first one was the "completely independent" pairs, the second was the "60-minute apart" pairs, the third and fourth were respectively "10-minute apart" and "5-minute apart" pairs. In the completely independent pair scenario, a new pair is selected 5 minutes after "both" echoes dissipate. In 60-minute-apart scenario, a new pair is selected 60 minutes after the "pair history" ends (one of the. echoes might still be alive at the selection time). The 10-minute and 5-minute-apart scenarios are similarly defined.

Results of fitting various distribution to various parameters of echo pairs are shown in Table C-2. There are 134 completely independent pairs, and 145, 177, and 186, respectively 60-, 10-, and 5-minute pairs. Mean duration of echo pair is 22 minutes in all 4 scenarios, with an average of 6-7 radar scan (frames). Mean difference between the durations of individual echo is near 15 minutes; however, there is a considerable variation associated. Mean minimum distance between the echoes is near 57 km. Mean difference of echo sizes is 118.5 sq mi for completely independent pairs, 111.8 sq mi for 60-minute pairs, 98.4 sq mi for 10-minute pairs, and 95.6 sq mi for 5-minute pairs. Mean differences of echo sum-rr and max-rr also show similar pattern of decreasing with shorter separation time between consecutive echo pairs. The first echo of the pair show distinctively advantage over the second echo in the sense that the first-echo size, sum-rr, and max-rr are all larger.

This might be caused by the selection process of echo in that echoes originated from outside the radar scanning area (as shown in Fig. C-2) were not excluded from the analysis, which rendered the first echo to be likely more 'mature' than the second echo. Study is underway that uses only echoes whose entire life history are within the radar scanning area.

The analyses performed in this study use a trial-and-error process. Changing the threshold values of parameters, different pair populations can be obtained, which in turn can tell us how to decide the appropriate threshold values. Frequency distributions of other variables important to the design of the PACE experiment are to be derived. They include life history of echo pairs and the temporal variation, medium and maximum difference of areal extent and maximum intensity, as well as their temporal evolution, minimum and median separation of echo pairs. Also to be calculated are the probability that one echo of the pair will last longer than the other for various time intervals.

Table C-2. Distribution Fitting To Echo Pairs, CHAP 1977-79.

(Minimum individual echo duration: 8 minutes
Minimum echo pair duration: 5 minutes
Minimum distance distance between echoes: 20 km
Maximum distance distance between echoes: 150 km
Minimum lapse time between echo pairs: 5 minutes
New echo resulting from splitting was not included)

Distribution: EP=exponential; N=normal; LN=lognormal;
El=extreme-1; E2=extreme-2; W=weibull

Var.	Mean	Std. D.	Distribution accepted by Kolmogorov-Smirnov Test 5Z	1Z
Completely Independent Pairs, total number of echo pairs = 134				
Begin Time (hr.min)				
echo 1	13.26	6.20	N	W
echo 2	13.36	6.19	N	W
difference	.18	.12		
Duration (min)				
pair	22.8	21.3		E2
echo 1	51.6	46.3	LN, E2, W	
echo 2	36.7	38.7	E2, LN	
difference	15.9	53.4		N, E1
abs difference	36.3	42.3	LN, W, E2	EP
Pair Distance (km)				
minimum	57.7	37.2	LN, W, E1	
maximum	72.2	36.3	LN, V, E1, E2	N
average	65.1	36.0	LN, E2, E1, W	N
Avg Size Diff (sq mi)	118.5	235.6		
Avg Sum-rr Diff (mm/hr)	283.5	694.0		
Avg Max-rr Diff (mm/hr)	31.5	43.7	LN, E2, W	
No Frames of Pair	6.5	4.8		
First Echo				
size echo 1	115.6	217.2	E2	
echo 2	52.3	105.4		
difference	63.7	215.5		
abs difference	95.1	204.4		
sum-rr echo 1	498.6	1256.4	E2	
echo 2	157.6	396.7		
difference	341.1	1188.4		
abs difference	432.3	1162.7	E2	LN
max-rr echo 1	37.7	58.5		
echo 2	25.8	39.3		
difference	15.4	52.6		
abs difference	26.7	48.1	LN, E2	W

Table C-2 continued.

Var.	Mean	Std. D.	Distribution accepted by Kolmogorov-Smirnov Test 5%	1%
Minimum separation between pairs: 60 minutes; 177 pairs				
Begin Time (hr.min)				
echo 1	13.19	6.17	N	
echo 2	13.27	6.17	N	
difference	.18	.12		
Duration (min)				
pair	22.5	20.9		
echo 1	50.5	45.3	LN, E2, W	
echo 2	37.0	38.4	E2, LN	
difference	14.2	53.5		N
abs difference	36.2	41.9	LN, E2, W	
Pair Distance (km)				
minimum	57.9	36.2	LN, W, E1	
maximum	71.6	35.6	LN, W, E1, E2	N
average	64.9	35.2	LN, E2, E1, W	N
Avg Size Diff (sq mi)	111.8	228.4		
Avg Sum-rr Diff (mm/hr)	267.1	669.7		
Avg Max-rr Diff (mm/hr)	30.3	42.5	LN, E2, W	
No Frames of Fair	6.4	4.8		
First Echo				
size echo 1	109.8	210.2		E2
echo 2	50.6	101.8		
difference	59.6	208.0		
abs difference	89.5	197.7		
sum-rr echo 1	466.5	1213.2	E2	
echo 2	150.4	382.6		
difference	316.1	1146.1		
abs difference	404.1	1121.9	E2	LN
max-rr echo 1	36.2	56.8		
echo 2	21.9	31.1		
difference	14.5	51.3		
abs difference	26.0	46.7	E2, LN	W
Minimum separation between pairs: 10 minutes; 177 pairs				
Begin Time (hr.min)				
echo 1	13.15	6.18		N
echo 2	13.24	6.18		N
difference	.19	.08		
Duration (min)				
pair	21.9	20.2		
echo 1	48.5	44.3	E2, LN	W
echo 2	35.7	34.5	E2, LN	
difference	15.4	50.2		
abs difference	34.2	39.8	LN, E2, W	EP
Pair Distance (km)				

Table C-2 continued.

Var.	Mean	Std. D.	Distribution accepted by Kolmogorov-Smirnov Test 5%	1%
minimum	57.3	35.6	W, LN, E1	
maximum	70.9	35.4	LN, E2, W	E1, N
average	64.4	34.7	LN, E1, W, E2	
Avg Size Diff (sq mi)	98.4	210.1		
Avg Sum-rr Diff (mm/hr)	260.3	639.9		
Avg Max-rr Diff (mm/hr)	29.3	40.6	LN, E2	W
No Frames of Pair	6.3	4.6		
First Echo				
size echo 1	95.1	193.1		
echo 2	45.3	92.9		
difference	50.3	189.5		
abs difference	75.9	181.3		
sum-rr echo 1	399.1	1109.3	E2	
echo 2	129.8	349.0		
difference	269.3	1043.9		
abs difference	342.5	1025.1	E2	LN
max-rr echo 1	33.8	52.4		
echo 2	19.8	28.2		
difference	14.3	47.2		
abs difference	23.6	43.3	LN, E2	W

Minimum separation between pairs: 5 minutes; 186 pairs

Begin Time (hr.min)				
echo 1	13.24	6.14		N
echo 2	13.33	6.19		N
difference	.18	.12		
Duration (min)				
pair	22.0	20.3		
echo 1	50.6	45.5	LN, E2	W
echo 2	34.3	35.6	E2	LN
difference	16.7	50.9		
abs difference	34.8	40.6	LN, E2, W	EP
Pair Distance (km)				
minimum	57.0	36.3	LN, W, E2	
maximum	70.3	36.3	LN, E2, W	E1, N
average	63.8	35.5	LN, E1, W, E2	
Avg Size Diff (sq mi)	95.6	205.6		
Avg Sum-rr Diff (mm/hr)	253.3	625.7		
Avg Max-rr Diff (mm/hr)	29.0	40.8	LN, E2	W
No Frames of Pair	6.3	4.8		
First Echo				
size echo 1	92.7	188.9		
echo 2	44.7	90.8		
difference	48.4	185.3		
abs difference	74.0	177.1		
sum-rr echo 1	382.5	1084.6	E2	

Table C-2 continued.

	Var.	Mean	Std. D.	Distribution accepted by Kolmogorov-Smirnov Test 5%	1%
	echo 2	127.6	340.9		
	difference	255.0	1020.4		
	abs difference	328.9	1001.7	E2	LN
max-rr	echo 1	33.0	51.5		
	echo 2	19.8	27.7		
	difference	23.2	42.3		
	aba difference	23.2	42.5	LN, E2	

REFERENCES

Changnon, S. A., D. Brunkow, G. Dzurisin, and C. F. Hsu, 1982: Studies of urban and lake effects on summer precipitation in the Chicago area. Contract Report 295, Illinois State Water Survey, Champaign, IL, 118 pp.

Tsonis, A. A., G. L. Austin, S. Lovejoy, 1984: A proposal for a new statistic and technique development for the design and evaluation cloud seeding experiments. Atmosphere-Ocean, 22(1), 67-82.

Wiggert, V., and S. Ostlund, 1975: Computer rain assessment and tracking of south Florida weather radar echoes. Bull. Amer. Meteor. Soc., 56, 17-26.

3. Cloud and Storm Morphology

Bernice Ackerman and Nancy Westcott

Introduction

Modification hypotheses are based on the premise that is possible to "trigger" natural physical and dynamical processes such that they will change the rates at which they would occur naturally, resulting in an altered structure and evolution of the cloud mass. In order to develop seeding hypotheses and experiments which are most likely to lead to definitive answers, it is necessary to first develop conceptual/numerical models (i.e., suitable hypotheses) of the natural development and evolution of convective cloud masses. Although the preferred approach is to do intensive and complete case studies, these are very time consuming and usually far short of comprehensive because of measurement and/or computational limitations. Thus case studies focused on specific questions and complementary ensemble studies are required.

Ensemble Studies

Our ensemble studies are based on the CHAP radar data from 1977 and 1978. In this project the HOT radar was used in a feasibility test for real-time prediction of storm rainfall. (The HOT is a high-powered, 10 cm radar with beam width of 1.65°.) Unfortunately the demands of this project did not always allow the complete volume-scan sequence required for morphology/evolution studies. Thus it has been necessary to review the entire data archive to identify a suitable data set.

All of the data from these two years were processed through a "housekeeping" program which allowed us to identify days and times when volume scans were available. We then examined these days for potential "total history" echo coverage. Because of the beam width, we added a range criterion of 60 km, which gives resolution of 1.5 km or better. This data review indicated 95 to 100 total history cases may be available for ensemble studies. These come on 8 days with synoptic weather characterized as stationary fronts on four days, and squall lines, squall zones, cold front, and airmass on one day each.

Case Studies

We have encountered a major difficulty in carrying out comprehensive case studies, namely the lack of adequate data sets. When aircraft data are available (e.g., PACE, 1978) surface and radar data are lacking. During PACE 1980 when the CHILL radar was on station, the aircraft was out of commission for approximately half of its 3-week assignment because of an unfortunate encounter with lightning; for the rest of the time, the weather provided only high-based convection, often embedded in mid-tropospheric layers. When extensive radar and surface data are available (e.g., VIN 1979, NIMROD 1978), in-situ aircraft data are not. Moreover fast-scan satellite data are generally unavailable when other data are available. Reliance on standard satellite data provides 30-min time resolution, not good enough for studies of the evolution of individual cloud masses.

The approach we have adopted in our case studies is to limit our objective to a single tractable problem, one for which the crucial data are available. We are currently addressing two problems:

(i) identification of indicators in the satellite data which are precursors of the main convective development, as seen in radar and surface data, and

(ii) the process of cloud aggregation and its consequences.

(I) Precursors of major convection

We had identified two days in 1979 from the VIN data base, on which 15-min GOES data were catalogued as available for the time period of interest. Unfortunately it turned out that the crucial fast-scan satellite data was not available on one of the two days. The remaining day was 24 July, which was discussed above in Section C-1. Of particular interest for these case studies are some of the smaller "mini-lines", and of the first convection well in front of the major squall line. The basic objective is to determine how satellite data can best be used to locate where echoes will form and how much "nowcasting" lead time is available by using satellite pictures. This will have great importance for determining the usefulness of real-time satellite data in directing the operations during a cloud seeding experiment. This study will also provide semi-quantitative information on the natural modification of the troposphere by small cumuli and layer clouds.

(II) Cloud aggregation

It has long been recognized that aggregation of individual clouds are a frequent feature in the evolution of convective rainstorms. It is possible to propose a number of scenarios as to how and where individual convective elements join. Among the most promising are:

(i) clouds may simply grow together as they individually expand;

(ii) new cloud, triggered by downdraft-induced convergence, can bridge two older storms;

(iii) detrained or decaying cloud material from two systems may join aloft, providing a better environment for expansion of the original clouds or the development of new ones between;

(iv) large convective storms may so modify the environment so as to cause new clouds to form nearby and to be drawn into the existing cloud mass.

An exploratory study based on two days in the VIN data set has shown that, indeed, clouds can join in different ways. On both days, these events occurred during the early stages of the development of major cloud lines. Cloud areas were considered to have merged if separation between echoes with boundaries defined by the minimum reflectivity of 10 dbz, was less than the spatial resolution of gridded radar data (1 or 1.65 km in the horizontal, 1 km in the vertical). This study not only demonstrated that cloud unions may occur in different ways but that the resultant storm structure may differ. In two instances, merger occurred because of expansion in the lower cloud levels: in one case there was complete merger of reflectivity cores, whereas in the other, the components retained independent cores at the higher reflectivities. In a third case outflow-induced surface convergence caused a new cloud to form between two shower clouds with all three joining as one cloud mass. However, in a fourth event, strong convergence associated with outflow produced only a feeder 'cloud and then only after a relatively long time. In this case evidence of evaporating middle level "shelves" from both storms were noted for some minutes before they were joined, suggesting that modification of the air at the mid-levels may have been a factor in the final merging of the cloud masses. In two other instances weak echo shelves (reflectivities less than 25 or 30 dbz) extended from the stronger of the two clouds, over the gap between two echoes before they joined. These cases suggest that the overhanging shelves often observed from convective clouds in the Midwest may influence cloud unions under some conditions.

More information about this exploratory study may be found in Ackerman and Westcott, 1985. A more intensive investigation of the mechanisms associated with cloud mergers was initiated in March 1985, with funding from NSF and the State of Illinois. This study will concentrate on the velocity fields just prior to, during and following the echo union, utilizing multiple Doppler measurements in an examination of the role of cloud circulations in the merger process, and of the possibility of particle transfer. The necessary data will be drawn from the NIMROD project archives. (NIMROD was a field investigation carried out in northern Illinois in 1978 by the University of Chicago, with its main goal the investigation of downbursts.)

The NIMROD data base does not include (on suitable days for PACE studies) any fast scan satellite data. However, data from the July 24, 1979 case study (described above), will be used in the merger study. The objectives will be to detect aggregation of small, pre-echo clouds, and to see if, and how, these lead to large cumuli.

REFERENCES

Ackerman, B., and N. E. Westcott, 1985: The morphology of merging clouds. Proc. 9th Int. Cloud Physics Conf., V. 2, Tallinn, Est. 403-406.

D. REVIEW OF PAST FINDINGS AND HYPOTHESIS DEVELOPMENT

1. Past Studies of Midwestern Convectlve Weather

Bernice Ackerman and Nancy E. Westcott

Introduction

An intensive review, integration and interpretation of past studies dealing with convective clouds and precipitation in the Midwest, has been an important part of our effort during this year. Our objectives are to assess the state of our knowledge with regard to convective precipitation processes in this area, and to identify and prioritize additional crucial measurements and theory. This is extremely important for developing a) physical hypotheses related to natural convection and precipitation, b) physical and technological hypotheses for modification, and c) suitable statistical hypotheses for a seeding experiment.

In our review we are emphasizing the PACE task areas dealing with the structure of convective clouds and precipitation and the evolution of that structure. In particular, we are looking for clues to the precipitation-forming processes active in midwestern clouds and the interactions between microphysics and dynamics. We will also be seeking information regarding interactions and controls between cloud and local environment (e.g., entrainment and the role of local convergence on cloud development), and between cloud and the larger environment both on the meso- and macro-scale.

The results of these past studies are in a number of sources: contract reports, journal articles, miscellaneous reports: they number nearly a thousand. Most are studies carried out by the Water Survey and the University of Chicago. There are some redundancies as reports were turned into journal articles. However we have found that often there is information in a report, but not in a journal, that is very useful in the light of our present state of knowledge, or is presented in a way that is more amenable to an integration. Conversely, frequently there is information in a journal article that was not in a report. To attack the staggering number of references, we developed a computer data base and key-worded the articles so that articles and reports dealing with a particular topic could be reviewed in sequence. We have concentrated on observational studies of the physical and dynamical characteristics of clouds and mesoscale factors in the Midwest and on associated numerical studies.

Documentation of the characteristics of convective clouds and precipitation in the Midwest are available from the field projects shown in Table D-1, in which are also indicated the type of facilities employed in the projects.

Table D-1. Projects which have provided documentation of midwestern convective weather. In the four end columns, X's indicate facilities utilized; (X) indicates that the facility was not dedicated to this project.

Project	Year of Field Experiment	A/C	Radar	Sfce.	Sdgs.
Thunderstorm (W.B.)	1947	X	X	X	X
**ACN (U of C)	1954	X	X	(X)	
**Whitetop (U of C)	1960-64	X	X	X	
Misc. Early SWS	1950-70		X	X	X
*"HOT WIRE"	1960-62	X	X	X	
Metromex (Cooperative)	1971-75	X	X	X	
Illinois PEP	1973	X	(X)	(X)	X
*DESH	1973,1974		X	X	
*PACE	(1977),1978,80	X	(X)		
*VIN (Cooperative)	1979		X	X	X
CHAP	1976-1979		X	X	
NIMROD (U of C)	1978		X	X	X

*Weather modification program, no cloud seeding.
**Weather modification program, with cloud seeding.

The Thunderstorm Project (Byers and Braham, 1949) was the first systematic study of midwestern convective weather in which aircraft was an integral component. It has provided the most comprehensive documentation to date of the dynamic characteristics of cumulus congestus and thunderstorms in the middle west. However, because suitable sensors were not available, no microphysical measurements were obtained.

The ACN project (Braham et al., 1957) was a weather modification program carried out by the University of Chicago, one of four such projects funded by the government in the early 1950's. Cumulus cloud studies were carried out in both the subtropics (winter of 1953-54) and in the Midwest (summer of 1954, unfortunately the "middle year" of a severe 3-year drought). The ACN projects, which came to an untimely termination in 1955 due to cutback in federal budgets, incorporated theoretical, laboratory and field studies, as well as randomized cloud seeding. In-situ aircraft measurement, including airborne radar sensing, was the key field facility of the project.

Periodically throughout the 1950's and 1960's, the Water Survey operated dense raingage networks to serve a variety of rainfall studies (Huff and Changnon, 1966). These projects were located in several locations in Illinois and provide (as do the later projects) a great deal of information about the characteristics of surface rainfall in the Midwest, for rain "events" covering a wide range of temporal/spatial scales. Extensive climatological studies complement the former by identifying the dominant rainfall characteristics on expanded time scales. Radar observations were also made and analyzed during the 1950's and 1960. These provide information on cloud and cloud system morphology.

The Hot Wire experiment (Semonin et al., 1964) was conducted in Central Illinois to determine the effect of artificially produced space charge on the electrification and precipitation formation of cumulus clouds. A network of high voltage wires provided a source for charging the lower atmosphere. Instrumented aircraft traced the movement of the artificial charge and radar (3 cm CPS-9) and raingages were used to detect any effect of the charge on the formation and amount of rain.

Whitetop was a randomized seeding experiment, carried out by the University of Chicago in the early 1960's (Braham, 1966). It also had a strong effort in basic research, based in both aircraft and radar measurements.

The overall objective of METROMEX, which was conducted around St. Louis, was to study the inadvertent modification of atmospheric processes by a city (Changnon, 1981). However the particular objectives of the researchers from several cooperating institutions involved in the project were quite variable. Despite the fact that the main focus was on the effect of urban development on precipitation, a great deal of data were collected by radar, aircraft and surface networks in the upwind and rural areas which were unaffected by the city. Thus METROMEX provides some very valuable information about the natural precipitation and cloud development. In addition, the detection of the causes for the inadvertent modification of precipitation by the urban area may provide insight for deliberate weather modification.

Illinois PEP (Changnon, 1973) was to have been a long term, comprehensive, phased weather modification program. Unfortunately, it too fell to major federal budgetary cutbacks in FY73. Some aircraft measurements were obtained under this program in the summer of 1973, and by moving the program from central Illinois to the rural areas around St. Louis, METROMEX provided supporting data. PEP also included a strong effort in background and socio-economic-impact studies.

DESH was a 2 1/2 year project concerned with development of a hail suppression experiment in Illinois (Changnon and Morgan, 1976). Since one of the goals was to determine the desirability of hail suppression, it also included socio-economic components. A dense raingage/hail network was operated during the fall of 1973 and the Spring of 1974 and the CHILL radar was operated when suitable weather was forecasted. Extensive climatological and weather analysis and forecasting studies were also conducted.

PACE started in 1977 with a very small "pre-PACE" study, with the NOAA P-3, on a forecast of convection, flying to Illinois from Miami for a single scientific flight. A somewhat more extensive flight program occurred in June of 1978 during which 9 cloud flights were made, most into major frontal cloud systems more typical of spring then summer clouds. Local radar support or surface measurements were not available during these flights. The last observational program under PACE was in 1980. The observational facilities included the Wyoming King Air, a light airplane for a survey of cloud base heights, and the CHILL radar which was operated only during the King Air flights. An unfortunate encounter with lightning on its second flight put the King Air out of commission for most of the period it was to be on station. Data were collected on 5 days, during a period when, unfortunately, stratiform clouds, in a couple of instances with embedded convection, dominated the weather.

The main field effort in PACE was to have been in 1979. However the decision to do a confirmatory FACE reduced the NOAA effort in PACE and there was no aircraft support. VIN, (Ackerman, 1982) a program that was to supplement PACE, and was funded by the Army Research Office, the Air Force Office of Scientific Research, and the National Science Foundation, did go forward, however. This program was cooperative with the University of Virginia and the NOAA cumulus group with the Water Survey being the prime grantee. The primary objective of VIN was to investigate the relationship between the surface divergence field and cloud and precipitation development. The key observational components were comprehensive surveillance by radar, a dense surface network and special wind observations in the boundary layer.

CHAP (Huff and Changnon, 1977) was a 4-year program concerned with hydrometeorological studies which addressed the needs of urban water resources. One of the primary objectives was to develop better real-time information on rainfall approaching and over the urban watershed. The Water Survey operated a 10 cm radar and a dense surface network in Chicago and surrounding rural areas during the summers 1976-79. This is a good example of a program with primary objectives different from those of PACE but which provides a data and information base which is very useful for PACE. The echo studies in Section C-2 are based on radar data collected during CHAP.

The final project listed, NIMROD, was a University of Chicago project conducted southwest of Chicago. It's main objective was to study downbursts and gust fronts but the data provide information on convective cloud development which is of value for weather modification.

It should be evident from the above that both measurements and analyses were likely to differ from program to program. In fact many studies have utilized data collected during a field project carried out years earlier, and often had different objectives than those for which the project was designed. We are basing our review on this information base, i.e., studies and analyses as presented in various reports and journals. We are however sometimes finding that it may be useful and/or necessary to go into the data base, i.e., the archive of the basic measurements that were obtained in these projects.

The integration of findings from the many projects and studies in this information base is frequently difficult and sometimes impossible because insufficient information is given or results are presented in different ways and cannot always be interpreted adequately for integration (e.g., altitude of measurement may not be given, or results are given as ratios). Nevertheless an attempt for an integration is important since each one contributes some information not available from others. For instance, the documentation of the dynamic structure of congestus showers and thunderstorms that was collected during the Thunderstorm Project remains as the most comprehensive to date. However no quantitative microphysical measurements were made, because there was, at that time, no suitable instrumentation available. On the other hand, later projects (e.g., Whitetop, PACE) provide quantitative measurements of detailed and bulk microphysics but have not matched the documentation of cumulus dynamics obtained during the Thunderstorm Project.

Cloud Structure: In-Situ Measurements and Observations

In the late 1940's The Thunderstorm Project established that most convective clouds of significant size were composed of several dynamic units, i.e., cells defined by velocity characteristics which evolved with time. Subsequent observations, both in-situ measurements by aircraft and remote sensing with radar, have confirmed that deep convection in the Midwest in summer is usually multicellular.

In situ measurements have been made of a number of parameters in convective clouds in the Midwest. In general they fall into two categories: dynamic (velocity and acceleration) and microphysical (bulk and detailed condensate). These measurements are summarized below, first at cloud base then for upper levels of the clouds.

Cloud Base Properties

One of the most important variables determining the microphysical characteristics of clouds is the temperature at the cloud base. It not only determines the distance through which the air and its condensate will travel before reaching the freezing level, and thus partially the time available for coalescence, but also the total amount of moisture available for condensation in the rising parcel. Although cloud base temperatures in the Middle West can vary over a wide range (from about +2 to +24°C), in most cases during the summer season they are in the region of 16 to 22°C (Johnson, 1982). On the 15 days on which cloud penetrations were made through deep convective clouds in the PEP project, the cloud base temperature varied from 15.3 to 21.8°C, with 50% of the days having cloud base temperatures warmer than 19.5°C (Ackerman et al., 1979).

Measurements were made of the updraft velocity just below cloud base during METROMEX and just above during the Thunderstorm Project. The updrafts below cloud base were, in general, not easily found and were most easily detectable in large cumulus congestus clouds or thunderstorms with durations greater than 30 minutes. The inflow areas were typically of small diameter and short duration. Of 69 updrafts detected during flights on 13 days, the strongest updraft was 7.1 ms^{-1} and the median was 2.5 ms^{-1} (Semonin, 1978).

From the Thunderstorm Project a few updraft measurements are available within the cloud at 5000 ft, approximately 500 meters above cloud base. The sample of updrafts is small (12 cases), all of which were less than 9 ms^{-1} in strength, with the median value at slightly over 4 ms^{-1}. The updrafts reported in "The Thunderstorm" are generally larger than those that were measured below cloud base, as one would expect, since the updraft would be accelerated by added buoyancy resulting from the latent heat released in condensation. Moreover the measurements that are cited were made in thunderstorms, with the airplane being routed into the most active areas as indicated by radar, whereas the sample taken in METROMEX probably included some relatively small cumulus congestus. Nearly all of the thunderstorm updrafts fell into the upper *50%* of the distribution of below-cloud drafts.

Cloud droplet spectra were measured near cloud base during METROMEX using the formvar replicator in 1973, and the axial light-scattering spectrometer during 1971 and 1975. The latter instruments measure particle concentration for radii from 1 to about 15 or 16 microns; drop concentrations based on measurements with the formvar replicator extended to drops of 25 microns radius (Dytch, 1977). Drop concentration within 600 meters of the base in clouds unaffected by the city, i.e., upwind, varied with cloud type as well as from day-to-day by quite large amounts (Table D-2). Concentrations in individual small cumulus clouds (depths between 0.7 and 1.6 km), had drop concentrations which averaged from 280 to nearly 1000 cm~3, with daily averages ranging from 280-666 cm~3 (Table D-2).

Cloud droplet distributions were also measured during the ACN project (Battan and Reitan, 1957). Three silicone-oil covered slides were exposed to the airstream on each traverse, giving a sampling volume of only about 7.5 cm^3. No specific information is given for measurement altitude or temperature but sample cases presented indicate that cloud bases were generally 4° to 17°C, colder than normally experienced during METR0MEX flights. The concentrations reported from the ACN flights are lower than those from METR0MEX possibly because of the measurement technique and smaller sampling volume. Concentrations in cumulus humulus, most a kilometer thick or less, were about 300 per cm3.

The droplet concentrations measured near cloud base during METR0MEX are not inconsistent with measurements of CCN concentrations in the same area. CCN concentrations were determined by passing air collected aloft through a ground-based thermal gradient diffusion chamber. The concentrations thus determined will represent nuclei which are super-saturation dependent and because of limited sampling volumes will tend to emphasize smaller particles. However, Byers et al. (1957) have shown that large chloride particles (diameters greater than 10 microns) are quite common at heights around cloud base during influxes of air from the Gulf into the Midwest. These particles were found in concentrations of 10^3 m^{-3}, of the same order as found in the Caribbean. Such particles, because of their size and hygroscopicity, very rapidly develop into large drops, broadening the drop spectra and initiating the coalescence process. Moreover Johnson (1976) has documented the existence of large aerosol particles between 5 and 55 microns in diameter. He found number concentrations of airborne particles larger than 10 microns in diameter to be of the order of 7500 m^{-3} and particles larger than 30 microns in diameter in concentrations of 200 m"3. It has been shown (Johnson, 1982b; Ochs and Semonin, 1979) that these giant and ultra giant particles serve effectively as "collectors" to initiate the coalescence process. Thus the midwestern aerosol contains suitable particles, in sufficient numbers, to initiate a very effective coalescence process.

Cloud Structures in Deep Convection

During the Thunderstorm Project five airplanes flew simultaneously at 5000 ft intervals starting at 5000 ft. From a number of case studies, Byers and Braham (1948, 1949) deduced a conceptual model of a Midwestern thunderstorm which was a multicellular complex with an evolutionary circulation for each cell. Thus it is difficult to derive average or mean vertical profiles.

The frequency distributions of updraft velocities measured at the 5 levels, as tabulated by Byers and Braham, are shown in Fig. D-1. Although there is some problem associated with the varying sizes of the individual

Table D-2. Average cloud droplet concentrations measured in the rural areas upwind of St. Louis, 1973-75. (From data given in Dytch, 1977). Cloud base, depth and penetration level are characteristic averages of all cloud penetrations.

Date	Cloud Base (km)	Cloud Depth (km)	Height Above Cloud Base (km)	No. of Clouds	Average Concentration (cm^{-3})
			Cumulus Congestus		
8/11/74	1.3	2.3	1.7	14	549
8/23/74	0.9	2.8	2.1	14	355
7/30/75	1.2	3.2	1.6	5	376
			Cumulus		
8/ 5/73	1.4	1.6	0.6	9	281
8/ 2/74	1.5	1.4	0.6	8	606
8/ 2/74	2.4	1.2	0.3	3	666
7/ 8/75	1.8	1.1	0.6	26	380
			Strato-cumulus		
8/ 4/74	1.5	0.3	0.1	25	536
			Stratus		
8/10/74	0.5	0.3	0.1	8	434

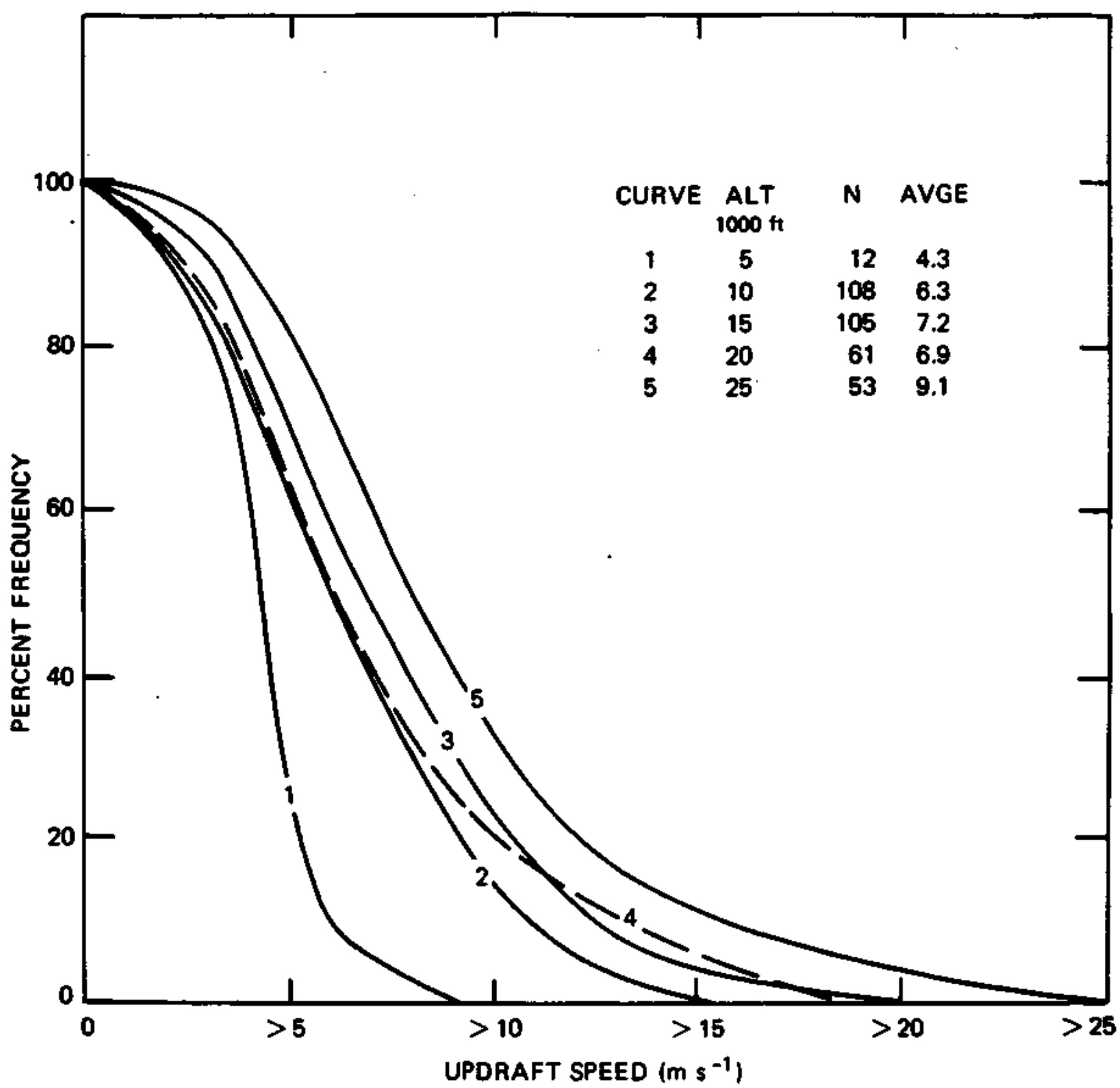

Figure D-1. Cumulative frequency distributions of updraft speeds measured during the Thunderstorm Project. (From tabulations in Byers and Braham, 1949.)

samples, these distributions indicate that the updraft normally accelerates from the 5000 ft level upward, at least through 15,000 ft. The distribution for 20,000 ft suggests no acceleration, possibly deceleration, in the next 5,000 ft interval. This may be an artifact of sampling but there is an indication of updraft acceleration between 20,000 and 25,000 ft as well. Vertical updraft velocities were determined from the total displacement of the aircraft over the width of the draft and thus represents an average for the whole draft.

Updrafts were estimated during the PEP flights using a rate-of-climb meter, and during the PACE 1978 flights, using the most sophisticated technique based on the inertial navigation system and gust probe. The PEP flights were at about 15000 ft (0°C) and the PACE at -8 to -10C (approximately 20000 ft). The cumulative frequency distribution of the updrafts measured in PACE (Johnson, 1980) and the distribution of updrafts measured during the Thunderstorm Project at the same heights are shown in Fig. D-2a. Both distributions are of the average velocity for the whole updraft: the PACE data are for drafts that covered 1 km or more; this is true in all but 4 of the Thunderstorm drafts. The close agreement between the two may appear fortuitous in view of the different ways in which the measurements were made, but it should also be noted that most of the clouds that were penetrated in PACE 1978 were associated with frontal system and were in the category of small thunderstorms.

The PEP measurements (Fig. D-2b) represent the average speed over 350 or 400 meters around the peak (Ackerman et al., 1979), whereas the Thunderstorm data are averages for the whole updraft. The PEP distribution indicates lower values than found by the Thunderstorm Project. This difference may be due to the difference in measurement technique, with the PEP data probably less representative of true air motion. However the discrepancy could also have been due to sampling different parts of the cloud population. The PEP (and PACE) p'enetrations were made through growing clouds as they were passing through the altitude of the airplane, whereas many of the Thunderstorm penetrations were made later in the cloud's evolution. This is supported in the distributions of updraft widths (Fig. D-3) which indicate generally larger clouds in the Thunderstorm data set.

The thermal properties of the Thunderstorm model are evolutionary, as was the circulation. It is not in-cloud temperature itself that is important, but the deviation of the in-cloud virtual temperature (a measure of air density) from that in the surrounding environment. This represents the "thermal buoyancy" which is a partial measure of the degree of acceleration to which the updraft is subjected. In Table D-3 are shown the deviations of the maximum in-cloud virtual temperatures from the mean virtual temperature in the surrounding clear environment reported during the Thunderstorm project, the ACN project, and Illinois PEP. Only a relatively few estimates of the thermal buoyancy were listed in "The Thunderstorm" (op. cit.); only those for updrafts are tabulated here. It can be seen that, in the building and early mature stages of a thunderstorm cell, the thermal buoyancy (and thus the acceleration) can be considerable.

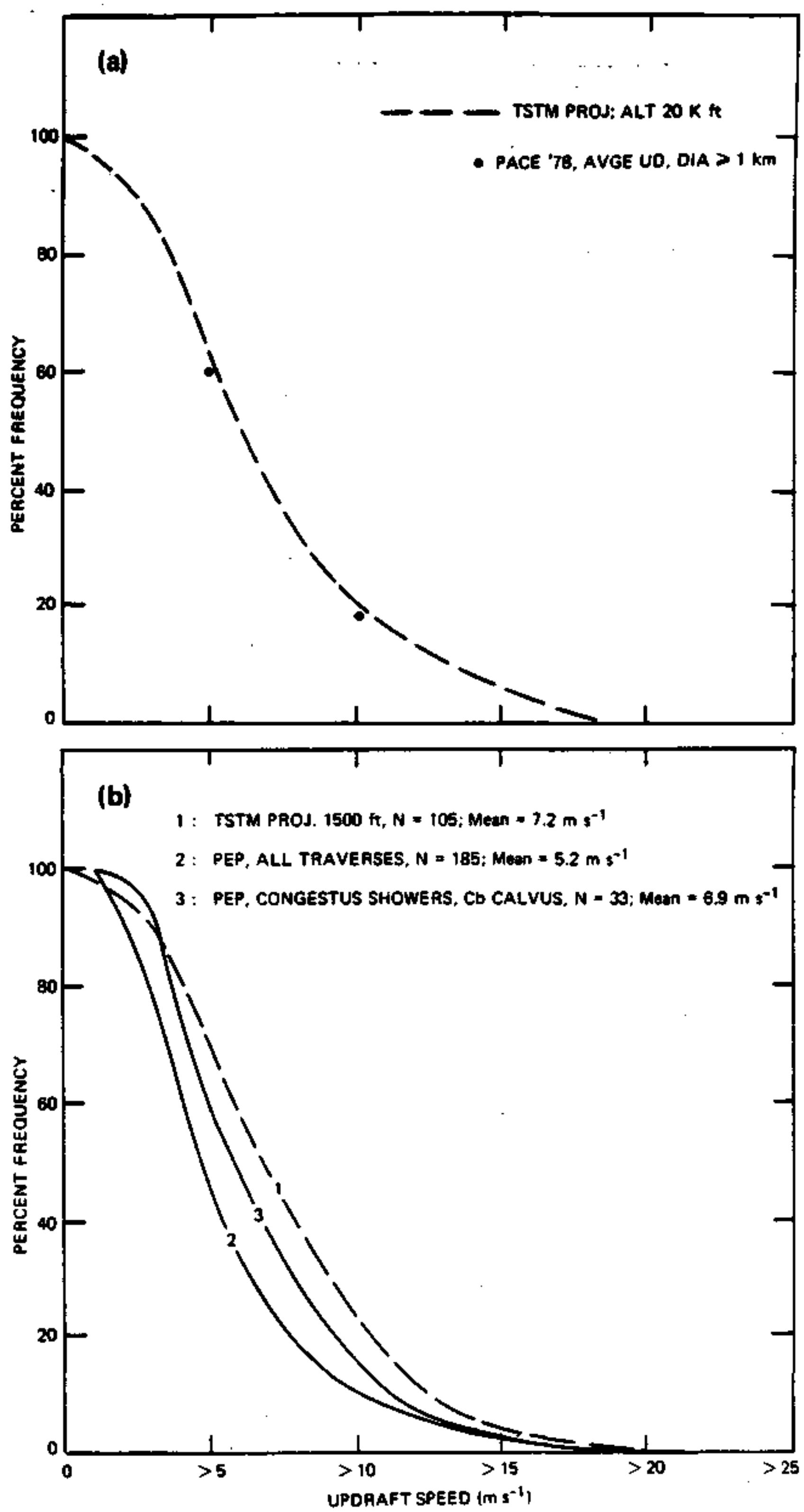

Figure D-2. Cumulative frequency distributions of updraft speeds (a) at approximately -8 to -10°C, and (b) around the freezing level. (From tabulations in Byers and Braham, 1949; Johnson, 1980; and Ackerman, et al., 1979.)

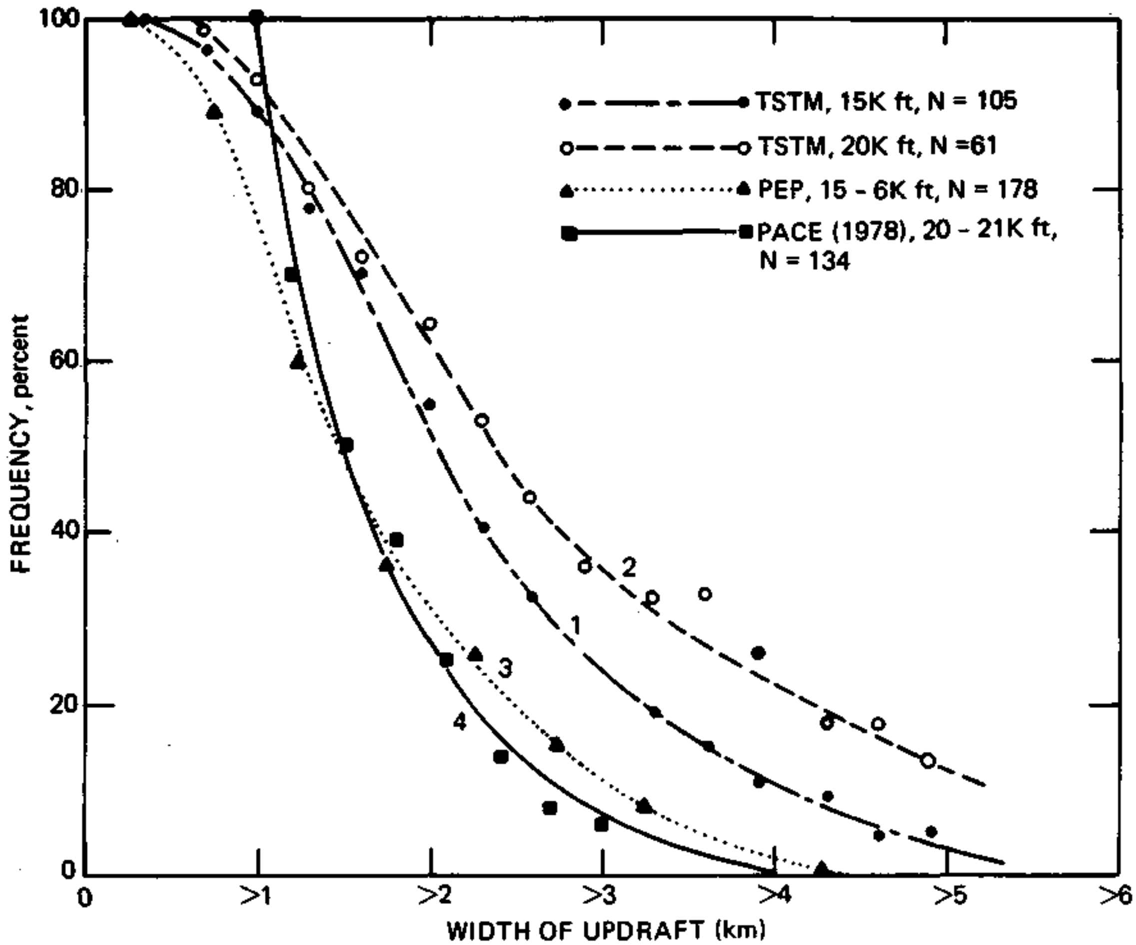

Figure D-3. Cumulative frequency distributions of updraft widths measured during the Thunderstorm Project, Illinois PEP and PACE. (From tabulations in Byers and Braham, 1949; Johnson, 1980; and Ackerman, et al., 1979.)

Table D-3. Difference ($\overline{\Delta T_x}$, °C) between the virtual temperature maximum (T_x) in cloud and mean virtual temperature (T_e) in surrounding clear air. The total number of cases and the number of cases where $\overline{\Delta T_x}$ was negative (i.e., cloud virtual temperature less than that in the environment) are given in parentheses.

a. Thunderstorm Project (updrafts only)

Alt. (km)	$\overline{T}_e$ (°C)	Average ΔT_x		Range ΔT_x
		Bldg. Stage	Early Mat. Stage	Both Stages
1.8	+17	+0.9 (1,0)	(0,0)	
3.0	+8	(0,0)	+0.8 (4,0)	0.1-1.7
4.6	0	+3.6 (1.0)	+0.3 (1,0)	0.3-3.6
6.1	-8	+2.3 (4,0	+2.0 (6,0)	0.3-4.0

b. ACN Project (whole traverse)

T_x (°C)	Average ΔT_x	Range ΔT_x
$T_x > -2$	1.24 (27,0)	0.2-3.1
$-4 \leq T_x \geq +4$	1.21 (20,0)	0.2-2.9
$T_x < +2$	1.20 (23,0)	0.2-2.9

c. PEP ($-4°C \leq T_e \leq +4°C$)

	Average ΔT_x	Range ΔT_x
Whole traverse	1.37 (140,5)	-0.5-+5.1
Cloud units	1.06 (276,31)	-1.0-+5.1

Average temperature deviations and the range of penetration values measured during the ACN project were obtained from an. unpublished tabulation. This tabulation divides the data into warm and cold clouds, as indicated in rows 1 and 3 of Table D-3b and then for penetrations around the freezing level. (Note that these cases are also included in the other two categories; total sample was 50.) It can be seen that the averages and ranges in the thermal buoyancy did not differ significantly between "warm" and "cold" clouds, the full temperature range of the cloud sample was from +8.0°C to about -10°C.

In PEP the maximum buoyancy was estimated for both individual cloud cells and for the whole traverse, which was composed of anywhere from 1 to 3 or 4 cells, (Table D-3c). All of these data are from around the freezing level. The average values, and even the range (considering differences in the sample size) for both the ACN and PEP data are quite consistent. This implies that as clouds penetrate the freezing level they usually have warm (less dense) cores which indicates acceleration of the updraft. (To some extent the samples are biased, since in both projects clouds were selected on the basis of visual appearances which suggested active growth.)

Data at around 0°C level are very sparse in the Thunderstorm data. The averages at 0 and -8°C suggest that updrafts measured in the Thunderstorm Project were somewhat more buoyant that those from the other projects, although the ranges suggest that they may not have been as different as the averages would imply. However as indicated above, it is not unlikely that the Thunderstorm Project data came from somewhat larger clouds.

Liquid water content measurements were made during the ACN Project in 1954, during PEP in 1973; and during PACE in 1978. As was true for the other parameters, measurements were made in several ways. The Johnson-Williams (J.W.) Liquid Water Content Meter was used in all but the ACN Project. The total liquid water (i.e., including that in precipitation particles) was measured during PEP using the Ruskin Evaporator. This along with the JW provided a method for partitioning the condensate between cloud water, i.e., the water in drops of less than 50-70 microns, and the water that is in larger drops. In the ACN Project, the liquid water measurement was obtained using the Australian Paper-Tape Liquid Water Meter which operated on the principal of change in conductivity of a wetted paper tape as a function of the moisture content. The size range of the droplets that were detected by this instrument is broader than that of the JW and certainly extends into the precipitation particle size. The paper became saturated and would tear at liquid water contents of the order of 8 grams m"3, a value much larger than was experienced during the 1954 flights in the Midwest.

Only first passes on clouds were analyzed for liquid water content during the ACN project. Using visual observations (the clouds were observed until they dissipated), Draginis (1958) classified the water contents for 24 clouds as being "non-echo" clouds (i.e., ones did not contain and never developed an echo), clouds which did not contain at the time of penetration an echo but eventually did develop one, and a third group of clouds that contained echoes at the time of, but not necessarily in the location of, the measurement. About two thirds of the measurements were from non-echo clouds. The clouds which, at some time in their life, had echoes generally had larger liquid water contents than did the non-echo clouds and, except in one instance, contained regions where the water content equaled or exceeded the adiabatic value (Fig. D-4). Since the adiabatic water increases with height, one can see from Fig. D-4 that the ratio of the maximum liquid water content to the adiabatic water content decreased with height in non echo clouds from about 1 at about 500 meters above cloud base, to about .65 at 1 or 1.2 km above cloud base, to about 0.40 at 2.5 to 3 km above cloud base. (Draginis does not indicate the altitude of the measurements, except that they were made at temperatures warmer than -2°C, but if one assumes cloud base temperatures between 10 and 20°C, the height of each measurement can be estimated approximately from the adiabatic water content.) On the other hand there is no consistent trend with height for maximum liquid water contents in clouds in which there was an echo, or one subsequently developed. Draginis also found that in clouds that dissipated within 5 minutes of the measurement, the liquid water content was always below 0.3 of the adiabatic value. On the other hand, in clouds that dissipated in 15 minutes, water contents exceeded this fraction over about 38% of the traverse. An even larger fraction of the measurements on a penetration (about 57%) exceeded 0.3 of adiabatic in echo clouds.

The <u>total</u> liquid water content (TLWC) measured during the PEP project was much <u>greater</u> than that found during the ACN project (considering only the measurements at the greatest height in ACN and small and towering cumuli in PEP). <u>Total</u> liquid water contents averaging about 3 g m^{-3} across the whole <u>traverse</u> and peak values of the order of 4.5 to 5 g m^{-3} were reported in PEP (Ackerman <u>et al</u>., 1979) whereas between 1 and 2 g m^{-3} was reported by Draginis for ACN. The Draginis values are similar to the <u>cloud</u> water contents (CWC) observed in PEP: maximum CWC in towering <u>cumuli</u> averaged about 1.5 g m^{-3}. This difference in the values of TLWC from the two project could have been due to differences in instrumentation. However, the ACN field program was in a year in which rainfall was greatly below normal. There is some implicit indications in several papers from this project that cloud bases were unusually cold for the Midwest, some possibly below 10°C. In addition during drought years macroscale conditions are often unfavorable for deep convection, either because of subsidence aloft or dry conditions in the cloud layer which will cause evaporation of cloud water due to entrainment.

All of the measurements in PEP were made around the freezing level (+4°C). The clouds penetrated usually had significant supercooled liquid water at this level. The total liquid water content (TLWC) exceeded 2 g m^{-3} over some portion of the traverse on all but 2 penetrations, and on 50% of the passes the peak water content measured on a traverse was over 6 g m^{-3}. The traverse-averaged TLWC was almost always over 1 g m^{-3} and was more than 3.4 g m~3 on half the penetrations. Although the average water content was less than the adiabatic value on about 84% of the traverses, on at least 2/3 the highest water contents, that is the maxima, exceeded

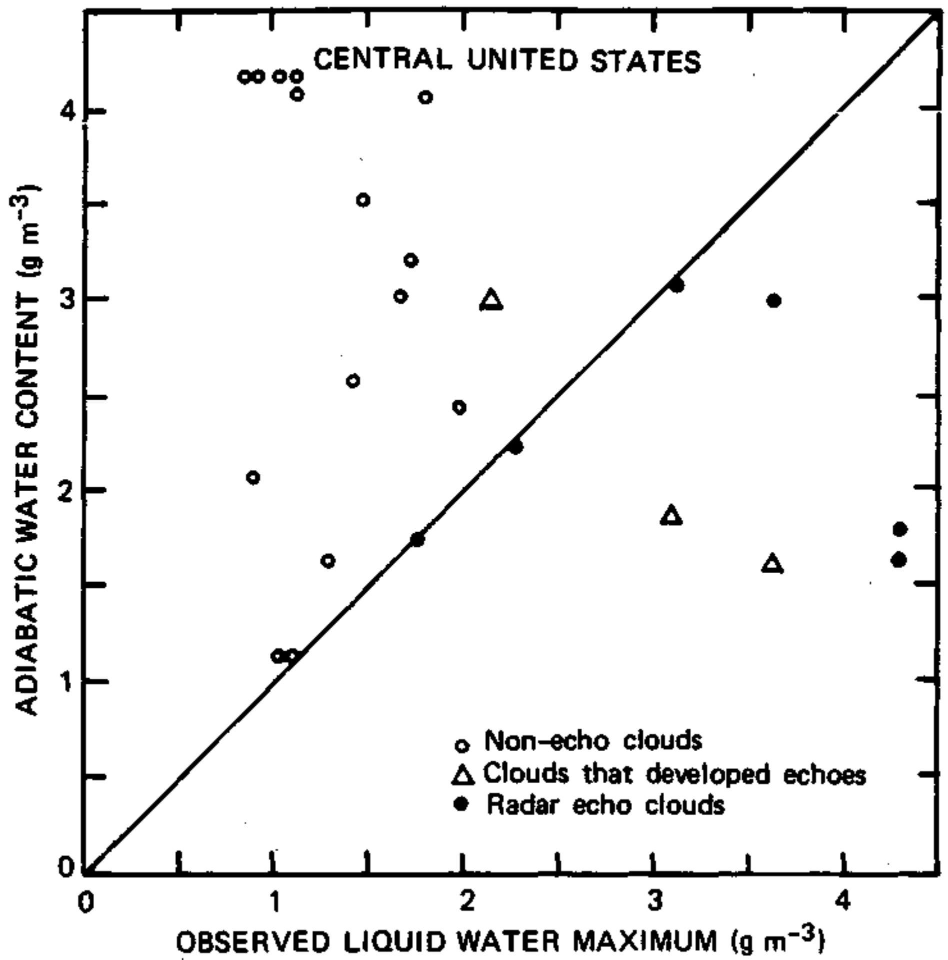

Figure D-4. A plot of the peak liquid water content measured on a traverse (abscissa), and the theoretical value computed for adiabatic ascent (ordinate). (From Draginis, 1958.)

the adiabatic, indicating a high incidence of accumulation of water in some sections, probably because of sedimentation of large drops from cloud parcels above. The cloud water fraction, i.e., the ratio of the J.W. liquid water content to the total liquid water content represented only a small fraction of the condensate, less than 0.5 on all but a few traverses, and averaged only 0.25. In the mean, the maximum CWC encountered on a traverse was a little over 2 g m^{-3} with the cloud water exceeding 1 g m~3 over some segment of the traverse on most of the penetrations.

The distributions of the CWC for individual cells in PEP was very similar to that for the cloud traverse, with an average peak value of 1.8 g m^{-3}, about 0.3 g m^{-3} below that for the whole traverse. Even in the active cells, the CWC was generally below adiabatic, although there were a few cases in which the peak value approached it. The TLWC was frequently quite large, but the average across a cloud cell was less than adiabatic in most cases and 2/3 of the cloud units had an average TLWC less than 75% of the adiabatic water. However the existence of portions of the cloud where the TLWC exceeded the adiabatic value indicates that during ascent, a cloud parcel in the updraft had water added to it by non-adiabatic processes, e.g., by larger drops which are sifting downward from an upper region.

The cloud water contents measured with the J.W. in the PACE 1978 flights (Johnson, 1980) were of the same order as those that had been measured in PEP, particularly when considering the average values in updrafts in PACE and in the active cloud units in PEP. However, the peak water contents in the PACE updrafts tended to be lower than those found in PEP.

PACE measurements are particularly pertinent to weather modification because they were made at -8 to -10C, temperatures where seeding is likely to be implemented. The criterion used in FACE for cloud eligibility for seeding was 1 g m^{-3} of supercooled water. At least 75% of the clouds penetrated in the Midwest in 1978 would have met this criterion and would have qualified as candidates for modification. Moreover, in nearly 1/3 of the updrafts, the CWC exceeded 1 g m^{-3} over more than half their length. This fraction increased as the size of the updraft (but not necessarily the magnitude) increased. For updrafts larger than 500 m in dimension, 45% of the updrafts had liquid water contents of 1 g m^{-3} over half or more of their length and for larger updrafts yet, those exceeding 1 km in length, *60%* had water contents of 1 g m^{-3} over at least half their length.

Bulk water contents were measured only for cloud droplets in PACE, (i.e., by the J.W.). However microphysical measurements in Whitetop and in PACE indicate that some of the condensate at these levels, possibly a significant amount, was in larger drops than detected by the J.W.

Measurements of the detailed microphysics in midwestern clouds have been fragmentary. They tended to be limited to a particular size range, and are also limited in number.

Cloud droplet concentrations measured in cumulus congestus during the ACN flights (Battan and Reitan,. 1957) indicated an average of 188 cm^{-3} for ten clouds that did subsequently develop echoes and about 250 cm^{-3} for 21 clouds that did not develop echoes subsequently. It is not known how large the clouds were or at what altitude the measurements were made but it is likely that the penetrations were in the upper half to the upper third of the cloud. Cloud droplet concentrations reported in METROMEX for small cumulus congestus were somewhat less than those in smaller cumulus clouds (Dytch, 1977). Daily means of average concentrations ranged from 355 to 550 cm^{-3}, depending on the day (Table D-2). The clouds had tops below the freezing level; the measurements were made in the upper half and 1 1/2 to 2 km above cloud base. These concentrations are relatively low for a central continental region such as southwestern Illinois and eastern Missouri, as were those cited for cloud base.

Measurements of larger drop sizes have been made using a continuous metal-foil belt and formvar replicator in Whitetop and the Knollenberg cloud and precipitation probes in PACE 1978. Brown and Braham (1963) summarzied measurements by the foil sampler on 133 traverses through 58 clouds during Whitetop. There were day-to-day variations in cloud types and sizes; the majority of clouds were cumulus congestus, a few were Cb capillatus and the remainder were cumulonimbus calvus. Some cumulus congestus developing into Cb's while being observed. Data presented are primarily from clouds with bases 1.0 to 1.5 km msl and tops 4.3 to 6.5 km (freezing level usually 4.2 to 5 km). Penetrations were usually in upper third of cloud. They concluded that for clouds of this type, nearly every one contains large particles (d > 250 p) in the upper levels at some point, with 40 to 50% developing concentrations of at least 100 m^{-3} and 20% developing concentrations of 1000 m^{-3} or more. Horizontal profiles for three traverses on which high concentrations had been found indicated horizontal variability in the concentrations of large sizes, those in size range of 550-750 microns had concentrations around 100 m^{-3} per 100 μ interval in parts of the cloud.

Koenig (1962, 1963) examined the hydrometeors indicated by the foil samples and formvar replicator for 84 clouds penetrated on 33 flights during the Whitetop field program in 1960. All clouds had summit heights between approximately 15,000 to 16,000 ft and 20,000 ft msl. A total of 226 traverses were made through 84 clouds, most at temperatures between 0°C and -4°C. No precipitation size particles were found on 42% of the traverses (32% of the clouds). Of the 57 remaining clouds, 52 contained liquid precipitation size drops, and 34 contained solid hydrometeors at some time and place during their lifetime. Of the latter, 18 clouds developed ice particles subsequent to traverses on which only liquid precipitation particles were observed and another 11 had mixed phase hydrometeors on the first penetration. From study of the nature of the precipitation particles found in this larger sample, and the evolution of the precipitation particles in case studies of 7 clouds through which multiple penetrations had been made, Koenig deduced certain characteristics of the glaciation of relatively small cumulus congestus and small Cb Calvus clouds in this area. Rapid glaciation was characteristic of clouds of this type with liquid to solid phase transition spreading through the cloud volume within 10 or 15 minutes. (In one instance this time interval was only 5 minutes, but introduction of ice crystals from a higher altitude was indicated). Clouds that developed large concentrations in comparatively short time (less than 10 min) did so only after the occurrence of precipitation-size liquid drops (about 1 mm diameter in concentration of 50 m^{-3}). Moreover in mixed phase volumes of small Cb clouds, the largest liquid and solid hydrometeors were similar in size, suggesting that the solid phase built on the size structure achieved by the liquid phase prior to glaciation.

The solid-phase hydrometeors which were collected were almost universally irregular in shape, and even particles as small as 20 microns appeared to have no crystal symmetry. On the basis of this observation, supported by the fact that ice concentrations were much larger (by a magnitude or more) than ice nuclei concentrations, Koenig concluded that most of the ice particles detected had not been created by sorption nucleation and that sublimation could not account for their shapes and sizes. Thus he proposed that satellite ice particles form as large liquid water drops freeze and that these particles act as nucleating agents for the smaller drops, causing them to freeze.

Many of the clouds in Koenig's sample developed rain showers before the ice phase was present, most did not develop into large Cb, and in some cases, the lower regions decayed leaving an upper glaciated "anvil" and virga. An eighth case study presented in Koenig (1962), however was more vigorous and grew to an estimated altitude of 30,000 ft by the fourth penetration, (from 19,000 ft when first selected some 8-10 min. earlier). Penetrations on this cloud were at 17,000 ft (approximately -2 to -4°C) and continued for 38 minutes. Throughout its active life (first 5 passes) large quantities of supercooled water drops were found in the interior of the cloud, while small, dry solid particles were found on the edges, with the size of the solid material increasing toward the interior. By the sixth penetration the cloud started to decay and mixed phase was encountered in the interior.

The PACE 1978 penetrations were generally through larger and more vigorous cloud systems and at a colder temperature (-10°C), than those on which Koenig's data were collected. (In both data sets the penetrations were made near the top of growing turrets.) The microphysical observations obtained with the Knollenberg probes on the PACE flights generally agree with the general pattern deduced by Koenig, and in particular with the eighth case study mentioned above (Johnson, 1980). The Knollenberg 2D probes records the time-dependent shape of the particle shadows and thus cannot distinguish between a supercooled liquid drop or a frozen drop crossing its field of view (unless the ice particle is highly irregular in shape). In actual operation, however, the presence of large drops of supercooled water could be inferred from the distinctive patterns associated with shedding of the liquid water which built up on the probe tips. These elongated patterns are termed "streamers" and are easily distinguished from frozen graupel or crystalline ice.

While the streamers seem to provide a way of monitoring the glaciation of the large drops, they unfortunately prevent a more quantitative assessment of the actual size and numbers of drops. In the PACE 1978 data, the onset of glaciation was evidenced by reduced numbers of streamers on the Knollenburg probes, increased indications of ice measured by the Mee ice particle counter, and hot wire liquid water contents that were only slightly lowered. While this process is presumably going on in all active clouds growing past the -10°C level, this pattern was most often found in the later passes through a cloud as the updraft began to weaken. On occasion, as the updraft died a "shower" of millimeter-sized ice pellets in concentrations of over 1000 m^{-3} were detected with little or no evidence of supercooled liquid water.

On a couple of days the cloud forms were stratiform layers with embedded convective elements. In these instances there seemed to be a different form of ice evolution. In the layers between active cells ice crystals apparently grew by diffusion, resulting in large number of millimeter-sized crystals and/or aggregates. These crystals appeared to mix into the convective cores pushing up through the stratiform layers where they showed evidence of riming, eventually producing large pellets. The ingestion of the crystals into these growing cells did not seem to seriously deplete the "small drop" liquid water content, since the J-W liquid water meter indicated significant liquid water contents in these cells.

Koenig (1962) also describes hydrometeors found in multiple layer cloud systems. In the one case of known embedded convection, the airplane circled in the cloud mass for 25 minutes at about 16,000 ft (-4°C). (Tops of convective turrets pushed up through the layers to altitudes of 17,000-19,000 ft.) The data were in general agreement with that found during PACE. One convective element (with three turrets) contained no ice during the time it remained above the general layer. In a second cloud all solid hydrometeors were found in one area and "slush" in another. The solid hydrometeors were a mix of small pellets and flake-like solids. Koenig hypothesized that the latter consisted of loose aggregates of rimed crystals.

Cloud Structure and Evolution; Radar Measurements and Observations

Radar has been an invaluable tool for studying cloud systems since the mid 1940's. It has been an important facility in most of the research projects in the Midwest (Table D-1). It has provided important information for severe storm studies - hail, tornadoes, and heavy rains; for planned and inadvertent weather modification studies; and for basic research on the evolution and dynamics of convective storms. While these projects have had diverse objectives, the data gathered have all contributed toward identifying the characteristic structure, dynamics and precipitation initiation mechanisms of midwestern convective storms. A large fraction of the information base used in this review lies in reports and articles dealing with radar analyses. Most of these are reviewed and discussed in the Appendix (Part 2). Key points from that review are presented below.

Precipitation-Echo Initiation

In a landmark paper, Battan (1953) reported that the majority of the initial echoes (56%) detected by radar during the Thunderstorm Project were at heights totally warmer than 0°C, another third straddled the freezing level, and only a few percent were totally colder than 0°C. A number of subsequent studies of first echoes (FE) in the Midwest have been in general agreement with these findings, although there have been some differences in detail. These studies provide solid support for an active coalescence process in this area leading to the initiation of precipitation-sized particles, often without the involvement of ice. This conclusion is further supported by the in-situ microphysical and bulk water measurements discussed above and in theoretical calculations as well (Johnson and Dungey, 1978).

Temperatures at the tops of first echoes detected in the Thunderstorm Project, Whitetop, and METROMEX averaged between 0°C and -2°C and those at the bases averaged between 10° and 11°C, (considering total sample populations). However, the range of temperatures at both tops and bases of the echoes is very large: 24 to 26° in the thunderstorm data (Battan, 1953) and, with a very large sample, about 45°C in the METROMEX data (Braham and Dungey, 1978). The question then arises as to what factors may affect the initiation of precipitation and result in such broad distributions.

One factor is related to the way the observations were taken. The interval between "looks" at the area where an echo is detected is customarily around 3-4 minutes, except in the case of the thunderstorm data, for which scan intervals were between 15 sec and 3 min and 15 sec. If a cloud is developing and growing, one would expect both top and base temperatures at time of first detection to depend on whether the echo developed near the beginning or end of the interval. Recognizing this problem, Braham and Dungey (op. cit.) analyzed the location of first echoes with thicknesses less than 1 km and found that a much higher fraction were totally warmer than 0°C than occurred in the total METROMEX first echo population (Table D-4a). The Thunderstorm FE, which tended to be warmer than the full METROMEX population, were also shallower (Table D-4b).

In his study of first echoes during METROMEX, Changnon (1978) stratified the data into organized and isolated systems (Table D-5). The bases and tops of the FE in more organized storms were markedly higher (and presumably colder) than those in isolated systems, and also deeper. This would suggest that meso- and macro-scale dynamic and thermodynamic differences may strongly influence variations in echo characteristics. This in turn suggests that there may be day-to-day differences in first echo development. This contention is supported for a pooled Whitetop and METROMEX FE data set in which daily average top heights ranged from 10,000 to 22,000 ft (Johnson and Dungey, 1978). The data presented by Johnson and Dungey also suggests that colder, or at least taller, first echo heights occur on days with more echoes, which is most likely to occur when cloud systems are organized.

Table D-4a. Percent of echoes forming completely above 0°C; completely below 0°C; or with tops below and bases above 0°C from the Thunderstorm Project (TSP), Project Whitetop (WTP) and METROMEX (MMX). (All based on TPS-10 3 cm radar).

	Group	N	Totally Warmer N	Totally Warmer %	Totally Colder N	Totally Colder %	Echo Base >0°C Echo Top <0°C N	Echo Base >0°C Echo Top <0°C %
TSP	Grew <1.5 km	47	26	55	7	15	14	30
	Grew 1.5-3 km	35	19	54	3	9	13	37
	Grew >3 km	30	18	60	2	7	10	33
	All	112	63	56	12	11	37	33
WTP	All[1]			50		10		40
MMX	All	4553	1825	40	326	7	2402	53
	Smallest	486	334	69				

Table D 4b. Mean height and temperature of first echo bases and tops from the Thunderstorm Project, estimated from growth curves and from METROMEX.

	Group	N	Tops km Ht_T	Tops °C T_T	Bases km Ht_B	Bases °C T_B	km Thickness	km Ht_{max}
TSP	A	41	4.9	-1.1	3.0	8.8	1.9	5.2
	B	30	4.3	0.8	2.7	10.2	1.6	6.4
	C	26	3.9	2.1	2.4	11.7	1.5	8.5
	All	97	4.4	0.35	2.7	10.0	1.7	
MMX	All	4553	4.6	-2.0	2.4	11.0	2.2	
	Rural	3413	4.6	-2.3	2.4	10.8	2.2	
	44 Days[2]	1950	4.7	-2.8	2.5	9.8	2.2	
	Smallest	486	3.7	+2.0[3]	3.0	6.4	0.7	

Sample size not given but it is believed to be 2000-2500, from 3 years of data.

2 A subsample of days on which clouds were most likely to have roots in the boundary layer.

3 Value of -2 given in Braham and Dungey (1978) is believed to have an error in sign.

Table D-5. Average heights (km) of first echo tops and bases observed in July-August 1973 with the Pere Marquette TPS-10 3 cm radar (27 dbz - minimum reflectivity), stratified by degree of organization of echoes.

First Echoes	N	Height (km) Top	Base	Thickness
All	811	5.7	2.5	3.2
Organized system*	426	6.5	3.0	3.5
Isolated system**	385	4.9	2.1	2.8

* Cold front, squall lines
**Squall zones, air mass storms, stationary fronts, warm fronts

Significant day-to-day differences in first echo heights also occurred in the Thunderstorm Project data (Fig. D-5, plotted from tabulations in Battan, 1953). Daily average temperatures of bases and tops differed by as much as 10 to 12°C. Although not entirely consistent, there was a suggestion of an inverse relationship between the height of the freezing level and the height of the first echo, (10 September 1947 is an exception). The distribution of FE bases and tops, for three stratifications on the daily mean echo base temperature, indicate that not only means but also the distributions are shifted (Fig. D-6). The narrowest distributions occurred with the warmest first echoes. In this category almost all of the first echoes originated entirely below the freezing level.

Supporting the importance of dynamic influences on cloud growth as indicated by the results in Changnon (1976, 1978) are numerical simulations of warm cloud processes, which have shown that the updraft velocity has an important effect on the height of the FE (Johnson and Dungey, 1978; Ochs and Semonin, 1979; Johnson, 1982b). With a stronger updraft, the echo top height is increased; the bases also occur at greater heights both because of the required time for development of large drops and because of a decrease in "sedimentation" of larger drops. Updraft speeds are known from in-situ measure to depend on cloud size and type and therefore will vary from cloud-to-cloud within a day as well as from day-to-day, with larger values probably occurring on days conducive to well organized echoes.

Growth and Duration of Radar Clouds

A goodly fraction of the first echoes in the studies described above exhibited little or no growth after initial detection. In Battan's (1953) sample of 112, 42% grew less than 5000 ft and only 27% grew more than 5000 ft. During 1960, the first year of Whitetop, Braham (1963, 1964) found

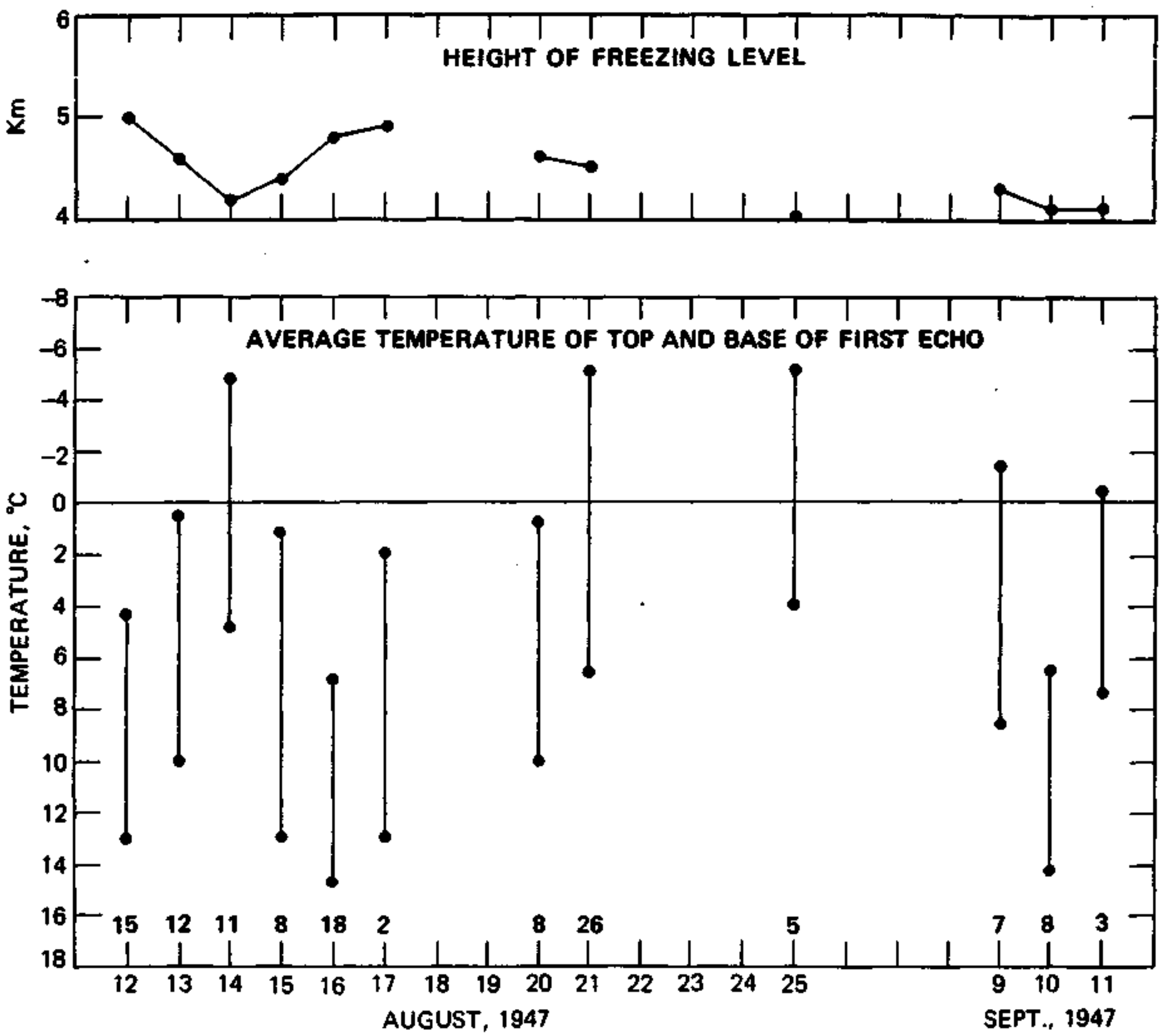

Figure D-5. The daily average temperatures at the tops and bases of first echoes and the heights of the freezing level, for 12 summer in Ohio. The number of first echoes on each day is given above the date. (Based on tabulations in Battan, 1953.)

THUNDERSTORM PROJECT, 1947
(After Battan, 1953)

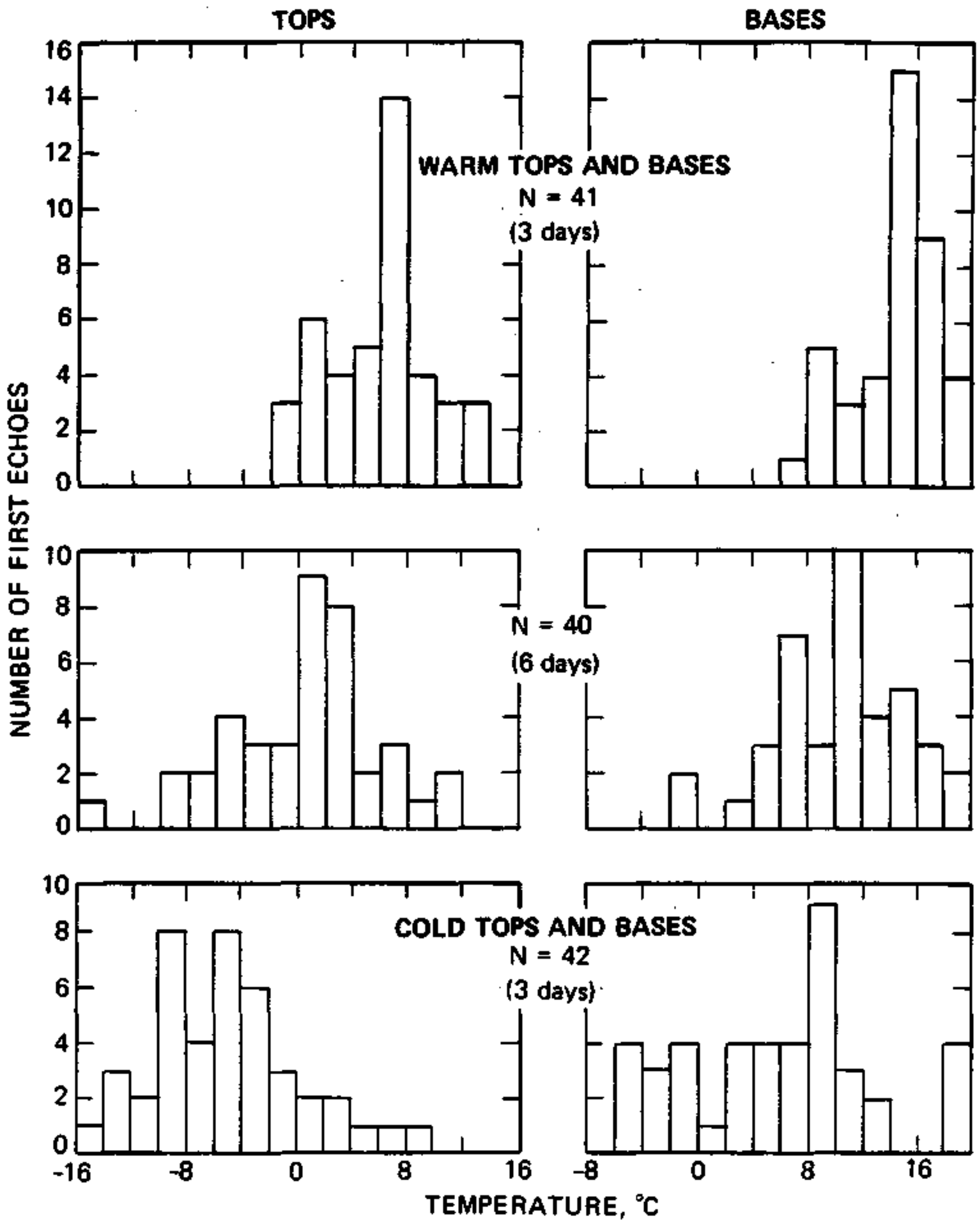

Figure D-6. Frequency distributions of the temperatures of first echoes and tops for three stratifications based on daily mean first echo temperature. (From tabulations in Battan, 1953.)

that only 38% of 749 single convective clouds showed subsequent grdwth with daily percentages varying from 19 to 54%. However the shallower first echoes in the METROMEX data set (i.e., those with depth of less than 1 km) were more likely to experience growth (the fraction was 68%). This tends to support the earlier contention that the scan interval may contribute to the broad distribution, although it is not likely (given the growth rates commonly observed) to be the major factor. Braham (1963) found, that in a Whitetop subsample of 600 single isolated, rain clouds (i.e., echoes that descended to the surface), only 44% of the echoes grew. Of these, only 22% grew 5000 ft or more. Although a few experienced growth for relatively long periods (15-30 minutes), most (86%) did so for less than 9 minutes. This seems to indicate that rain at the ground can be produced quickly and from rather small echoes.

The growth habit of 32 radar clouds studied during the Thunderstorm Project has been described as a series of steps, each one associated with new cell or turret development adjacent to the original cloud mass (Byers and Braham, 1949, Ch. 5). Successive turrets usually (but not always) grew taller than the previous ones. The growth period averaged about 16 minutes and was followed by a period of subsidence at the top of approximately 4 minutes. Thus the cell duration was of the order of 20 minutes which had been found to be typical of the active stages of the dynamic cells. A similar type of growth was reported in a case study from PEP data (Ackerman and Greenman, 1978). In this case, each successive cell (7 in all) was formed roughly upshear of an earlier one. Although none of these "feeder" cells reached the height of the original one (14 km), there was a successive increase in top height of these feeders from the initial one to a maximum growth for the third, fourth and fifth (all reaching 11 km), and the last two only reaching successively lower heights. Dynamic interaction between cells was suggested by the time history of the summit of the main echo, with descent of the original slowed or stopped as each new feeder cell developed. Growth periods of the individual cells were 10 to 15 minutes, and identifiable life histories extended up to 20 or 30 minutes, in general agreement with the Thunderstorm data.

Byers and Braham found that the average rate of growth of the top of single-turret clouds (only 8 cases) was about 5 m s^{-1} and that of the top of individual turrets of a multi-turreted echo about 5.5 m s^{-1}; in both cases the average growth period was around 16 minutes. However, they also presented data which indicates that growth rates are greater for radar clouds penetrating to greater altitudes, with average values of about 5.5 m s^{-1} for growth from 15,000 to 25,000 ft, and about 7.5 m s^{-1} for growth from 35,000 to 45,000 ft (Table D-6).

Changnon and Bigler (1957) found good correspondence between vertical growth of the cloud and of the top of the echo within them. For the four clouds for which there was adequate data, the average rate of growth for the echo was 5.1 m s^{-1} and for the cloud 3.8 m s^{-1}. The echo top was usually 3000 to 4000 ft below the cloud top and started to descend while the cloud was still growing.

Table D-6. Average rates of growth of radar clouds (after Byers and Braham, 1949).

	Height (103 ft)						
	15-19.9	20-24.9	25-29.9	30-34.9	35-39.9	40-44.9	45-49.9
Mean growth rate, ft s^{-1}	18	18	21	22	24	26	23
Mean growth rate, m s^{-1}	5.5	5.5	6.4	6.7	7.3	7.9	7.0
Number of clouds	109	273	305	257	157	87	50

Most of the convective rain in the Midwest is produced from relatively organized cloud systems, which frequently develop by union of two or more entities. Changnon (1976) examined the life histories of 565 rural radar echoes observed during the 1973 METROMEX field program, 23% of which were "merger echoes" i.e., independent echoes which joined. The "merger" echoes were found to have different characteristics at initiation and different histories as well. Echoes that later merged with another were taller at initiation, grew more and were longer-lived than those echoes which remained "isolated." Thirty-five percent of the merged echoes grew more than 3 km and only 6% of the more isolated echoes grew as much. Moreover, the maximum 5-minute growth rate of merged echoes was 4 times greater (8 m s^{-1}). The merged echoes also lasted, on average, 3 times longer (73 minutes versus 25 minutes for isolated echoes). The criteria used by Changnon in this two-way stratification allowed the "isolated" echo to incorporate adjacent echoes within 4 km without losing that status. Johnson and Dungey (1978), using more stringent criteria and a much larger sample from Whitetop found shorter durations. Sixty percent of the echoes they studied lasted less than 15 minutes, although a few lasted longer than 45 minutes. "Raining" echoes (i.e., those that reached the ground) had about the same duration as the whole population (62% lasted 15 minutes or less). On average, only 4 minutes elapsed between detection and rain on the ground, with 87% reaching the ground within 9 minutes.

Storm Organization

Organized storm systems in the Midwest tend to be lines of radar echoes. The individual cells in the line are not necessarily contiguous; they may number 4-5 during the early stages of the line formation, increasing to 40 or 50 when the line is mature. Changnon and Huff (1961) studied the characteristics of 196 lines of echoes detected by the CPS-9 3-cm radar during the growing seasons of 1954-55. Most lines were oriented SW-NE and moved eastward at an average speed of about 12 m s^{-1}. Their lifetimes ranged from less than an hour to 15 minutes with 58% lasting less than two hours. Lines associated with severe weather were more persistent: half of these lasted four hours or more. The average length and width of the lines were 187 km and 16.7 km respectively, but 34 lines associated with severe weather were, on the average, longer (263 km) and wider (20.4 km) than the others. (Averages were taken over space and time.) Byers and Braham also calculated dimensions of a smaller sample of lines from the Thunderstorm Project data, most of which were pre-cold frontal. The length of these lines averaged 262 km, approximately that of the severe weather lines of Changnon and Huff. The width quoted by Byers and Braham was the maximum along the line, 58 km, significantly larger than the average width given by Changnon and Huff. "Air mass" lines (those not associated with fronts) tended to be shorter (most were between 120 and 160 km) and the echoes tended to be well spaced. They were most frequently observed during the times of maximum heating between noon and midnight.

Byers and Braham also describe "the squall-line zone," most commonly pre-frontal, in which there are several lines that are not always distinguishable. These zones occur particularly during the day when the surface heating causes a "filling-in" of the individual lines by new or reincorporated cloud to the point where individual lines are not clearly separated. These zones were from 175 to 400 km wide and had lengths sometimes greater than 322 km. Most frequently there were 3 lines in the zone, though on occasion there were as many as 5.

REFERENCES

Ackerman, B., 1982: Low Level Convergence and the Prediction of Convective Precipitation. Final Report for Grant NSF ATM 78-08865, ISWS Contract Report 316, 128 pp.

Ackerman, B., and H. A. Greenman, 1978: The evaluation of a multicellular convective cloud mass: a case study, Preprint, Conf. on Cloud Physics and Atmospheric Electricity, Issaquah, 655-660.

Ackerman, B., R. C. Grosh, and R. Y. Sun, 1979: Assessing Midwest Cloud Characteristics for Weather Modification. Final Report, NSF ENV77-11527, 128 pp.

Battan, L. J., 1953: Observations on the formation and spread of precipitation in convective clouds. J. Meteor., 10(5):311-324.

Battan, L. J., and C. H. Reitan, 1957: Droplet size measurements in convective clouds. Artificial Stimulation of Rain, Proc. of the 1st Conference on the Physics of Cloud and Precipitation Particles, Woodshole, 1955, Pergamon Press, 84-191.

Braham, R. R., Jr., 1963: Project Whitetop, April 4, 1962 to April 3, 1963. Final Report to National Science Foundation, Grant NSF G-22419. Univ. Chicago Cloud Physics Lab., Chicago, IL, 36 pp.

Braham, R. R., Jr., 1964: What is the role of ice in summer rain-showers? J. Atmos. Sci., 21(6):640-645.

Braham, R. R., Jr., 1966: Final Report of Project Whitetop: Part I - Design of the Experiment; Part II - Summary of Operations. Univ. of Chicago, Dept. of Geophys. Sci., Chicago, IL, 156 pp.

Braham, R. R., Jr., L. J., Battan, and H. R. Byers, 1957: Artificial Nucleation of Cumulus Clouds. Meteorological Monographs, Vol. 2, No. 11, Cloud and Weather Modification: A Group of Field Experiments, 47-85.

Braham, R. R., Jr., and M. J. Dungey, 1978: A study of urban effects on radar first echoes. J. Appl. Meteor., 17(5):644-654.

Brown, E. N., and R. R. Braham, Jr., 1963: Precipitation particle measurements in cumulus congestus. J. Atmos. Sci., 20(1):23-28.

Byers, H. R., J. R. Sievers, B. J. Tujts, 1957: Distribution in the atmosphere of certain particles capable of serving as condensation nuclei. Artificial Stimulation of Rain, Proc. of the 1st Conf. on the Physics of Cloud and Precipitation Particles, Woodshole, 1955, Pergamon Press, 47-72.

Byers. H. R., and R, R, Braham, Jr., 1948: Thunderstorm structure and circulation. J. Meteor., 5(3):71-86.

Byers, H. R., 1949: The Thunderstorm, U.S. G.P.O., Washington, DC, 287 pp.

Changnon, S. A., Jr., 1973: Precipitation Enhancement Program for Illinois. Proc. ASCE, 99:215-226.

Changnon, S. A., Jr., 1976: Effects of urban areas and echo merging on radar echo behavior. J. Appl. Meteor., 15(6):561-570.

Changnon, S. A., Jr., 1978: Vertical characteristics and behavior of radar echoes. Summary of METROMEX, Vol. 2: Causes of Precipitation Anomalies; ISWS Bull. 63, 274-279.

Changnon, S. A., Jr., 1981: Introduction. METROMEX: A Review and Summary, S. A. Changnon, Ed., Meteor. Monog. 18(40), 1-16.

Changnon, S. A., Jr., and S. G. Bigler, 1957: On the observation of convective clouds and radar-precipitation echoes within them. Bull. Amer. Meteor. Soc, 38, 279-282.

Changnon, S. A., Jr., and F. A. Huff, 1961: Studies of Radar-Depicted Precipitation Lines. Scientific Report 2, Contract AF 19(604)-4940, ISWS Contract Publication 21, 63 pp.

Changnon, S. A., Jr., and G. M. Morgan, Jr., 1976: Design of an Experiment to Suppress Hail in Illinois. ISWS Bull. 61, 194 pp.

Draginis, M., 1958: Liquid water content within convective clouds. J. Meteor., 15(6):481-485.

Dytch, H. E., 1977: Urban influences on Cloud Microstructure Downwind from St. Louis, Missouri (Project METROMEX). Univ. Chicago Cloud Physics Lab. Tech. Note 51, Chicago, 119 pp.

Huff, F. A., and S. A. Changnon, Jr., 1966: Development and Utilization of Illinois Precipitation Networks. IASH, extract of Publication 67:97-125.

Huff, F. A. and S. A. Changnon, Jr., 1977: A hydrometeorological research program. AWRA Water Resources Bulletin, 13(3):573-581.

Johnson, D. B., 1976: Ultragiant urban aerosol particles. Science, 194: 941-942.

Johnson, D. B., 1980: PACE microphysical studies. Precipitation Augmentation for Crops Experiment (PACE) - Pre-Experiment Studies. Final Rpt. NOAA Contract NA 79 RAC00114, S. A. Changnon, Jr., and R. G. Semonin, Ed., 40-63.

Johnson, D. B., 1982a: Geographical variations in cloud base temperature, Proc. Conf. on Cloud Physics, Chicago, Nov. 1982, 187-189.

Johnson, D. B., 1982b: The role of giant and ultragiant aerosol particles in warm rain initiation. J. Atmos. Sci., 39:448-460.

Johnson, D. B., and M. J. Dungey, 1978: Microphysical interpretation of radar first echoes. Preprint, 18th Conf. on Radar Meteorology, Atlanta, 117-120.

Koenig, L. R., 1962: Ice in the Summer Atmosphere: An Inquiry into Its Structure, Genesis and Metamorphosis. Univ. Chicago Cloud Physics Lab. Tech. Note 24, Chicago, 176 pp.

Koenig, L. R., 1963: The glaciating behavior of small cumulonimbus clouds. J. Atmos. Sci., 20(1):29-47.

Ochs, H. T., and R. G. Semonin, 1979: Sensitivity of a cloud micro-physical model to an urban environment. J. Appl. Meteor., 18(9): 1118-1129.

Semonin, R. G., 1978: Cloud Characteristics. Summary of METROMEX, Vol. 2, Causes of Precipitation Anomalies. ISWS Bull. 63, 236-239.

Semonin, R. G., D. W. Staggs, and G. E. Stout, 1964: Cloud Electrification Studies in Illinois. Final Report, NSF G-17038. ISWS Contract Report 47, 24 pp.

2. Assessment of Problems, Successes, and Failures in Past Weather Modification Projects

Chin-Fei Hsu

Introduction

A comprehensive weather modification project, Precipitation Augmentation for Crops Experiment (PACE), has been undertaken by the Illinois State Water Survey to determine whether agriculturally useful increases in summer convective rainfall can be produced in the Midwest. As part of this research, a literature survey of relevant subjects and integration of statistical methods are being carried out in the pre-experimental phase, with primary emphasis on establishing the salient points of success and failure in the design and performance of past weather modification projects and thereby, to avoid past mistakes and take advantages of useful information developed in those projects. The projects reviewed included many major randomized weather modification since the 1950's, with focus on the summertime convective rainfall modification (Table D-7).

The precision of an experiment depends on size and shape of the target, unit of observations, predictor variables, method and rate of seeding, seeding agent used, location and topographic feature of the target, methods of selecting suitable occa'sions, and synoptic conditions.

Among subjects being studied and evaluated are: sampling and/or experimental units; design features used to insure separation of seeded from unseeded effects; cloud physics parameters measured and used in evaluation; seeding techniques (method and place of dispension, agent and rates); responses variables used in the evaluation; statistical methods employed in evaluation (including transformation and stratification of data, covariates used, significance determinations, etc.); and investigation of extra-area effects.

Special attention was given to randomization procedures, 'blindness' of project personnel in implementing and executing randomization plan, as well as to key project questions unanswered, major problems encountered in the project, and criticism of the methodology. Summary of the reviewed are presented in the following sections. Details of the projects are included in the appendix.

Experimental Unit, Design and Implementation

The experimental unit (e. u.) used in the projects reviewed included single cloud, cloud pair, convective rainband, day or 24-hour, 2-day, and 12-day (Table D-8).

Table D-7. Features of Projects Reviewed.

Project	Where/Terrain	When	Specific
Australian Isolated Cumulus Cloud Proj.	south Australia	10/1962 to 2/1965	
Stormfury Proj.	Caribbean Ocean	7/28 to 8/10, 1965	dynamic seeding
Florida Cumulus Proj.	south Florida	May-June, 1968	dynamic seeding
FACE 1	south Florida	summer of 1970,71, 73,75,76	dynamic seeding
FACE 2	south Florida	June-Aug, 1978-80	dynamic seeding
HIPLEX-1	central Montana	summer of 1976-79 (pre-experim.) and 1979-80 (phase 1)	static seeding
Israeli 1 Exp.	semi-orographic	Oct-Apr, 1961-67	static seeding
Israeli II Exp.	semi-orographic	Nov-Apr, 1969-75	static seeding
North Dakota Pilot Proj.	North Dakota	summer of 1969-72	rain/hail
Santa Barbara-2	south California, orographic	winter of 1967-71 (phase 1); 1971-74 (phase 2)	
Proj. Sierra Cumulus	near San Joaquin River, Calif., orographic	summer of 1966-8	
Tasmania Project	Australia, 2500-5000 ft	1964,66,68,70	
Whitetop Project	south Missouri and north Arkansas	summer of 1969-65	

Table D-8. Design of Projects Reviewed.

Proj.	Design(1)	Sampling	Unit Exper.
AUSTR	un-restricted	12 min to 1 hr after seeding	
STORM	block (3:2)		single cloud
FLCDP	block (2:1)		single cloud
FACE1	complete rand in 1970, 71,73; variable block in 75; restricted in 76		day
FACE2	restricted (4 schemes)(2)		day
HPLX1	2-stage block(3)	single cloud	single cloud
ISRL1	crossover	rainy day	day(4)
1SRL2	unrestricted	rainy day	24 hr
NDPP	periodic (8 days;3:1) (5)	12 hr	2 days
SNBB2	unrestricted		rain-band
SEACD	restricted		single cloud
TASMN	periodic (12 days)(6)	day	12 days
WHITE	unre8tricted(7)	14 hr	day

(1) The seed/no seed ratio for block design is enclosed in parentheses.
(2) Mean layer vector wind from West Palm Beach morning sounding was used to selected 1 of 4 schemes (Barnston et al., 1983).
(3) rand. block of size 2 was used in 1979; 2-stage block (6:4) was used in 1980
(4) Week was used as e.u. in earlier part of 1961; day was defined as 2000-2000 in 1961-64, and 0800-0800 in 1965-67.
(5) One out of four 2-day block was selected for non-seeding.
(6) One of the 2 consecutive 12-day was selected for seeding.
(7) Target size varied.

Most of the projects using single cloud as e. u. selected non-seed cloud that occurred at time different from that of seeded clouds. In addition, clouds selected for study in HIPLEX-1 must be separated by at least 15 km if they had to be separated by 20 to 70 miles (Williams and Lehrman, 1970).

Two of the projects, the Florida Cumulus Project (Simpson et al., 1970) and the Project Sierra Cumulus (Williams and Lehrman, 1970) employed "equivalent cloud pair" as e. u., which consisted of two clouds occurring approximately about the same time. The clouds pairs were selected by visual inspection for criteria of size, growth and spatial separation. Minimum separation between clouds in the pair was 20 miles in the Project Sierra Cumulus. In yet another project, the Stormfury Project, nearby unseeded clouds were "later" paired with seeded clouds for comparison if they occurred within one hour of each other and were less than 50 miles apart (Simpson et al., 1967).

The Santa Barbara-2 project used convective "rainband" as e. u. (Elliott et al., 1971), which had a variable length of time.

Unrestricted randomized design (or complete randomized design) was often used in earlier projects, including the Australian Isolated Cumulus Project (Bethwaite et al., 1966), FACE 1, Israeli II, Santa Barbara 2 and Whitetop Projects. Restricted randomized design was used in FACE 1 and 2, and Project Sierra Cumulus. Periodic design was used in the North Dakota Pilot project (Koscielski and Dennis, 1976), and the Tasmania Project (Smith et al., 1977). Randomized block design was used in FACE 1, HIPLEX-1, and Stormfury Projects (Table D-8).

Control area was used for comparison in the Israeli II, Santa Barbara-2 and Tasmania (3 controls) projects. The Whitetop project used a moving target-control approach. Separation between the target and control was 20 mile in Israeli II, 11 mile in Santa Barbara-2, and variables in Tasmania.

During the course of FACE 1 , three designs were employed - complete randomized, variable block, and restricted designs. In FACE 2, one of the four restricted randomized schemes were selected for use depending on the mean layer vector wind observed by the West Palm Beach morning sounding. The block design used in HIPLEX-1 was a two-stage design to ensure doubles-blindness (Smith et al., 1984).

Projects which terminated before obtaining the planned sample size included FACE 2, HIPLEX-1, and phase 2 of the Santa Barbara 2 Project.

Cloud models, notably in the Florida and North Dakota projects, were used in deciding seedability (Table D-9); while other projects used a combination of sounding, radar or aircraft measurements to decide suitability. A unique approach was employed in HIPLEX-1 that a computer onboard an aircraft made the decision of cloud seedability after being fed with relevant measurements.

Table D-9. Cloud Physics Parameters.

Proj.	Single Cloud/ Pair	Cloud Used	Seedability Criteria	Who Decide
ADSTR	yes/no	isolated cumulus with flat and substantial base	cloud depth > 1000m, top temp. < -5 C, base < 3500m, no visible rain within 30 km, at least 30 km apart from other clouds	'experimenter' on board the seeding aircraft
STORM	yes/no (1)	tropical cloud	cloud top between 17-26000 ft	
FLCUP	yes	single cloud	used EML cumulus model	EML personnel
FACE1	yes/yes(2)			scientist
FACE2		hard caulifolwer head cloud	EML suitability index > 1.5, updraft > 5m per sec, cloud water > lg per cubic meter, cloud top between 18-23000 ft	
HPLX1	yes/no	individual small, semi-isolated congestus cloud without radar-detectable echo	cloud base temp > 0 C, top temp between -6 to -12 C, l-km-average liquid water content > .5g per cubic meter, updraft > 1 m/sec	computer on board the cloud physics aircraft
ISRL1	no/no		cloud top temp <= -5 C, base < 2 km	
ISRL2	no/no	cold front or post-frontal cloud	same as ISRL1	
NDPP			used 1D steady-state cloud model	
SNBB2			used radar	
SRACU	yes/yes (3)	cumulus	cloud forecasted and occurred by 1400 PDT, cloud depth > 5500 ft	
TASMN		solid, compact stratus or cumulus clouds	cloud top contains supercooled water > -5 C (stratus) or < -10 C (cumulus), depth > half terrain clearance	
WHITE			used 0600 CDT soundings at Columbia and Little Rock, wind at 400 msl from between 170 and 340 degree	

(1) Unseeded clouds were later paired with seeded clouds, if within 1 hour and less than 50 miles.
(2) See Simpson et al (1975) for details of pair definition.
(3) Pair was determined by visual observations of cloud size, growth, and separation (>20 miles).

Usually, decision of seeding was revealed only after a unit was declared as suitable. A "randomizer" on board the seeding aircraft opened an envelope for random plan in Australian, FACE 1, Stormfury, and Tasmania projects; while ground personnel opened the envelope in FACE 2 and HIPLEX-1. The "randomizer" also served as "seeder" to dispense seeding material in the Australian and FACE 1 projects.

The time that project scientists learned of the random (seeding) decision was varies. They could be before the seeding operation (the North Dakota Pilot Project), by the end of a unit (FACE 1 in 1970-1971), after each seeding flight (HIPLEX-1) at the end of season (FACE 1 in 1972-1976), after completing all data processing (Australian project and Santa Barbara 2), or one year after project completed (FACE 2).

Most projects used silver iodide as seeding agent except HIPLEX-1, in which only dry ice was used. Dry ice was also used in Project Sierra Cumulus in addition to silver iodide. In FACE 1 (1976 only), FACE 2 and HIPLEX-1, a placebo was used for nonseed unit for blindness. A "noise" device was used during seeding in HIPLEX-1 for additional blindness. The flares used in FACE 1 were changed to a new type after August 1975. Usually one aircraft was used for delivering seeding material; three aircraft were used for seeding in FACE 2 and Whitetop projects. One of the FACE 2 aircraft also served as cloud physics aircraft.

Ground generator was the only seeding device used in phase 1 of the Santa Barbara Project. Forty-two ground generators were employed to supplement aircraft in the Israeli II Project. One (non-seeding) aircraft was used for cloud physics measurements in HIPLEX-1; while 4 additional aircraft were used in Stormfury Project for cloud measurements.

For most projects, seeding usually took place at cloud top; a few projects seeded at cloud base level, including Israeli I and II, phase 1 of NDPP, and Whitetop.

Evaluation and Statistical Techniques

Radar-estimated rainfall was the main response variables used in the evaluation of the Florida Cumulus Project, FACE 1 and 2, NADP, and Project Sierra Cumulus (Table D-10). The radar rain was adjusted by supplementary raingage networks in the Florida Cumulus Project and the two FACE projects (Simpson et al., 1971; Simpson et al., 1975). Rainfall estimated from raingage network was the main response variables in the Israeli I and II, Santa Barbara 2, Tasmania, and Whitetop projects. Cloud base rainfall was the response variables in the Australian project. Cloud top height was used as the main response variable in the Stormfury Project. The HIPLEX-1 employed 12 primary and 7 secondary response variables, which were derived from radar/aircraft measured variables (Smith et al., 1984).

The most popular statistical test used in the project evaluation was the Wilcoxon-Mann-Whitney test. The double ratio or single ratio were also frequently used. The t-test was mostly used in the Florida projects.

Table D-10. Evaluation and Statistics Techniques.

Proj.	Response Var.	Statistics Techniques	Seeding Effect
AUSTR	rainfall at cloud base	rank sum test	sig. at 5% for larger burner
STORK	cloud top height, stability	none, visual observation	two-third of seeded clouds grow larger(l)
FLCDP	radar rainfall	t-test, Wilcoxon test, normal score test	100% (.10 level)
FACE1	radar rainfall	t-test after regression, Wilcoxon test	50% increase for floating target (1)
FACE2	radar rainfall	analysis of covariance	23% increase for floating target
HPLX1	12 promary and 7 secondary cloud/ radar vars.	multi-response permutation procedure	10 C rainfall increased more than 300% (.19 level); ice concentration significantly larger 2- and 5-minutes after seeding
ISRL1	raingage rainfall	Wilcoxon test, ratio (re-ran)	15% increase (.01 level) (1)
ISRL2	raingage rainfall	double ratio (re-ran)	13% increase (.03 level)
NDPP	radar rainfall	several tests	non-significant overall (1)
SNBB2	raingage rainfall	several tests	sig. at 5% for phase 1
SRACD	radar rainfall	chi-square test, McNemar test	sig. at 0.1% level
TASMN	raingage rainfall	double ratio, regression	30% increase (5%) in autumn, 5-10% increase in summer (1)
WHITE	raingage/radar rainfall	Wilcoxon test	30-40% less rain (5% level) (1)

(1) Possible multiplicity problem.

Bayesian inference was first used in FACE 1 (Simpson et al., 1975). The multi-response permutation procedure (MRPP) was used In HIPLEX-1 (Mielke et al., 1984).

Re-randomization procedure was used in NDPP, Israeli I and II (Gabriel, 1970; Gagin and Neumann, 1981) evaluations; however, the Monte Carlo procedure in NDPP was questionable (Biondini, 1977). In HIPLEX-1, FACE 2, and the two Israeli projects, the statistical techniques were specified in advance of seeding operations (Mielke et al., 1984; Woodley, et al., 1983; Gabriel, 1970).

The evaluation in Israeli I and II was restricted to days in which a measurable rain fell in at least one of the 3 stations ins a designated buffer area (Gabriel, 1970; Gagin and Neumann, 1981).

Among the projects reviewed, positive seeding effects (rainfall increases, more cloud growth, or more ice concentration) were reported in all the projects except the North Dakota Pilot Project, phase 2 of Santa Barbara 2, the Whitetop Project (Table D-10). The results of FACE 1 showed a 50% rain increase for the floating targets; however, the overall increase was not statistically significant.

Discussion

Two main criticisms concerning statistical evaluation of the projects are (1) problems of multiplicity, and (2) "subjective judgment" in making decisions about seeding operations. The multiplicity problems were caused mostly because of many analyses performed on the data (mainly various stratifications) without prior specification in the design. This rendered the computed significance levels less conclusive than they appeared (WMAB, 1978). Projects which might have the multiplicity problems include FACE 1, Israeli I, NDPP, Stormfury, Tasmania, and Whitetop.

Examples of "subjective judgment" include the posterior definition of "floating target" in FACE 1, and the choice of deciding to seed rain or hail in the NDPP operation. Concern has been expressed whether data handling persons are allowed to know the seed/nosed random plan before processing any data (WMAB, 1978). Questions were expressed on the positive seeding effect of the Santa Barbara 2 results (WMAB, 1978).

In FACE 1, the large rainfall increases was largely due to rainfall on 5-6 seeded days. The rainfall increase in FACE 1 was re-analyzed by Nickerson (1979) using neighboring area as controls and claimed to be due to natural variability; although the neighboring area might have been contaminated by seeding (Flueck et al., 1981). The failure of FACE 2 to confirm the results of FACE 1 was shown to be due to the unusually heavy rainfall on one "unseed" day (Woodley et al., 1983).

Because of the great variability of natural precipitation, a typical experiment may require a large number of observations to detect possible experimental effects, usually over a period of several years. The longer the period of experimentation, the more difficult it is to maintain a standard set of experimental procedures. The personnel may change, the operational methods may be altered as new technology becomes available, administrative (or political) constraints may vary, etc.

An exploratory experiment, leading to the identification of positive or negative effect, must be richer than the classical experiment and may involve seeding in a variety of conditions. Changes in operations are often unavoidable, and even desirable during an exploratory phase, but should not occur in a confirmatory phase.

Another difficulty in evaluation include the problem of "zero precipitation." Solutions to this problem involve fitting the data by using gamma or similar distributions: 1) mixture of gamma distribution and a degenerated point distribution, 2) truncated gamma distribution at a pre-assigned value, 3) truncated gamma distribution with estimated cutoff point.

The use of transformation on the data set need a 'conceptual chance mechanism' to back it up (Neyman and Scott, 1967).

A non-randomized single cloud project took place in central Pennsylvania by dropping CO_2 pellets from cloudtop (Davis and Hosier, 1967). Two aircraft were employed, one for seeding, the other for cloud measurement. Neighboring cloud with similar 'environment' was used as control cloud. The project was not reviewed in this report.

REFERENCES

Barston, A. G., W. L. Woodley, J. A. Flueck, and M. H. Brown, 1983: The Florida Area Cumulus Experiment's second phase (FACE-2). Part I: the experimental design, implementation and basic data. J. Appl. Meteor., 22(9), 1504-1528.

Bethwaite, F. D., E. J. Smith, J. A. Warburton, and K. J. Heffernan, 1966: Effects of seeding isolated cumulus clouds with silver iodide. J. Appl. Meteor., 5(4), 513-520.

Biondini, R., 1977: Review of the North Dakota Pilot Project. Tech. Report, NCAR-7100-77/1, Boulder, CO, 29 pp.

Bradley, R. A., S. S. Srivastava, and A. Lanzdorf, 1977: Data Summarization in a Weather Modification Experiment: I. A Response Surface Approach. Tech. Report M417, Dept. Statist., Florida State Univ., Tallahassee, FL.

Bradley, R. A., S. S. Srivastava, and A. Lanzdorf, 1979: Some approaches to statistical analysis of a weather modification experiment. Commun. Statist. Theor. Meth., 1049-1081.

Braham, R. R., Jr., 1966: Project Whitetop: Part I - Design of the Experiment, Part II - Summary of Operations. Final Report, Dept. of Geophys. Sci., University of Chicago, 156 pp.

Calvin, L. D., 1969: Review of Vol. V. Weather modification experiments, Proc. of Fifth Berkeley Symp. on Math. Statist. and Prob., (Le Cam and Neyman, eds.), J. Amer. Statist. Assoc, 64, 1085-1087.

Cooper, W. A., 1981: Characteristics of seeded and unseeded HIPLEX-1 clouds. Eighth Conf. on Inadv. and Plann. Wea. Mod., Oct. 5-7, Reno, Amer. Meteor. Sco., 120-121.

Cooper, W. A., E. W. Holroyd, J. R. Middleton, and A. B. Super, 1981: Response variables of the HIPLEX-1 experiment. Eighth Conf. on Inadv. and Plann. Wea. Mod., Oct. 5-7, Reno, Amer. Meteor. Soc, 118-119.

Cooper, W. A., and R. P. Lawson, 1984: Physical interpretation of results from the HIPLEX-1 experiment. J. Appl. Meteor., 23(4), 522-523.

Cunning, J. B., Jr., 1976: Comparison of the Z-R relationships for seeded and nonseeded Florida cumuli. J. Appl. Meteor., 15, 1121-1125.

Davis, L. G., and C. L. Hosier, 1967: The design, execution and evaluation of a weather modification experiment. Proc. Fifth Berkeley Symp. on Math. Statist. and Prob., V, 253-269.

Decker, W. L., and P. T. Schickedanz, 1966: Project Whitetop: Part IV - A Summary of the Rainfall Analysis. Final Report, Soils Department, University of Missouri, Columbia, 362 pp.

Decker, W. L., and P. T. Schickedanz, 1967: The evaluation of rainfall records from a five year cloud seeding experiment in Missouri. Proc. Fifth Berkeley Symp. on Math. Statist. and Prob., V, 55-63.

Dennis, A. S., J. R. Millers, and D. E. Cain, 1974: Effects of cloud seeding on growing season rainfall in North Dakota. Fourth Conf. on Wea. Mod., Amer. Meteor. Soc, 484-489.

Dennis, A. S., J. R. Miller, E. I. Boyd, and D. E. Cain, 1975: Effect of Cloud Seeding on Summertime Precipitation in North Dakota. Report 75-1, Inst. Atmos. Sci., South Dakota School of Mines and Technology, Rapid City, 97 pp.

Dennis, A. S., P. W. Mielke, K. J. Berry, P. L. Smith, A. B. Super, and B. A. Silverman, 1981: Preliminary HIPLEX-1 results derived by mulit-response permutation procedures (MRPP). Eighth Conf. on Inadv. and Plann. Wea. Mod., Oct. 5-7, Reno, Amer. Meteor. Soc, 122-123.

Elliott, R. D., and J. R. Thompson, 1970: Santa Barbara pyrotechnic seeding device test program 1967-68 and 1968-69 seasons. Second Nat. Conf. on Wea. Mod., Amer. Meteor. Soc, Santa Barbara, 6-9, April, 76-80.

Elliott, R. D., P. St.-Amand, and J. R. Thompson, 1971: Santa Barbara pyrotechnic cloud seeding test results 1967-80. J. Appl. Meteor., 10(4), 785-795.

Elliott, R. D., and K. J. Brown, 1971: The Santa Barbara II project - downwind effects. Proc. Internat. Conf. on Wea. Mod., Canberra, Australia, 6-11 Sept., 179-184.

Flueck, J. A., 1971: Project Whitetop: Part V - Statistical Analyses of the Ground Level Precipitation Data. Final Report, Cloud Physics Lab., University of Chicago, 294 pp.

Flueck, J. A., W. L. Woodley, R. W. Burpee, and D. 0. Stram, 1981: Comments on "FACE rainfall results: Seeding effect or natural variability?" J. Appl. Meteor., 20(1), 98-107.

Gabriel, K. R., Y. Avichai, and R. Steinberg, 1967: A statistical investigation of persistence in the Israeli artificial rainfall stimulation experiment. J. Appl. Meteor., 6(2), 323-325.

Gabriel, K. R., 1967a: Recent results of the Israeli artificial rainfall stimulation experiment. J. Appl. Meteor., 6(2), 437-438.

Gabriel, K. R., 1967b: The Israeli artificial rainfall stimulation experiment. Proc. Fifth Berkeley Symp. on Math. Statist. and Prob., 91-113.

Gabriel, K. R., 1970: The Israeli Rainmaking Experiment 1961-67. Final Statistical Tables and Evaluation. Report, Hebrew, Jerusalem, 47 pp.

Gabriel, K. R., and J. Nuemann, 1978: A note of explanation on the 1961-67 Israeli rainfall stimulation experiment. J. Appl. Meteor., 17, 552-554.

Gagin, A., and J. Neumann, 1976: The second Israeli cloud seeding experiment—The effect of seeding on varying cloud population. Second WMO Sci. Conf. on Wea. Mod., Boulder, CO, 195-204.

Gagin, A., and J. Neumann, 1981: The second Israeli randomized cloud seeding experiment: evaluation of the results. J. Appl. Meteor., 20(11), 1301-1311.

Gleeson, T. A., 1977: Data Summarization in a Weather Modification Experiment: II. Concomitant variables. Tech. Report M419, Dept. Statist., Florida State University, Tallahassee, FL.

Hartzell, C. L., and T. C. Jameson, 1981: Identifying sounding predictor variables for HIPLEX-1 cumulus congestus clouds. Eighth Conf. on Inadv. and Plann. Wea. Mod., Oct. 5-7, Reno, Amer. Meteor. Soc, 98-99.

Koscielski, A., and A. S. Dennis, 1976: Comparison of first radar echoes in seeded and unseeded conveotive clouds in North Dakota. J. Appl. Meteor., 15, 309-311.

Lawson, R. P., 1981: The ice/water budget in seeded HIPLEX-1 clouds. Eighth Conf. on Inadv. and Plann. Wea. Mod., Oct. 5-7, Reno, Amer. Meteor. Soc, 110-111.

Lawson, R. P., A. B. Super, and J. T. McPartlad, 1981: Cloud selection, treatment procedures, and seeding verification in HIPLEX-1 test clouds. Eighth Conf. on Inadv. and Plann. Wea. Mod., Oct. 5-7, Reno, Amer. Meteor. Soc, 116-117.

Lovasich, J. L., J. Neyman, E. L. Scott, and J. A. Smith, 1969: Wind directions aloft and effects of seeding on precipitation in the Whitetop experiment. Proc. Nat. Acad. Sci., 64, 810-817.

Lovasich, J. L., J. Neyman, E. L. Scott, and M. A. Wells, 1971: Further studies of the Whitetop cloud-seeding experiment. Proc. Nat. Acad. Sci., 68, 147-151.

Mielke, P. W., Jr., 1978: On criticism concerning the Israeli experiment. J. Appl. Meteor., 17, 555-556.

Mielke, P. W., K. J. Berry, A. S. Dennis, P. L. Smith, J. R. Miller, Jr., and B. A. Silverman, 1984: HIPLEX-1: statistical evaluation. J. Appl. Meteor., 23(4), 513-522.

Miller, J. R., A. S. Dennis, D. E. Cain, and J. H. Hirsch, 1975: Precipitation Management Potential in Western North Dakota as Rescaled by Radar Echoes and Cloud Models. Report 75-4, Inst. Atmos. Sci., South Dakota School of Mines and Technology, Rapid City, 163 pp.

National Academy of Sciences, 1973: Weather and Climate Modification: Problems and Progress. Committee on Atmos. Sci., NAS, Washington, D.C., 258 pp.

Neyman, J., and E. L. Scott, 1967: Some outstanding problems relating to rain modification. Proc. Fifth Berkeley Symp. on Math. Statist. and Prob., 293-326.

Neyman, J., E. L. Scott, and J. A. Smith, 1969a: Areal spread of the effect of cloud seeding at the Whitetop experiment. Science, 163, 1445-1449.

Neyman, J., E. L. Scott, and J. A. Smith, 1969b: Whitetop experiment. Science, 165, 618.

Neyman, J., 1977: Experimentation with Weather Control and Statistical Problems Generated by it. Proc. Symp. on Applications of Statistics, P. R. Krishnaiah (ed.), North Holland, 1-25.

Nickerson, E. C., 1979: FACE rainfall results: seeding effect or natural variability. J. Appl. Meteor., 18(9), 1097-1105.

Nickerson, E. C., 1981: Reply-the FACE-1 seeding effect revisited. J. Appl. Meteor., 20(1), 108-114.

Sax, R. I., 1974: On the microphysical differences between populations of seeded vs. non-seeded Florida cumuli. Fifth Conf. on Wea. Mod., 65-68.

Sax, R. I., J. Thomas, M. Bonebrake, and J. Hallett, 1979: Ice evolution within seeded and nonseeded Florida cumuli. J. Appl. Meteor., 18(2), 203-214.

Schickedanz, P. S., and F. A. Huff, 1970: An evaluation of downwind seeding effects from the Whitetop experiment. Preprints of Second Nat. Conf. on Wea. Mod., Amer. Meteor. Soc, 180-185.

Scott, E., 1978: Data Summarization in a Weather Modification Experiment: II. A Multivariate Analysis. Tech. Report M442, Dept. Statist., Florida State University, Tallahassee, FL.

Simpson, J., R. H. Simpson, J. R. Stinson, and J. W. Kidd, 1966: Stormfury cumulus experiments: preliminary results 1965. J. Appl. Meteor., 5(4), 521-525.

Simpson, J., 1967: An experimental approach to cumulus clouds and hurricanes. Weather, 22(3), 95-114.

Simpson, J., G. W. Brier, and R. H. Simpson, 1967: Stormfury cumulus seeding experiment 1965: statistical analysis and main results. J. Atmos. Sci., 24, 508-521.

Simpson, J., W. L. Woodley, H. A. Friedman, T. W. Slusher, R. S. Scheffee, and R. L. Steele, 1970: An airborne pyrotechnic cloud seeding system and its use. J. Appl. Meteor., 9(1), 109-122.

Simpson, J., W. L. Woodley, A. H. Miller, and G. F. Cotton, 1971: Precipitation resutls of two randomized pyrotechnic cumulus seeding experiments. J. Appl. Meteor., 10, 526-544.

Simpson, J., W. L. Woodley, A. R. Olsen, and J. C. Eden, 1973: Bayesian statisticts applied to dynamic modification experiments on Florida cumulus clouds. J. Atmos. Sci., 30, 1178-1190.

Simpson, J., J. C. Eden, and A. R. Olsen, 1975: On the design and evaluation of cumulus modification experiments. J. Appl. Meteor., 14, 946-958.

Simpson, J., 1980: Downdrafts as linkages in dynamic cumulus seeding effects. J. Appl. Meteor., 19(4), 477-487.

Silverman, B. A., 1979: The Design of HIPLEX-1. U.S. Dept. of Interior, Office of Atmospheric Resource Management, 217 pp.

Smith, E. J., E. E. Adderley, L. G. Veitch, and E. Turton, 1971 : A cloud-seeding experiment in Tasmania. Proc. Internat. Conf. on Wea. Mod., Canberra, Australia, 6-11, Sept., 91-96.

Smith, E. J., L. G. Veitch, D. E. Shaw, and A. J. Miller, 1977: A Cloud-Seeding Experiment in Tasmania, 1964-1970. Final Report, Part 1, Desoription and Main Results. Div. of Cloud Physics, CSIRO, Australia, 120 pp.

Smith, P. L., A. S. Dennis, B. A. Silverman, A. B. Super, E. W. Holroyd III, W. A. Cooper, P. W. Mielke, Jr., K. J. Berry, H. D. Orville, and J. R. Miller, Jr., 1983: HIPLEX-1: experimental design and response variables. J. Appl. Meteor., 23(4), 497-512.

Thompson, J. R., K. J. Brown, and R. D. Elliott, 1975: Santa Barbara Convective Band Seeding Test Program. Final report, Tech. Publ. 5804, Naval Weapons Center, China Lake, CA.

Tsonis, A. A., G. L. Austin, and S. Lovejoy, 1984: A proposal for a new statistical and technique development for the design and evaluation of cloud seeding experiments. Atmos.-Ocean, 22(1) , 67-82.

Weather Modification Advisory Board, 1978: The Management of Weather Resources. Volume II, "The Role of Statistics in Weather Resources Management." Report of the Statistical Task Force, Dept. of Commerce, Washington, D.C.

Williams, M. C., and D. E. Lehrman, 1970: Sierra cumulus. Second Nat. Conf. on Wea. Mod., Amer. Meteor. Soc, Santa Barbara, 6-9 April, 81-86.

Wisniewski, J., C. R. Cotton, and R. I. Sax, 1974: Tracing silver iodide in the south Florida area. Fifth Conf. on Wea. Mod., 73-78.

Wisniewski, J., and R. I. Sax, 1979: Silver concentration in rainwater from seeded and nonseeded Florida cumui; 1973-1975 results. J. Appl. Meteor., 18(8), 1044-1055.

Woodley, W. L., 1970a: Precipitation results from a pyrotechnic cumulus seeding experiment. J. Appl. Meteor., 9(2) , 242-257.

Woodley, W. L., 1970b: Rainfall enhancement by dynamic cloud modification. Science, 170, 127-132.

Woodley, W. L., A. R. Olsen, A. Herndon, and V. Wiggert, 1975: Comparison of gage and radar methods of convective rain measurement. J. Appl. Meteor., 14(5), 909-928.

Woodley, W. L., J. Simpson, R. Biondini, and G. Sambataro, 1976: On NOAA's Florida Area Cumulus Experiment (FACE) main rainfall results 1970-1975. Second WMO Sci. Conf. on Wea. Mod., Boulder, CO, 151-158.

Woodley, W. L., J. Simpson, R. Biondini, and J. Berkeley, 1977: Rainfall results, 1970-1975, FACE. Science, 195, 735-742.

Woodley, W. L., R. I. Sax, J. Simpson, R. Biondini, J. A. Flueck, and A. Gagin, 1978: The FACE Confirmatory Program (FACE-2): Design and Evaluation Specifications. NOAA Tech. Memorandum. ERL NHEML-2, Coral Gables, FL, 51 pp.

Woodley, W. L., J. Jordan, J. Simpson, R. Biondini, J. Flueck, and A. Barston, 1982: Rainfall results of the Florida Area Cumulus Experiment, 1970-1976. J. Appl. Meteor., 21, 139-164.

Woodley, W. L., A. G. Barnston, J. A. Flueck, and R. Biondini, 1983: The Florida Area Cumulus Experiment's second phase (FACE-2). Part II: replicated and confirmatory analyses. J. Clim. and Appl. Meteor., 22(9), 1529-1540.

Wurtele, Z. S., 1971: Analysis of the Israeli cloud seeding experiment by means of concomitant meteorological variables. J. Appl. Meteor., 10, 1185-1192.

3. Hypothesis Development

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In the four decades since the possibility of modifying rainfall gained widespread scientific and public recognition (although not always acceptance), a number of of techniques have been proposed. Those which were directed toward modifying the mesoscale thermodynamics (e.g., by changing properties of the underlying surface) were rapidly discarded in favor of those based on "triggering" natural precipitation processes. At present, it is generally accepted that the only practical means of modifying cloud and precipitation processes is by altering the size spectrum, or the phase of the cloud condensate, through the manipulation of the natural populations of the condensation, freezing and/or sublimation nuceli, with the goal of initiating or enhancing natural processes and making them more productive, i.e., resulting in increased rain.

It is possible to distinguish between two objectives: a) initiation of precipitation, and b) augmentation. The first is used hereafter to refer to the initiation and production of rain in clouds which would not rain otherwise; the second indicates an increase in the precipitation naturally produced by a cloud, even though this may be effected by the initiation of the precipitation process earlier than it would have naturally or in a region other than it would have naturally.

Impact studies have shown that economic benefit to the Corn Belt will come primarily from increasing the precipitation on days when rainfall is over a tenth of an inch. Therefore, the goal in PACE is to augment the rainfall from multi-cellular clouds and organized cloud systems which research has shown are the more efficient rain producers in the Midwest. Such clouds usually extend above the freezing level and therefore are candidates for modification by manipulation of an ice process. Moreover, there is ample observerational and theoretical evidence to indicate that in these clouds a) coalescence processes are active and precipitation-size particles frequently develop below the freezing level and without the involvement of ice; b) large amounts of liquid water (> 1 g m^{-3}) are carried upward in updrafts through the 0°C level and frequently to the -10°C level; c) part of the liquid condensate is in large drops at altitudes in the temperature range of 0 to -10°C, and sometimes a goodly fraction. There is also evidence (albeit more limited) that d) supercooled drizzle drops freeze at -5 to -10°C and subsequently rime into graupels in cumulus congestus and small Cb (extending to no more than 7 km) and e) in larger clouds, the core of the updraft may be predominately liquid (at -5 to -10°C) with ice particles in the weaker outer edges.

The active coalescence and presence of large particles which can act as collectors at temperatures where seeding would occur indicates that "static" seeding, designed to produce such collectors is likely not be very productive. On the other hand, the goodly supply of liquid water at these temperatures represent a latent source of energy which can be imparted to the growing cloud through icing. Thus, a hypothesis based on initiating a favorable dynamic response to the artifically-induced freezing is a favored choice. Conceptually this method, i.e., dynamic seeding, is hypothesized to work as follows. Massive seeding will produce rapid icing throughout the supercooled cloud, releasing large amounts of latent heat, leading to an acceleration of the updraft because of increased buoyancy, greater vertical growth, increased inflow of water vapor, horizontal expansion of the cloud mass and finally greater precipitation. However, the sequence of events following inducement of icing may take a number of paths (Braham, 1968), most of which are very poorly understood. This is particularly true of the feedback loops between the dynamics and microphysics which can play a deciding role in the ultimate outcome of the treatment. It is for this reason that a seeding experiment must be designed to also answer key scientific questions. This applies, of course, to weather modification experiments based on other hypotheses as well.

For dynamic seeding to be effective, a number of conditions need to be met. First of all, in the temperature range of interest, the supercooled liquid water content must be high enough for significant amounts of heat to be released as it is converted from water drops to ice particles. Observations indicate that this is often the case in midwestern convective clouds that penetrate above the freezing level. Secondly, the seeding agent or its effects must be distributed throughout the active cloud volume in sufficiently high concentration and in a sufficiently short time so as to glaciate enough of the supercooled water to significantly increase the buoyancy. This is only partly a technological problem, since the main dispersion is expected to be through natural turbulence. Thirdly, the environmental conditions limiting natural cloud growth must not be so unfavorable that they cannot be overcome. Optimum results should occur when the enhanced updrafts allows the cloud to break through a stable layer or a shallow dry layer. However, if either of these is too strong or deep or if meso- or macro-scale divergence dominates in the middle troposphere, the induced growth may be negligible. The seeding may then cause a decrease in the precipitation since the increased vertical velocities, accompanied by no significant increase in depth, will cut down the time available for the microphysical processes to operate.

Given that the above conditions are satisfied, massive seeding of active cloud areas can increase the production of precipitation because the greater cloud depths provide more time for the microphysical mechanisms to operate and/or because the enhanced updraft causes an additional amount of the moisture to be drawn into the cloud from its surroundings. It is the latter that is believed to be the dominant factor. Although there are many occasions when the troposphere has high moisture content to great heights, for maximum increase in the vapor to be processed, it is necessary to hypothesize that the enhanced vertical motion results in moisture convergence below the cloud and in increased inflow of moist subcloud air into the cloud system. The net effect is increased organization of the updraft near the cloud base resulting in increases in the dimensions of the primary input scale of thermal energy and the areal extent of the updraft, and consequently in the width of the cloud.

A second, highly important hypothesized effect of the dynamic enhancement of a single cloud would occur in circumstances where the seeded cloud is a member of a group. This is associated with the 'merging' of unseeded cells or clouds with the seeded cell, to form a larger system with an overall longer lasting meso-scale inflow system. Merging has been observed to occur naturally in the atmosphere under certain conditions when one or two clouds in a group become large enough to cause a modification in the ambient flow field. If the dynamic enhancement of the seeded cloud is sufficient to cause it to pass into a larger class of clouds than it would have been normally, the outcome of the treatment may extend much beyond the simple 'leaching' of moisture from a given cloud; it can result in the development of an overall larger system which is known to be the better producer of precipitation at the ground.

Thus a hypothesized sequence of events following the massive seeding might be as follows.

(1) Conversion of water condensate to nearly total ice particles will occur very shortly after seeding.

(2) There will be an increase in temperature and net buoyancy throughout the region of freezing.

(3) The updraft speed will increase throughout the sub-zero region and probably below.

(4) In the absence of a strong synoptic-scale elevated inversion, the top will grow significantly beyond what it would naturally.

(5) A region of moisture convergence will develop just below the cloud and there will be an increase in the flow of moisture through the cloud base.

(6) The horizontal extent of the active cloud will increase and the updraft will increase in diameter.

(7) If the seeded cloud is one of a family, a merger with an adjacent cloud is likely to occur.

(8) There will be an increase in productivity (i.e., in the total surface rainfall) but not necessarily in precipitation efficiency.

(9) The rain intensity (rain/time/area) will not change significantly but the average rainfall (rainfall/total duration of rain) will increase.

It is important to note that only (1) is the direct result of applying a seeding agent. All others are a natural sequence following from glaciation. However, as indicated above, these natural processes and feedback loops are poorly understood, so at many critical points this hypothesized sequence is based as much on speculation as on scientific deduction.

Further explanation of point (8) is needed. Productivity[1] can be increased by an increase in the amount of vapor transported into the cloud system or by an increase in the efficiency[2] with which the cloud converts vapor to precipitation. It is important to realize that an increase in efficiency does not necessarily result in an increase in productivity. For example, if increased efficiency brought about by treatment is accompanied by a <u>decrease</u> in the active lifetime of the treated cloud so that, overall, less water vapor is drawn through the cloud system, the productivity could conceivably be decreased. Conversely, if an increase in productivity is due to an increase in the amount of vapor drawn into the cloud, as is hypothesized for dynamic seeding, there may be no change, or even decrease, in cloud efficiency.

One of the microphysical considerations related to this question of efficiency associated with glaciation, is the relative effectiveness of ice and water particles as "collectors" in a coalescence process, which remains an essential factor in the ultimate rainfall at the ground. Braham (1968) has indicated that introducing the ice phase earlier and in larger concentrations should increase precipitation efficiency because pellets were observed to grow by riming faster than the liquid drops had been growing through coalescence prior to freezing. He also speculated on reasons why this was so (Braham, 1964). Since this is an important factor in the ultimate outcome of the seeding, theoretical computations were undertaken during PACE to investigate whether ice particles were more effective collectors and, if so, under what conditions. The major issue that was explored in the initial effort was the expected growth rates of graupel particles and of liquid drops of the same mass.

Newly available results from these computations (Johnson, 1985) support Braham's conclusion that the freezing of large supercooled drops in warm-based clouds may significantly accelerate precipitation development. Newly frozen drizzle drops would be expected to have smooth surfaces. The theoretical calculations indicate that for these smooth-surface ice particles there should be an immediate jump in the accretional growth rate associated with an increase in coalescence efficiency to 1.0 (immediate freezing of cloud droplet and therefore no "bounce-off"). As the particle rimes, however, the surface will quickly roughen and there is a corresponding reduction in growth rates. Even after the spurt in growth has ended, however, the subsequent rime growth rates may be significantly larger than for water drops of the same mass in warm-based clouds in which the cloud droplets are relatively large. While the associated growth from the vapor (sublimation) would also be greater than for a comparable unfrozen drop, these growth rates are usually small for particles of this size, as compared to growth rates for coalescence or riming, and may be neglected.

One of the interesting features of the computational results is the relative insensitivity of the relative growth rates to the bulk density of the graupel. For collectors with melted diameter greater than about 0. 5

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[1]Productivity is defined as the total amount of precipitation produced at the ground by the cloud.

[2]Efficiency is defined as the ratio of precipitation produced to the amount of water vapor processed by the cloud system.

mm, the growth grate for rimed particles is larger than that for water drops for all graupel densities, for warm-based clouds with mean volume droplet diameter of about 20 μm.

Although these computations are based on generalized and simplified conditions, they do indicate that early icing could enhance coalescence growth and thus the precipitation efficiency under appropriate conditions and could serve to at least partially counteract decreases which might occur as a consequence of the increased updraft velocity. This would, of course, be highly desirable since the increase in rainfall due to seeding would be greater, if both moisture inflow and coalescence efficiency were enhanced.

REFERENCES

Braham, R. R., Jr., 1964: What is the role of ice in summer rain-showers? J. Atmos. Sol., 21(6):640-645.

Braham, R. R., Jr., 1968: Meteorological bases for precipitation development. Bull. Amer. Meteor. Soc., 49(4):343-353.

Johnson, D. B., 1985: Are cold clouds microphysically more efficient than warm clouds? (To be submitted to J. Atmos. Sci.).

APPENDIX

PART 1.

APPENDIX

Part 1.

A REVIEW OF PRECIPITATION ESTIMATION TECHNIQUES USING SATELLITE DATA APPLICABLE TO PACE

Stanley Q. Kidder

1.0 INTRODUCTION

The purpose of this study is to review the many schemes which have been developed to estimate precipitation using satellite data to see which ones might be useful in the Precipitation Augmentation for Crops Experiment (PACE). The history of precipitation estimation schemes using satellite data is now some 30 years old, having first been considered by Harry Wexler in a 1954 paper, six years before the first meteorological satellite. Reviewing all the schemes for estimating precipitation which have been developed since then would be a difficult task were it not for the work of E.C. Barrett and D.W. Martin. Much of the information contained in this paper comes from their excellent book _The Use of Satellite Data in Rainfall Monitoring_ (Barrett and Martin, 1981). Developments in the field since 1981 are taken from the general meteorological literature.

Because PACE concentrates on July and August precipitation from convective clouds in Illinois, many of the precipitation schemes can be eliminated without further discussion. Schemes which are designed primarily to estimate precipitation over climatological time periods (e.g. a month or longer) are not discussed. Schemes for estimating precipitation from stratiform clouds are not discussed. Finally, schemes which rely on data from polar orbiting satellites (2 to 4 observations per day) are not discussed because the observations are not frequent enough to be of use in PACE. This review is limited to schemes which employ visible and/or infrared data from the current Geostationary Operational Environmental Satellites (GOES). These are the only data which will be available on a frequent enough schedule to be of use to PACE.

It is important to point out that no satellite technique is universal; different techniques were developed for different purposes in different areas of the globe. The application of the precipitation estimates made using satellite data must be very carefully examined before selecting a particular technique. Section 2 will discuss the possible uses of the precipitation estimates made using the GOES data. This will provide a framework for judging the applicability of the various techniques to be discussed in Section 3. Finally, Section 4 will contain recommendations for satellite precipitation estimation work for PACE.

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[1]One exception to this rule will be made. A microwave imaging instrument called the SSM1 is scheduled to be launched in 1985 on a Defense Military Satellite Program (DMSP) satellite, which is a polar orbiter. Because microwave techniques are the only ones which directly sense precipitation, microwave instruments on future geosynchronous satellites may be extremely useful in precipitation estimation. Thus examination of some SSMI data is warranted.

2.0 POSSIBLE USES OF SATELLITE PRECIPITATION ESTIMATES IN PACE

Three uses for satellite precipitation estimates immediately come to mind.

1. Extra-area effects are an important consideration in any weather modification experiment. Because satellites view wide areas, and because precipitation estimates made using satellite data are most accurate when averaged over large areas, they can be quite useful in studying extra-area effects. In fact, one precipitation estimation scheme was developed specifically for studying extra-area effects.

2. Satellite data can be used either alone or in combination with radar and/or raingage data to estimate precipitation for the purpose of determining the magnitude of the modification or of the modification potential.

3. Forecasting where radar echoes will form can be very important in directing cloud seeding operations. Because of the high resolution and frequent coverage, satellite data may play an important role in this aspect.

3.0 PRECIPITATION ESTIMATION TECHNIQUES

Barrett and Martin divide precipitation estimation techniques using visible and infrared satellite data into four categories: cloud indexing methods, life history methods, bispectral methods, and cloud model methods. These methods are discussed in sections 3.1 through 3.4. Microwave methods are discussed in section 3.5.

3.1 Cloud Indexing Methods

These methods were developed primarily to estimate precipitation in areas of the globe where raingage data are sparse or absent entirely. The original work was done by Barrett (1970) of the University of Bristol, England, and by Follansbee (1973) of the National Environmental Satellite Service (NESS, now NESD1S). The basic idea is that different cloud types (for example, cumulonimbus) produce characteristic rainrates. The precipitation at a particular point (in a grid square) is proportional to the amount of time (fractional area) that the point (square) was covered with that cloud type. The total precipitation is the sum over all possible precipitation-producing cloud types.

Since the rainrate from a particular cloud type is not constant, the precipitation estimate is usually adjusted by a factor derived from coincident raingage measurements. This factor empirically takes into account such effects as synoptic forcing, seasonal differences and geographical variation.

A simple example of this approach is the method of Kilonsky and Ramage (1976). They were interested in estimating monthly precipitation over the tropical oceans. They reasoned that the significant precipitation falls from organized systems of convective clouds which are bright in visible satellite images. Once-daily Mercator mosaics of polar orbiter images were used. Their method consists essentially, then, of counting the number of days in a month in which a grid square is covered with what they call "highly reflective cloud." A linear relationship based on island precipitation data is used to estimate monthly precipitation.

The accuracy of these methods, indeed of all satellite precipitation estimation methods, is difficult to determine because "truth" is rarely known. Also the accuracy is a function of the size of the area and the length of time over which the precipitation is accumulated. In general, the accuracy improves with larger areas and with longer times. The rate of change of accuracy with area is not easy to assess from the literature, but there are several estimates for different time intervals. Very roughly, in an area a few hundred kilometers on a side the total precipitation estimated from satellite data in a one month period may differ from gage estimates or from radar estimates by a factor of 1.2 (-18% to +20%); in a one day period, by a factor of 1.5 (-33% to +50%); and in a one hour period, by a factor of 2 (-50% to +100%).[2] Of course satellite data does not have to be used alone to estimate precipitation. It can be used together with raingage or radar data, in which case errors (differences) will be less.

None of the cloud indexing methods estimate rainrate information from the satellite data. This is primarily because these methods were designed to be performed manually using hardcopy images from which accurate brightness levels or temperatures are difficult to determine. In addition most of the cloud indexing methods were designed to be used with once- or twice-daily polar orbiter data. Since instantaneous intensity values could not be expected to persist for 12 to 24 h, an

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[2] These numbers were compiled from the references and should be used only as a general guide. It should be kept in mind that the fact that satellite estimates differ from radar or raingage estimates does not mean that the satellite estimates are necessarily incorrect. It means that it is very difficult to assess the accuracy of precipitation estimates made by any method. The usefulness of satellite precipitation estimates must be analyzed in terms of each particular application.

assigned (climatological) intensity was sufficient. With the advent of geosynchronous satellites, the life history of clouds and cloud systems could be observed. Also, digital data became more widely available, allowing more accurate interpretation of the images. Most of the following precipitation estimation methods use the digital satellite data to estimate rainrate and/or to apportion the rain within the cloud.

3.2 Life History Methods

These methods were developed to estimate precipitation from convective clouds in which the rainrate varies during the cloud's lifetime.

3.2.1 Stout, Martin, And Sikdar

The most straightforward scheme is that of Stout et al. (1979). They show that when one compares volumetric rainrate with satellite images (Figure 1), the heaviest rain is in the growing stage of the cloud'8 life cycle. To take this into account, they assumed that the volumetric rainrate could be calculated as the sum of two terms:

$$R - bA + c(dA/dt),$$

where A is the area of the cloud above some predetermined brightness or temperature threshold,[3] R is the volumetric rainrate, and b and c are empirical constants. The introduction of the time rate of change of the

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[3]Detectable cloud size is limited by the resolution of the satellite instrument. The Visible and Infrared Spin Scan Radiometer (VISSR) in the GOES satellites has a visible resolution of about 1 km and an infrared resolution of about 8 km.

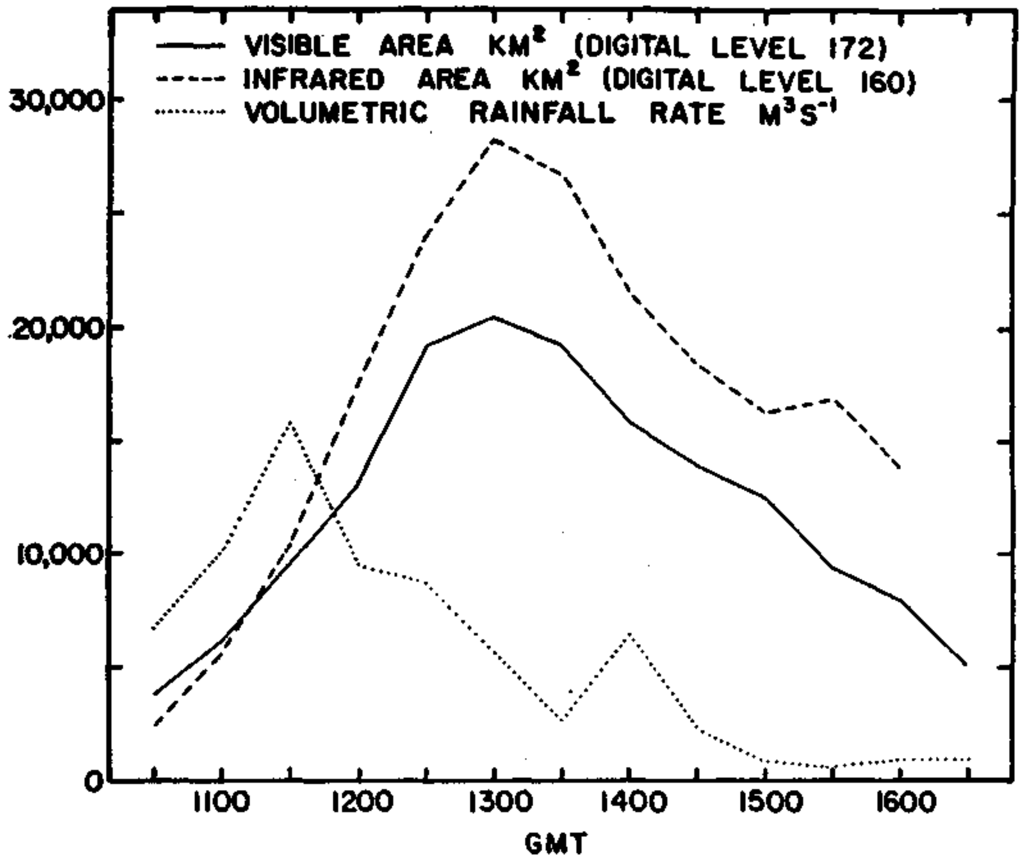

Fig. 1. A comparison of the radar-determined volumetric rain rate with cloud area estimated with visible and infrared satellite data for a typical convective cloud in the tropics. [After Stout et al. (1979).]

cloud area automatically increases R during the growing stage of the cloud and suppresses R during the decaying portion of the cloud (assuming that c is positive).

In practice, the precipitation from a cloud is estimated using picture pairs. The precipitation for the time period between two pictures (usually spaced 30 min apart) is estimated from the mean cloud area and from the change in area. Of course things like cloud mergers cause problems.

Stout et al. developed their technique to estimate precipitation beyond the range of shipboard radars during the GARP Atlantic Tropical Experiment (GATE). The scheme was calibrated using radar rain estimates, and overall results were quite good. The standard error of estimate for the estimation of precipitation from one cloud for one half hour was 60% for visible data and 75% for infrared data (compared to radar estimates).

Stout et al. have not tested their technique outside of the tropics. Its conceptual simplicity, however, makes it attractive for use in PACE.

3.2.2 Griffith-Woodley

A famous and much more complex precipitation estimation scheme was developed by Griffith and Woodley (Griffith et al., 1976; Woodley et al., 1980) originally to estimate extra-area effects of the Florida Area

Cumulus Experiment (FACE). They began by comparing satellite images (first visible, then infrared) with raingage-calibrated Miami radar data. The scheme rests on an empirical attempt to estimate from the satellite images what the associated radar echo for each cloud would look like.

To estimate the precipitation from a single cloud, the cloud—defined as anything colder than 253 K—is first followed for its entire lifetime to determine its maximum areal extent (A_m). Clouds which merge or split are terminated and the resulting clouds are treated as new clouds. Figure 2a (Griffith _et al_., 1978) shows the empirical curves used to determine the radar echo area from the satellite-estimated area of the cloud (A_c). The echo area (A_e) is estimated as a fraction of the maximum cloud area depending on the ratio A_c/A_m and the sign of the time rate of change of A_c. A_m itself determines which curve to use in Figure 2a. The rainrate is estimated using Figure 2b (Woodley _et al_., 1980; Griffith _et al_., 1980) and a knowledge of the ratio of the echo area to the maximum echo area. The rain volume falling from the cloud is then the product of 1) the rainrate, 2) the echo area, 3) the time interval between successive pictures, and 4) an empirical factor (Griffith _et al_., 1978) which starts at 1.00 and increases to a maximum of 3.24 essentially as the mean temperature of the cloud top decreases. Finally the total rain volume is apportioned within the cloud with one half of the rain falling below the coldest 10% of the cloud top, and the remaining half falling below the next warmest 40% of the cloud top, i.e., all of the rain falls below the coldest half of the cloud top. (It must be noted here that the Griffith-Woodley scheme has evolved over time; different papers use

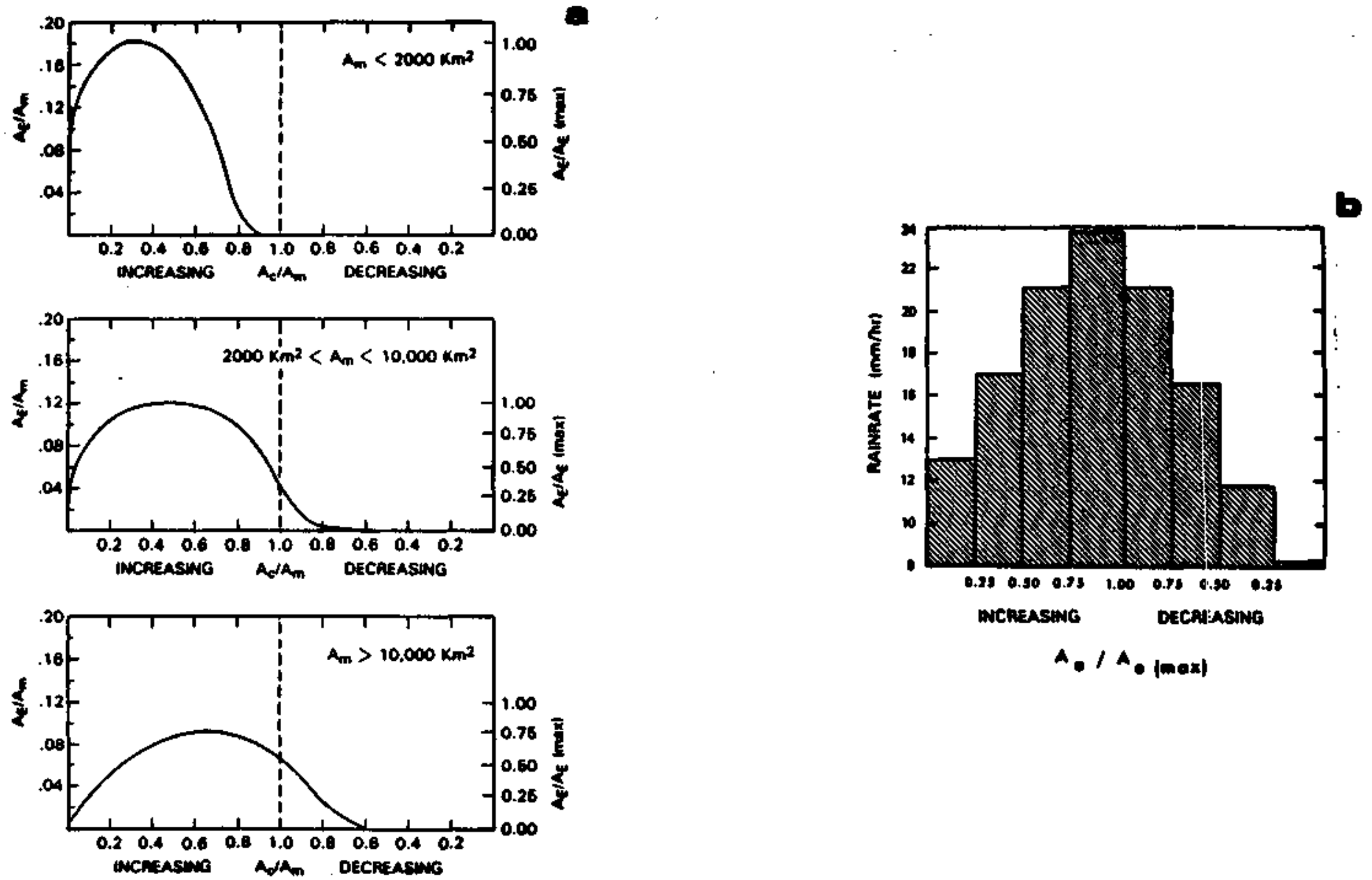

Fig. 2. (a) Echo area/cloud area relationships for infrared data in the Griffith-Woodley Technique, normalized by maximum cloud area. Curves are the actual Griffith-Woodley approximations to empirical data. [Adapted from Griffith et al. (1978) by Negri et al. (1984).] (b) The Griffith-Woodley relationship between rainrate and echo area. The singular point at 20.7 mm h is for clouds at their maximum echo area. [Adapted from Griffith et al. (1980) by Negri et al. (1984).]

slightly different parameterizations. A concise summary of the scheme is given in Negri et al., 1984.)

The Griffith-Woodley Technique has been applied to many areas of the globe: Florida, the U.S. High Plains, Venezuela, the tropical Atlantic. In each case the scheme was modified slightly, either in the way precipitation is apportioned below the cloud, or in the adjustment factor. In GATE, for example, the rain was uniformly distributed below the cloud (Woodley et al., 1980). In the U.S. High Plains, the precipitation was adjusted by a factor derived from the ratio of High Plains to Florida raingage data or from the ratio of cloud model precipitation in the High Plains and in Florida (Griffith et al., 1981). The basic relationships between cloud area and precipitation embodied in Figure 2, however, have remained unchanged. Accuracies vary widely but are generally in line with those listed above.

Because of the necessity of tracking clouds throughout their lifetimes, the Griffith-Woodley Technique is computationally intensive. Because of the complicated manner in which rain is estimated, the technique is difficult to apply. In addition, experience shows that the model of an isolated cloud going through its life cycle is not always applicable (see below). Since it cannot promise better results than other methods, it probably will not be generally useful for PACE. However, in the situation where clouds are isolated, the empirical relationship between cloud area and precipitation (Figure 2a) may be more realistic than the simple relationship used by Stout et al. (1979).

Recently, Negri *et al*. (1984) have critically examined the Griffith-Woodley Technique to determine its strengths and weaknesses. They found that its strongest point was the manner in which rain was apportioned within the cloud. The system where 50% of the rain is allocated to the coldest 10% of the cloud and the remaining 50% is allocated to the next warmer 40% seemed to give reasonable results when applied to some of the same FACE data which Griffith and Woodley examined. The weakest part of the Griffith-Woodley technique seems to be the process of tracking clouds throughout their lifetimes before assigning precipitation. Most clouds, it seems, last 1 h or less before interacting with other clouds. Therefore the simple model of a cumulus cloud going through its life cycle in isolation cannot be uniformly applied. Negri *et al*. tested a modified Griffith-Woodley scheme in which the life history of clouds was ignored. Instead they assumed that in the 30 min period represented by a single GOES infrared image, the volumetric rainfall from a cloud is proportional to its area (using the 253 K isotherm to outline the clouds). Then they apportioned the rainfall within the cloud according to the 10%-40% rule. The results for 3 FACE days showed that this modified Griffith-Woodley Technique had about the same accuracy as the Griffith-Woodley Technique itself, but it was far less expensive in computer calculations. It is quite possible that a modified Griffith-Woodley scheme along the lines suggested by Negri *et al*. could be used for precipitation estimation in PACE, especially in situations when clouds begin merging.

3.2.3 Scofield-Oliver

The final scheme to be discussed in the life history section is that developed by Scofield and Oliver (1977) for the purposes of flash flood forecasting and estimating rainfall in remote areas. Their scheme is designed to use hardcopy enhanced (MB curve) GOES infrared images, which are widely available in forecast offices. A decision tree is used to assign a rainrate to a particular point at the time of the satellite image. Significant rain is estimated only if the cloud is (1) convective, (2) cold, that is enhanced in the infrared image, and (3) the point (station) is under the active portion of the cloud, e.g. that part of the cloud which is coldest, or which displays the tightest gradient of cloud top temperature. Additional rain is assigned if the cloud is growing, merging, or has overshooting tops. A total of 48 a. priori rainrates ranging from Trace to 7 inches per hour are possible.

The gross features of heavy convective precpitation are almost always well described by the Scofield-Oliver Technique, which makes it quite useful for flash flood forecasting. Quantitative amounts are about as accurate as other schemes. In a test over Iowa, 6 h rainfall agreed with gage measurements to within 50%, and 24 h rainfall agreed to within 6%.

The technique is in the process of being automated, but work is not yet complete[4]. Because of this, it may not find general use in PACE. However, the idea of assigning more rain in areas of tight temperature gradients appears interesting.

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[4] Rod Scofield, personal communication, 29 April 1985.

3.3 Bispectral Methods

The above methods take advantage of the fact that clouds which are cold in infrared images and bright in visible images are more likely to precipitate than warm clouds or dark clouds. There are exceptions to these rules, however. Stratus clouds are bright, but do not rain as much, nor as often, as cumulonimbus clouds. Cirrus clouds are cold, but do not produce as much precipitation as warmer clouds. Bispectral methods attempt to combine these rules by saying that clouds which have the best chance of raining are both cold and bright. Lesser amounts (lower probabilities) can be expected from cold-but-dark and bright-but-warm clouds. Most notable of the bispectral methods is the work of Lovejoy and Austin (1979a,b) who compared SMS/GOES visible and infrared data in GATE and around Montreal with radar data. They attempted to determine brightness and temperature thresholds which, taken together, would best correspond to the radar-determined rain area. They found that at a single time a single pixel could be correctly determined to be raining between 55% and 65% of the time. Interestingly, however, they concluded that there was not much information on precipitation intensity in the visible and infrared data. They speculate that the optimum use of the data may be in determining where precipitation is falling. Precipitation amounts, then, would be calculated using climatological rainrates. This conclusion is at odds with those investigators who use life history techniques.

Bispectral techniques may be useful in PACE for determining where precipitation is falling, or perhaps, where precipitation is likely to fall.

3.4 Cloud Model Methods

A major difficulty with precipitation estimation techniques using visible and infrared data is that one only sees the top/side of the cloud; the raindrops are not directly sensed. To overcome this problem, various investigators have attempted to use cloud models to relate satellite observations to precipitation. The earliest such attempt was by Gruber (1973a) who noted that Kuo's (1965) parameterization of convection could be used to connect fractional cloud cover with rainrate. In extremely simplified form, the scheme is as follows. Consider a grid box into which moisture is flowing at the rate I. If Q is the amount of moisture necessary to completely saturate the box, then the rate at which the box is filling with cloud could be estimated as I/Q. However, convective clouds do not live forever. Suppose that all of the clouds which form are convective and have identical lifetimes t_L. Then the rate at which clouds are dying is approximately c/t_L, where c is the fractional cloud cover. If one makes the further assumption that the rate of influx of moisture I is exactly the same as the rainrate R, then one arrives at the equilibrium relationship $R = Qc/t_L$. Gruber developed his scheme using FACE data from June and July 1970. He calculated Q from a nearby sounding, c from infrared satellite data, and R from radar data. The resulting t_L correlated well with observed cloud lifetimes and averaged 30 min. He then tested this scheme on a squall line which moved through Illinois and Indiana on 3 July 1970 (Gruber, 1973b). Assuming t_L = 30 min, the mean R was estimated to be 3.8 mm h^{-1}, whereas gage measurements averaged 2.5 mm h^{-1}.

This scheme is very simple to put into practice, and could be of use in PACE for estimating extra-area effects, where one is concerned mostly with the total rain falling over a rather large (say, state-size) area.

Another use of cloud models is in adjusting calibration coefficients. Most of the above techniques were developed in a particular location. The changes necessary to apply them elsewhere are not obvious. Wylie (1979) attempted to use the one dimensional cloud model of Simpson and Wiggert (1969) to adjust the precipitation estimates. He used the method of Stout _et al_. to estimate precipitation in GATE and around Montreal. Wylie adjusted the satellite rain estimates for the six cases around Montreal by the ratio of precipitation estimates made using the cloud model. Substantially improved results were obtained in five of the six cases.

More recently Adler and Mack (1984) have studied the ability of a 1-D cloud model to explain differences in cloud top temperature-rainrate relationships in Florida and Oklahoma. In general they found that the 1-D model was able to explain differences in the curves. A preliminary attempt to apply the results of Adler and Mack (1984) to estimate precipitation in Florida has been reported by Negri and Adler (1984). They found precipitation estimates which were about as good as those produced by other methods, and they found several problems with the technique. It is too early to fully evaluate this technique.

Although 1-D cloud models leave much to be desired, there may be some advantage to using them to calibrate satellite precipitation estimation techniques used in PACE.

3.5 Microwave Methods

All of the above precipitation estimation techniques utilize visible and/or infrared measurements. At these wavelengths clouds are opaque; thus precipitation must be estimated from measurements made at the tops of clouds. Cloud droplets, on the other hand, are too small to interact significantly with microwave radiation. Microwaves pass nearly unaffected through clouds. Precipitation-size drops, however, modify the radiation stream passing through a cloud toward a satellite radiometer primarily by absorption and reemission. Using the Rayleigh-Jeans approximation,

$$\frac{dT_B}{dz} = a(T_A - T_B),$$

where T_B is the brightness temperature (equivalent blackbody temperature), T_A is the atmospheric temperature, z is height, and a is the volume absorption coefficient, which is nearly zero except in the presence of precipitation. Assuming that T_A is nearly constant in the rain layer, this equation can be integrated to give:

$$T_B = T_{BS}t + T_A(1 - t)$$

where T_{BS} is the brightness temperature of the surface (i.e. the product of the thermometric surface temperature and the surface emissivity), and t is the transmittance of the rain layer given by:

$$t = \exp[-a(R)D],$$

where D is the depth of the rain layer (snow above the rain is not well sensed by microwave radiometers), and a(R) is the rainrate-dependent volume absorption coefficient. Basically a satellite-borne microwave radiometer will sense the brightness temperature of the surface modified by the intervening atmosphere. If no precipitation-size drops exist within the radiometer beam, no modification takes place. In the presence of precipitation, the satellite-measured brightness temperature is greater than the surface brightness temperature if T_A is greater than T_{BS}; T_B is less than T_{BS} if T_A is less than T_{BS}.

Figure 3 (Savage and Weinman, 1975) shows the brightness temperature calculated as a function of rainrate for two frequencies of microwave radiation and for two surfaces: land and water. The reason for the difference in the land and water curves is that the emissivity of land and water are very different. Land has about a 0.9 emissivity, while water has about a 0.4 to 0.5 emissivity. Note that at higher rainrates, scattering becomes important: over water, T_B is no longer monotonic with R.

The problem of precipitation estimation using microwave data is one of contrast. Over water, precipitation appears bright (higher T_B) than the surrounding rainfree areas. Some success has been found (Wilheit et al., 1977) in relating rainrate with T . Over land the problem is more difficult; one looks for cold rain surrounded by hot land. One can be fooled, however, by water bodies and even by wet ground, which also appear cool. Fortunately, the microwave radiation originating from water bodies and wet ground is polarized while that originating from precipitation is not. Some success has been achieved in discriminating raining areas from nonraining areas using polarized microwave measurements near 37 GHz (Rodgers et al., 1979). If more than one channel is used, some of the background problems can be eliminated. Spencer (1984) has developed a screening regression technique to

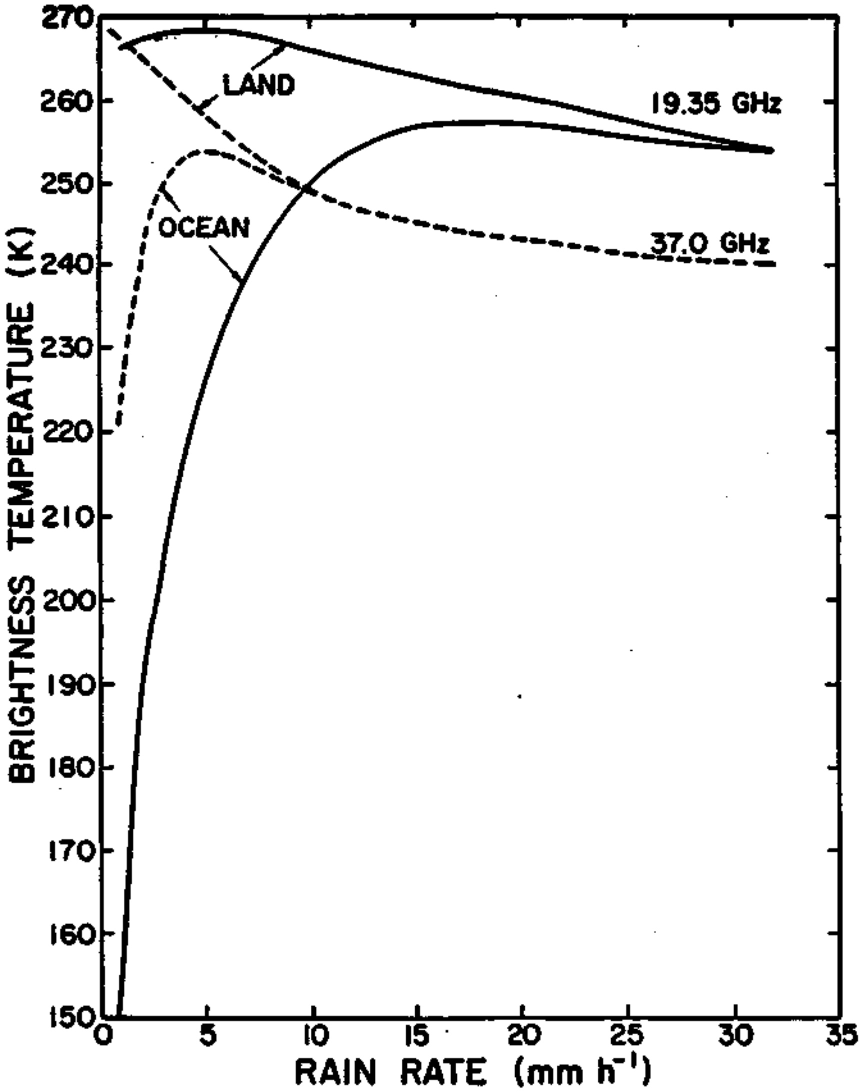


Fig. 3. The upwelling brightness temperature (zenith angle = 48.6°) of a 4.47 km thick rain-cloud over land (emissivity = 0.90) and ocean (emissivity = 0.42 at 19.35 GHz, 0.47 at 37.0 GHz) surfaces. [After Savage and Weinman (1975).]

estimate precipitation over croplands. He achieved a 0.80 correlation between rain estimates from the Scanning Multichannel Microwave Radiometer (SMMR) on board the Nimbus 7 satellite and rain estimates derived from the NWS Radar Summary Chart.

A microwave instrument called the SSMI is scheduled to be launched on a DMSP satellite in 1985. One of the goals of this seven-channel instrument is the measurement of precipitation intensity over land (Savage, 1981). Although the twice-daily observations are not sufficient for FACE, these data may be useful in calibrating techniques based on visible or IR data. In addition, the SSMI will be sensitive to soil moisture (Savage, 1981). It may be possible to use changes in soil moisture to augment direct precipitation estimates.

4.0 CONCLUSIONS AND RECOMMENDATIONS FOR PACE

Satellite observations of clouds offer a different view of the precipitation process than those offered by radar or raingages. It is likely that the addition of satellite data will improve our understanding of the relationship between clouds and precipitation, which in turn will improve our understanding of the modification potential of clouds.

The ultimate goal of PACE is to determine the feasibility, efficacy, and desirability of cloud seeding to increase rainfall. This places some constraints on satellite precipitation estimation schemes.

Mentioned above is the necessity of using GOES visible and/or infrared data because these are the only data available frequently enough to be useful in estimating precipitation from short-lived cumulus clouds. A further constraint is that the method should be conceptually and computationally simple so that it can be used in near-real time. Finally, the method should be automatable, which requires the use of digital satellite data. This will both increase speed and reduce subjectivity.

In fact, more than one method of inferring precipitation from satellite data will need to be investigated to accomplish the goals set out in Section 2. A technique which is useful in estimating extra-area effects in a large area may not be very good at estimating precipitation in a small target area for a short time period, a technique which uses visible data cannot be applied at night, and a technique which is useful for directing the operations of the seeding may not be useful for analyzing the results.

From the above, the most promising of the existing precipitation estimation techniques are the following. From the cloud indexing methods we learn that by combining satellite and raingage data, one can obtain useful precipitation fields even though satellite data is used only to infer the existence of cloud. From the life history methods, we learn that some information about the intensity of precipitation can be obtained from satellite data either through growth rates or through cloud top temperatures/temperature gradients. (We also learn that the life history approach can be taken to extremes without significant improvement in performance.) From the bispectral methods we learn that it is possible with good accuracy to determine whether or not rain is falling beneath a particular pixel. Combined with simple movement forecasts, this may be useful for the direction of cloud seeding operations. Finally, from the cloud model methods, we learn that cloud models may be a useful way of building additional physics into precipitation estimation techniques.

An alternate approach to the analysis of precipitation estimation methods is to classify those which are likely to be most useful for different cloud regimes. For small/isolated clouds, the life history techniques such as Stout et al. or Griffith-Woodley are likely to give the best results. For clouds which are merging or which cannot be considered to be isolated, the life history approach is unlikely to succeed. A cloud indexing method or an approach like that of Negri et al. seems more appropriate. For heavy precipitation, a scheme similar to that of Scofield-Oliver will probably be most suitable. For extra-area studies, a cloud indexing method, which allows for interpolation between raingage measurements, seems most promising. Finally, some sort of bispectral method will likely be most useful in directing cloud seeding operations. In all of these techniques, cloud models may be useful for adjusting the precipitation estimates to account for differing synoptic or stability conditions.

Precipitation estimation using satellite data is an applied science. Acquiring and analyzing actual data is the only way to develop a useful technique. Digital GOES data for 24 July 1979, which was a VIN case study day, have been acquired. Concurrent CHILL data have been obtained, and raingage data in the VIN network are available. Precipitation estimation techniques will be implemented and the results compared with CHILL and raingage measurements. It is also recommended that SSMI microwave data be acquired and analyzed for a 1985 case study to determine the potential of future geosynchronous microwave instruments.

REFERENCES

Adler, R.F. and R.A. Mack, 1984: Thunderstorm cloud height-rainfall rate relations for use with satellite rainfall estimation techniques. J. Climate Appl. Meteor., 23, 280-296.

Barrett, E.C., 1970: The estimation of monthly rainfall from satellite data. Mon. Wea. Rev., 98, 322–327.

Barrett E.C. and D.W. Martin, 1981: The Use of Satellite Data in Rainfall Monitoring. Academic Press, New York, 340 pp.

Follansbee, W.A., 1973: Estimation of Average Daily Rainfall from Satellite Cloud Photographs. NOAA Tech. Memo. NESS 44, Washington, D.C., 39 pp.

Griffith C.G., W.L. Woodley, S. Browner, J. Teijeiro, M. Maier, D.W. Martin, J. Stout, and D.N. Sikdar, 1976: Rainfall Estimation from Geosynchronous Satellite Imagery during Daylight Hours. NOAA Tech. Rep. ERL 356-WMP0 7, Boulder, CO, 106 pp.

Griffith, C.G., W.L. Woodley, P.G. Grube, D.W. Martin, J. Stout, and D.N. Sikdar, 1978: Rain estimation from geosynchronous satellite imagery—visible and infrared studies. Mon. Wea. Rev., 106. 1153-1171.

Griffith, C.G.,W.L. Woodley, J.S. Griffin, and S.C. Stromatt, 1980: Satellite-Derived Precipitation Atlas for the GARP Atlantic Tropical Experiment. Division of Public Documents, U.S. Government Printing Office, Washington, D.C., 284 pp.

Griffith C.G., J.A. Augustine, and W.L. Woodley, 1981: Satellite rain estimation in the U.S. High Plains. J. Appl. Meteor., 20. 53-56.

Gruber, A., 1973a: An. Examination of Tropical Cloud Clusters Using Simultaneously Observed Brightness and High Resolution Infrared Data from Satellites. NOAA Tech. Memo. NESS 50, Washington, D.C., 22 pp.

Gruber,A., 1973b: Estimating rainfall in regions of active convection. J. Appl. Meteor., 12, 110-118.

Kilonsky, B.J., and C.S. Ramage, 1976: A technique for estimating tropical open-ocean rainfall from satellite observations. J. Appl. Meteor., 15, 972-975.

Kuo, H.L., 1965: On formation and intensification of tropical cyclones through latent heat release by cumulus convection. J. Atmos. Sci., 22, 40-63.

Lovejoy, S., and G.L. Austin, 1979a: The delineation of rain areas from visible and IR satellite data for GATE and mid-latitudes. Atmosphere-Ocean, 17, 77-92.

Lovejoy, S., and G.L. Austin, 1979b: The sources of error in rain amount estimating schemes for GOES visible and IR satellite data. Hon. Wea. Rev., 107,1048-1054.

Negri, A.J., R.F. Adler, and F.J. Wetzel, 1984: Rain estimation from satellites: An examination of the Griffith-Woodley Technique. J. Climate Appl. Meteor., 23., 102-116.

Negri, A.J., and R.F. Adler, 1984: A new technique to infer convective rainfall from satellite infrared cloud observations. Preprints: AMS Conference on Satellite Meteorology/Remote Sensing and Applications. Clearwater Beach, FL, June 25-29, 58-63.

Rodgers, E.B., H. Siddalingaiah, A.T.C. Chang, and T.T. Wilheit, 1979: A statistical technique for determining rainfall over land employing Nimbus 6 ESMR measurements. J. Appl. Meteor., 18. 978-991.

Savage, R.C., and J.A. Weinman, 1975: Preliminary calculations of the upwelling radiance from rainclouds at 37.0 and 19.35 GHz. Bull. Amer. Meteor. Soc., 56, 1272-1274.

Savage, R.C., 1981: The DMSP microwave imager (SSMI)—Unfinished plans. in Atlas, D.W., and O.W. Thiele, eds.: Precipitation Measurements from Space: Workshop Report. NASA/Goddard Space Flight Center, Greenbelt, MD, D249-D251.

Scofield, R.A., and V.J. Oliver, 1977: A Scheme for Estimating Convective Rainfall from Satellite Imagery. NOAA Tech. Memo. NESS 86, Washington, D.C., 47 pp.

Simpson, J., and V. Wiggert, 1969: Models of precipitating cumulus towers. Mon. Wea. Rev., 97, 471-489.

Spencer, R.W., 1984: Satellite passive microwave rain rate measurement over croplands during spring, summer, and fall. J. Climate Appl. Meteor., 23, 1553-1562.

Stout, J.E., D.W. Martin, and D.N. Sikdar, 1979: Estimating GATE rainfall with geosynchronous satellite images. Mon. Wea. Rev., 107, 585-598.

Wilheit, T.T., A.T.C. Chang, M.S.V. Rao, E.B. Rodgers, and J.S. Theon, 1977: A satellite technique for quantitatively mapping rainfall rates over the oceans. J. Appl. Meteor., 16, 551-560.

Woodley, W.L., C.G. Griffith, J.S. Griffin, and S.C. Stromatt, 1980: The inference of GATE convective rainfall from SMS-1 imagery. J. Appl. Meteor., 19, 388-408.

Wylie, D.P., 1979: An application of a geostationary satellite rain estimation technique to an extratropical area. J. Appl. Meteor., 18, 1640-1648.

PART 2.

PART 2

RADAR SUMMARY

Hancy Westcott

Introduction

In the last 30 years, the radar has proven to be an invaluable tool for both meteorological research and forecasting applications. Radars operated on a number of research projects have provided important information for severe storm studies - hail, tornadoes and heavy rains; for planned and inadvertent weather modification studies; and in particular for basic research on the evolution and dynamics of convective storms. While these projects had diverse objectives, the data gathered are useful for establishing the characteristics, dynamics and precipitation initiation mechanisms of convective storms in the Midwest. This information later will be incorporated into the seeding hypothesis, operational design and equation criteria of PACE. The following questions will be addressed to attempt to determine what conditions will provide the best seeding opportunities for seeding, and how to recognize those opportunities:

1. What are the initial dimensions and location of newly formed radar echoes? What are the characteristics of these echoes in their growth stage, i.e. the rate of growth, the potential for rain at the ground, an estimate of intensity, and the duration?

2. What are the characteristics of multicellular storms and squall line storms? How do they grow and how are they organized? Can severe storm characteristics be distinquished from those of a large but non-severe storm? Can the severity of a storm be predicted during the growth stage of any particular storm?

Single Isolated Convective Clouds

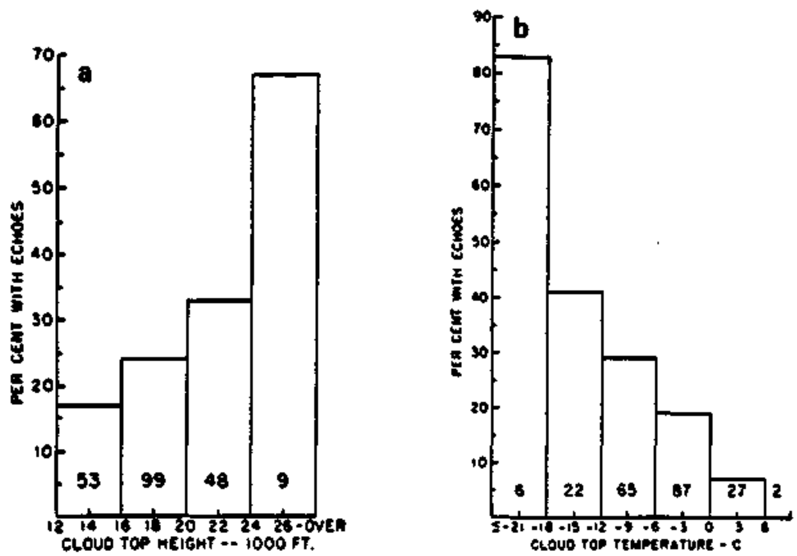
Small actively growing cumulus clouds, isolated, clustered or adjacent to large storms have been the subject of cloud physics studies and weather modification research for many years. These clouds are of particular interest for weather modification in that during their growth stage, they can presumably be modified by making existing precipitation growth processes more efficient or by initiating growth mechanisms not yet active. Also, as these clouds are in a relatively simple form, possible seeding effects can be more easily discerned.

Much of the early research in precipitation initiation in the midwest centered specifically on the naturally occurring microphysical processes potentially responsible for the onset of convective rainfall (Battan, 1953; Braham, 1964). The evidence to date indicates that the "warm rain" processes of cloud droplet growth by condensation, followed by precipitation growth by coalescence is the dominant initiation mechanism. However, various ice processes such as riming and ice multiplication are sometimes present. These early works, as well as more recent studies have been reviewed to extract pertinent information which is needed to develop the physical . hypothesis necessary for carrying out an experiment to modify midwest convective clouds for the purpose of increasing precipitation.

Much of our information comes from observations of radar first echoes. This information in conjunction with environmental temperature data, although not directly providing microphysical measurements, have yielded important insights into the mechanisms which may initiate precipitation growth. First echoes are defined as the first detection of precipitation sized particles in a particular volume of space by radar. They generally have been examined using a 3 cm height finding radar with a rapid vertical scan rate (approximately 1 sweep/second) and which could complete a full volume scan in 3 minutes. Variations in radar sensitivity, volume size and the 3 minute sampling interval contribute to an uncertainty in the actual height of the formation of embryonic precipitation drops. Nevertheless a fairly consistent picture can be drawn after examining first echoes from different projects.

At the onset of this discussion, it is important to note that not all first echoes produce rain at the surface, and not all clouds produce first echoes. In Project Whitetop, 2260 complete histories of isolated echoes were recorded. Of these, only 1760 (78%) reached the ground and presumably rained at the surface (Johnson and Dungey,1978). Battan and Braham (1956), reported on cloud top and precipitation observations made simultaneously by 2 aircraft, one instrumented with a radar from the ACN (Artificial Cloud Nucleation) study. This cloud census data was taken in an area from central Illinois to Kansas and from western Missouri to western Kentucky. Over 95% of the clouds formed below 7.3 km, and of these, only 25% contained precipitation echoes (Figure 1). More than 95% of the clouds examined had top temperatures greater than -18°C, and of these, about 23% of the clouds contained a radar echo. No clouds contained a precipitation echo with a top below 3.6 km (12,000 ft) in height or warmer than 6°C in temperature. The ACN project unfortunately took place during the severe drought year of 1954. However, in looking at the METROMEX first echo studies (Figure 11), no first echo formed with a top below 4 km, and less than 15% of tops were warmer than 6°C. This indicates that the ACN results may be reasonable. Also, this does not necessarily mean that a cloud would not contain precipitation sized particles once it reached an appropriate size. Braham (1956) estimated that a cumulus cloud in the central Midwest must grow to a height of about 7.6 km to have a 50Z probability of containing precipitation sized particles.

Figure 1. Percentage of cumulus clouds observed over the Central United States which contained precipitation echoes as a function of a) cloud top height and b) cloud top temperature. Numbers in columns represent the total number of clouds within each height interval. Battan and Braham, 1956.



First echo observations from the central Midwest were recorded in Ohio during the Thunderstorm project (1947), in south-central Missouri during project Whitetop (1960-1964), and in and around St. Louis, Missouri during METROMEX (1971-1975). Some of the properties of these first echoes will be summarized with attention given to their indication of convective strength. When available, additional information relating to cloud growth will be included.

A) <u>THUNDERSTORM PROJECT</u>

1) General Characteristics:

First echoes in the central midwest typically appear at or below the freezing level, in the vicinity of 4.5 km. Battan (1953), and Byers et al. (1953), in examining data from the Thunderstorm project of the summer of 1947, found that nearly 90Z of the first echo bases were located below the freezing level (Table 1; Figure 2). This table is relevant for single-celled convective echoes and for the first cell of a multi-cellular storm. To be selected, the echo had to be distinquishable from other echoes on the radar scope. The average temperature at the bases of the first echo was 10°C. Fifty-six percent of the echoes formed entirely below the 0°C isotherm, and another 33 percent straddled the freezing level. This clearly indicated the importance of coalescence in initiating the growth of precipitation particles.

Figure 2. Distribution of first echo base and top temperatures from the Thunderstorm Project. After Battan, 1953.

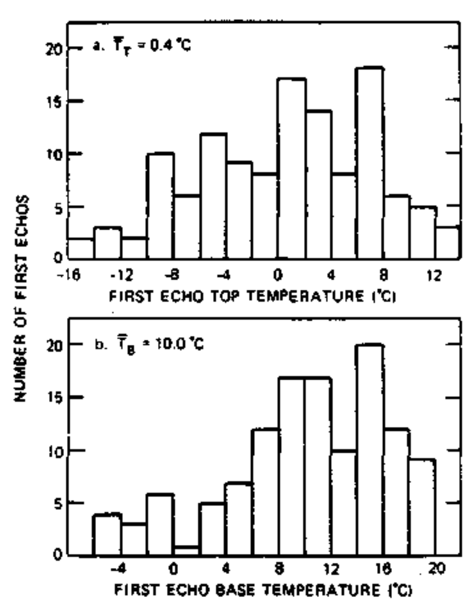


Table 1. Average temperature at tops and bases of first echoes in Ohio (Thunderstorm Project) for A. echoes growing < 1.5 km; B. echoes growing 1.5-3 km and C. echoes growing > 3 km. After Battan, 1953; Byers et al., 1953.

	Average cloud top temperature °C	Total sample N	Number <0°C	Number ≥0°C
A	-1.1	47	21	26
B	0.8	35	16	19
C	2.1	30	12	18
All	0.5	112	49	63

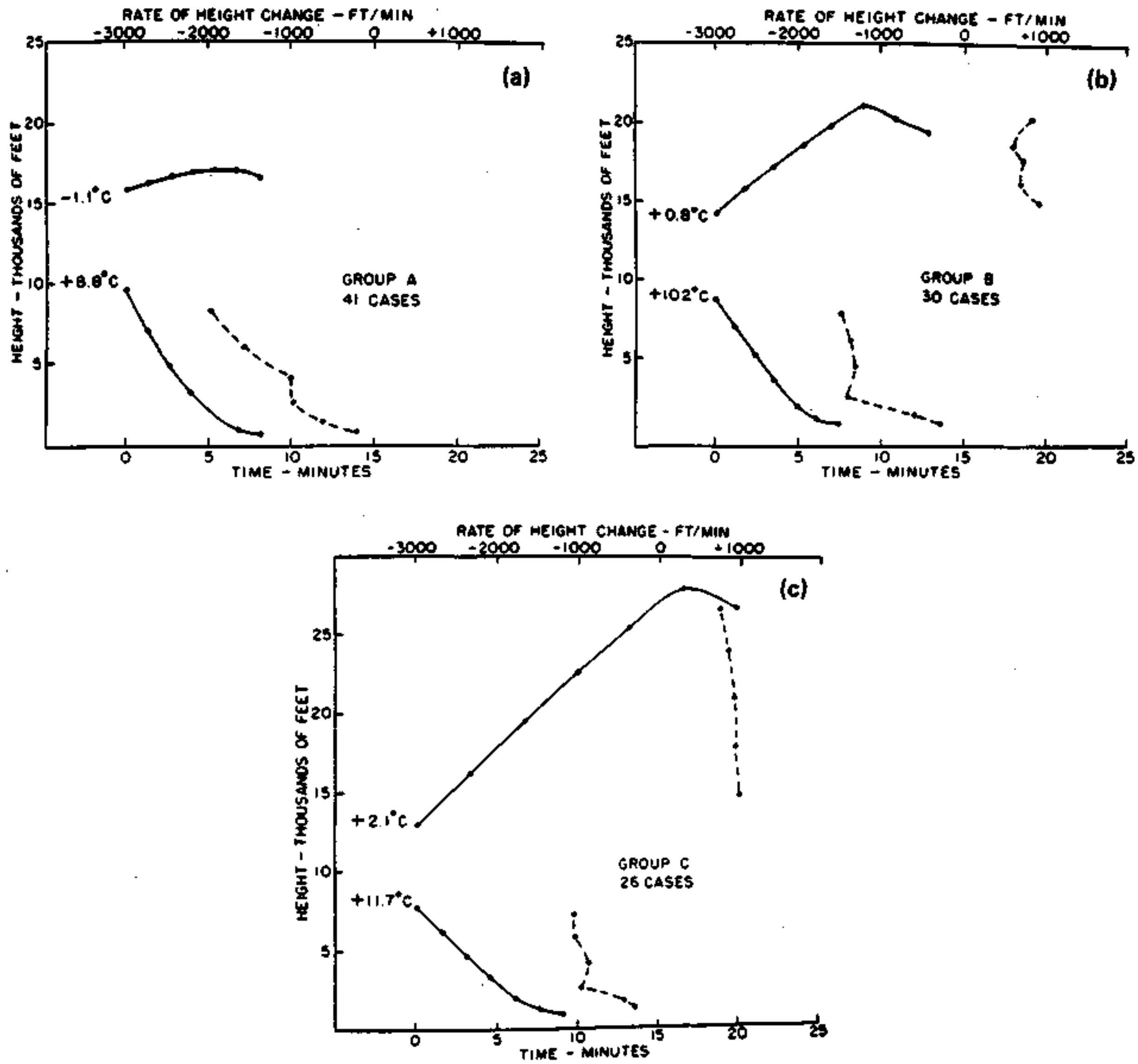
	Average cloud base temperature °C	Total Sample N	Number <0°C	Number ≥0°C
A	8.8	47	7	40
B	10.2	35	3	32
C	11.7	30	2	28
All	10.0	112	12	100

	Total Number of Echoes	Echoes Totally Warmer than 0°C		Echoes with Bases >0°C Tops <0°C		Echoes Totally Colder than 0°C	
		N	%	N	%	N	%
A	47	26	55	14	30	7	15
B	35	19	54	13	37	3	9
C	30	18	60	10	33	2	7
All	112	63	56	37	33	12	11

2) Growth Characteristics

The first echo observations also were classified into 3 categories based on the amount of subsequent growth in height of the echo after initial detection: group A, growth of less than 1.5 km; group B, growth of 1.5-3 km; and group C, growth of more than 3 km. The echoes which grew the most after the first observation generally were initially warmer at both the base and top of the echo'. (This result is supported somewhat by findings in METROMEX examination of the very shallowest and youngest first echoes only). A progressively smaller proportion of echoes were totally colder than 0°C as one approached the more actively growing clouds (Table 1 also). Battan (1953) in addition, presented average growth curves for these 3 groups (Figure 3a,b,c). For each group the average thickness of the first precipitable echoes is about 1.5 km (5,000 ft). The height of formation is lower on average for the more actively growing echoes as is suggested by Table 1. The bottom of the group A echoes falls at a faster rate than the other 2 groups, and the top rises more slowly. These echoes are also of shorter duration (approximately 8 mins). For the tallest growing echoes, group B and C, the average growth rate is about 4.1 to 5.0 m/s (800-1000 ft/min). The growth stage is longest for the tallest growing echoes, about 16 minutes.

Figure 3. Composite graph of the heights of the tops and bases of echoes stratified by growth: Group A: < 5000 ft (1.5 km); Group B: 5000-10,000 ft (1.5-3 km); and Group C: > 10,000 ft (3 km). Battan, 1953.

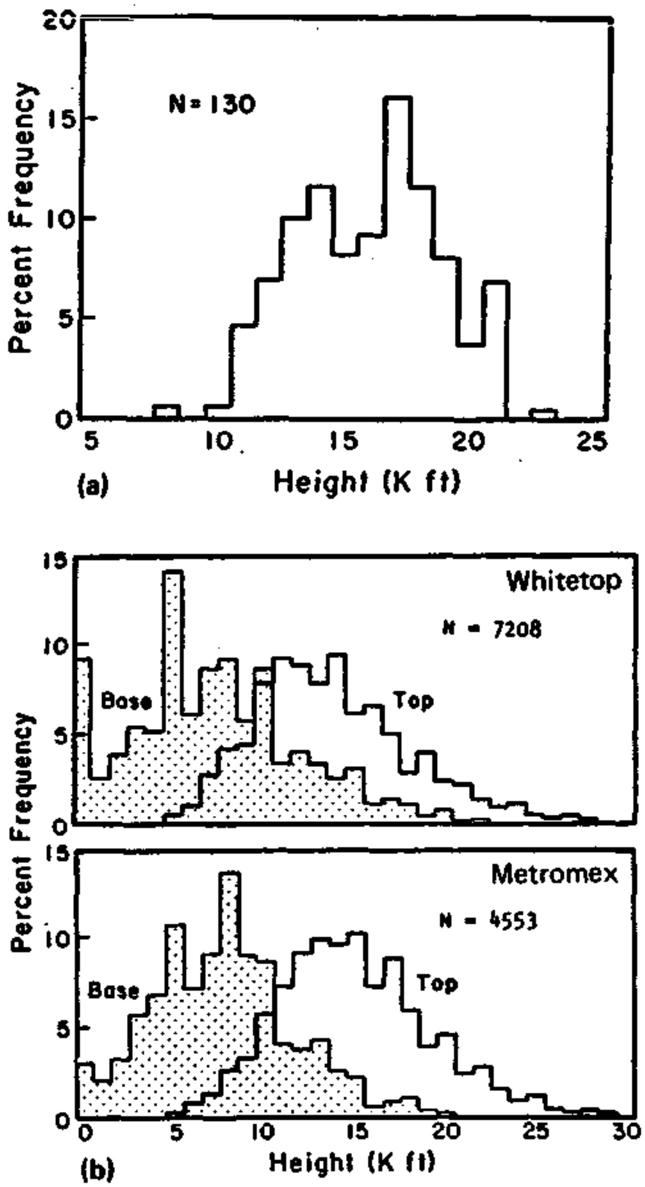


B) PROJECT WHITETOP

1) General Characteristics

Similar results concerning the location in height of the first echoes and their subsequent growth characteristics were found by Braham (1964) in Project Whitetop located in Missouri. Based on three summer's data, about 50% of the first echoes were entirely warmer than 0°C; 10% colder than 0°C; and 40% straddled the freezing level. The distribution of first echoes heights varied widely during any particular day and from day to day in both of these early studies as well as in METROMEX. A slight tendency was found by Braham (1964) for first echoes to be colder and higher on days with cyclonic curvature of the 850 mb and 700 mb isobars and/or low level convergence. However, no obvious correlation between the wide variation of first echoes heights and regional meteorological parameters was found. Johnson and Dungey (1978) in presenting the average daily first echoes top heights from days with 20 or more echoes in Project Whitetop and METROMEX, showed that the most frequent average daily echo top height was 4.9 km (16 kft). For the Whitetop sample as a whole, 4.3 km (14 kft) was the most frequent echo top height (Figure 4a,b) and for METROMEX, 4.6 km (14 kft). Changnon and Stout (1964), found for a severe storm case, a first echo top temperature of -40°C.

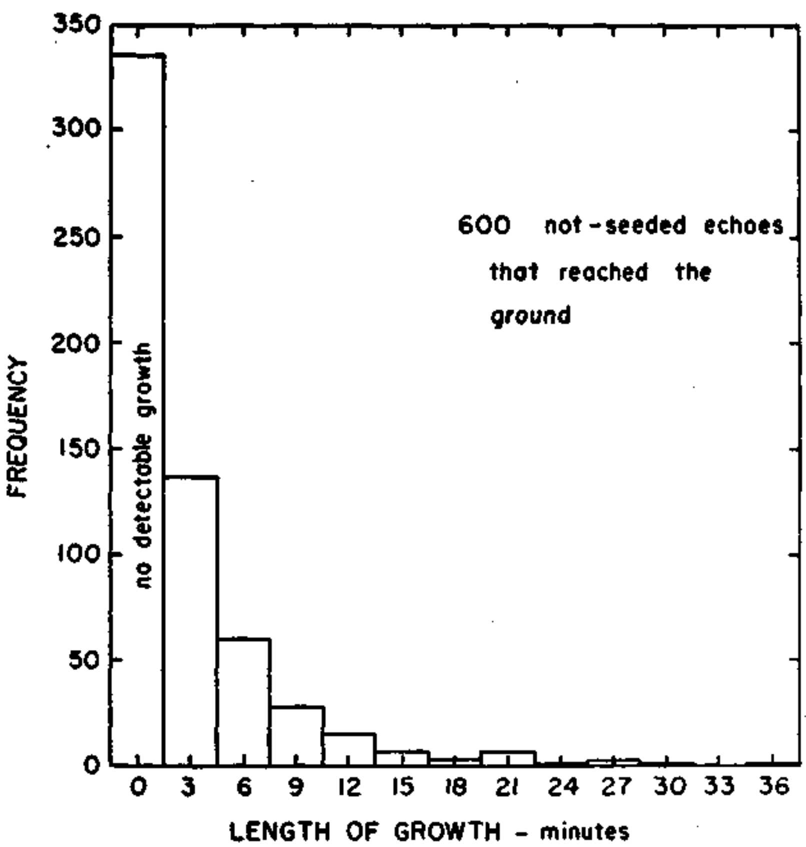
Figure 4. a. Daily average echo top heights for days with more than 20 echoes, from Project Whitetop and METROMEX. b. Distribution of heights (thousands of feet) of individual first echo bases and tops for Whitetop and METROMEX. Johnson and Dungey, 1978.



2) Growth Characteristics

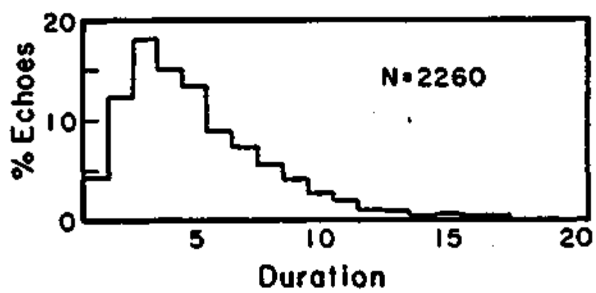
The growth characteristics of 749 single, nonseeded convective clouds from 15 days of the summer of 1960 were examined by Braham (1963; Braham, 1964). After initial detection, only 38% of the echoes showed subsequent growth. The daily average varied from 19-54%. Of the 600 echoes from this sample which rained, 44% subsequently grew. Only half of the echoes which grew did so for more than one sweep of the radar (Figure 5). Less than 1Z grew for more than 25 minutes. Over 90Z reached their maximum height within 9 minutes of detection, indicating a rather short growth stage.

Figure 5. Distribution of length of time an echo grows following initial detection. Braham, 1963.



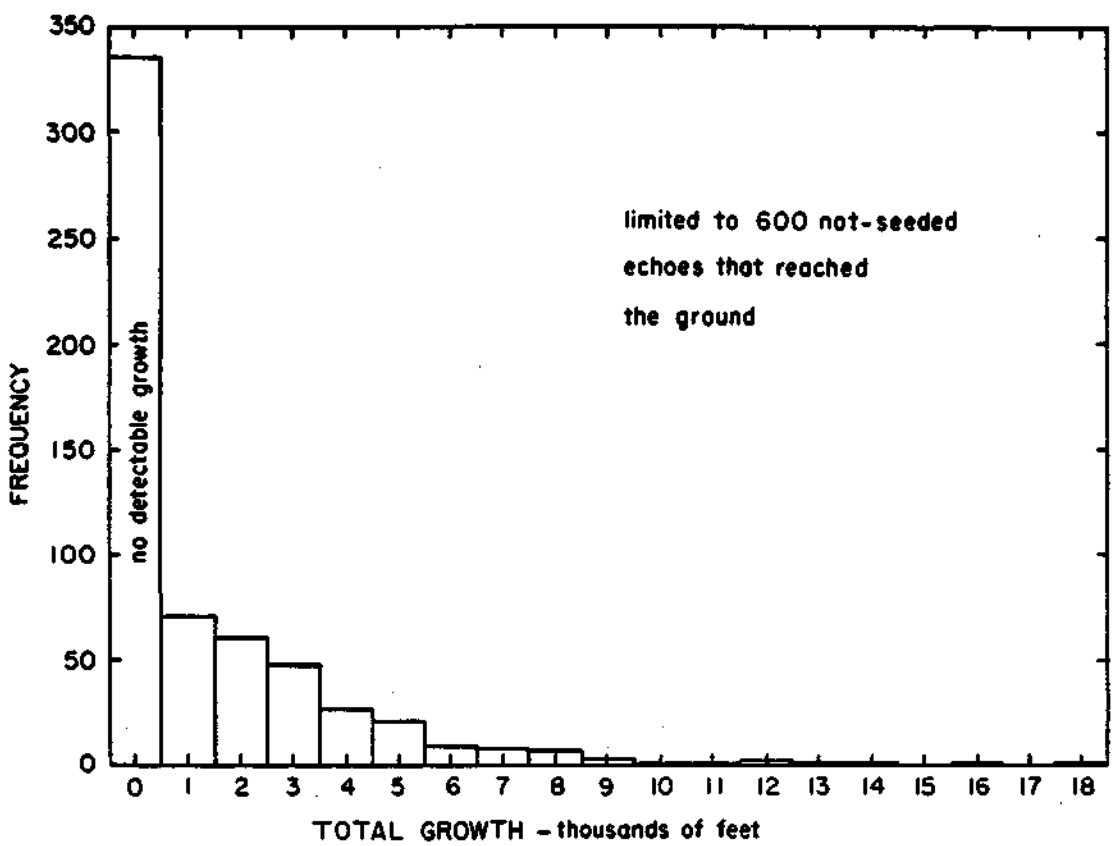
Johnson and Dungey (1978) looked at a much larger sample of Whitetop first echoes (only those discrete echoes which neither split nor merged with other echoes), from 1960-1962 whose complete histories were recorded (sample - 2206). They found that about 60% of the first echoes lasted less than 15 minutes after detection (Figure 6). Total echo durations ranged from less than 3 minutes to one hour.

Figure 6. Echo duration as expressed by the number of radar scans (3 minutes apart) during which the echo is visible. Johnson and Dungey, 1978.



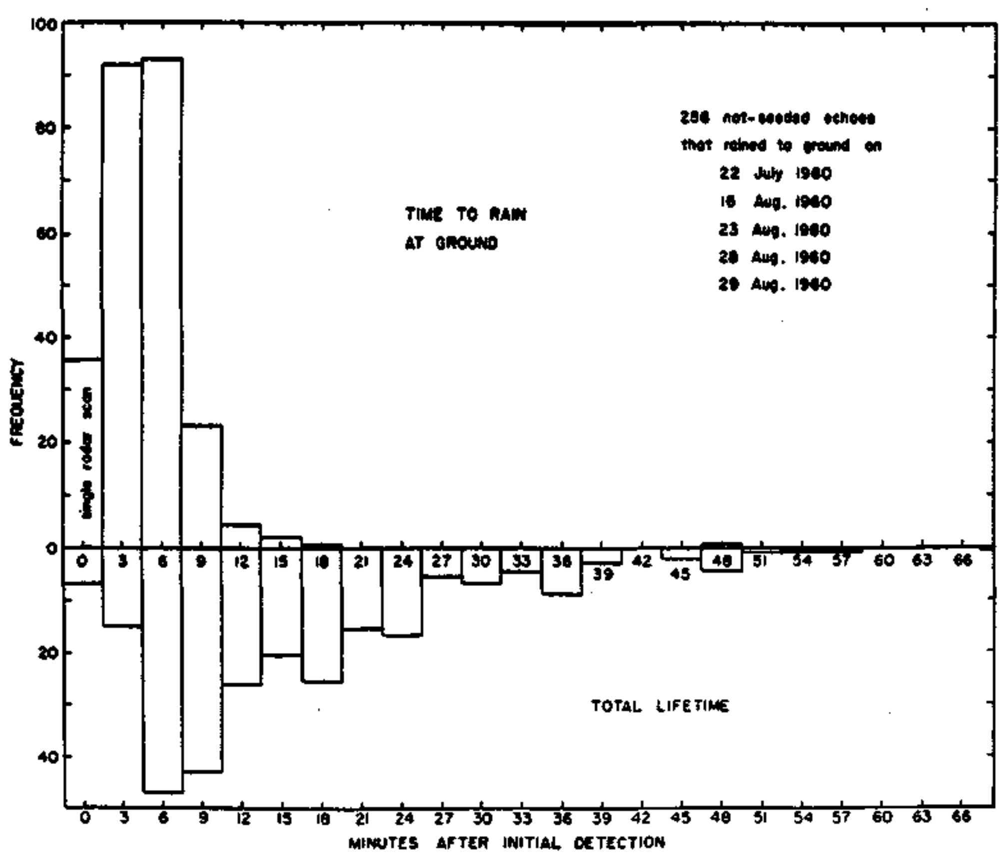
Again, of the 1960 Whitetop sample of echoes which rained (Figure 7) only 9Z (approximately 56) grew as much as 1.5 km (5000 ft) and fewer than 4Z (< 8 echoes) increased in height as much as 3 km (10,000 ft). While the percent of echoes which grew after initial detection is small, and the actual amount of growth is small, these 600 first echoes did produce measurable rain at the surface; that is, echo bases were detected by the 3 cm radar at the ground (Braham, 1964; Johnson and Dungey, 1978). This would indicate that precipitation sized particles were produced fairly quickly and at a low elevation.

Figure 7. Distribution of total growth of echoes. Braham, 1963.



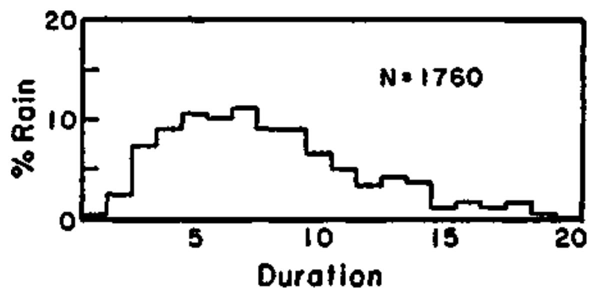
From a subsample of 256 nonseeded echoes on 5 days, on average only 4 minutes elapsed after initial detection before the echo was observed at the surface (Figure 8). About 87Z of the echoes began raining within 9 minutes after detection. Sixty-two percent of the echoes lasted 15 minutes or less, in agreement with the Johnson and Dungey (1978) results. While the smaller shorter lived clouds are the least likely to precipitate, they are capable of producing some amount of precipitation.

Figure 8. Distribution of time to rain and total duration of simple convective echoes. Braham, 1963.



The percentage of total rain falling (estimated by the total number of time periods with rain) from a distribution of echoes of various durations (Figure 9) was calculated by Johnson and Dungey (1978). From this it appears that 70Z of the rain falls from the taller, more actively growing echoes, which last more than 15 minutes. Although the shorter-lived clouds most likely contribute only 30Z of the total rain volume, this again indicates the speed of the precipitation mechanism.

Figure 9. Distribution of rainfall (percent of time periods with rain at the ground) as a function of echo duration, expressed as the number of radar scans (3 minutes apart). Johnson and Dungey, 1978.



C) METROMEX

1) General Characteristics

During project METROMEX, 4553 first echoes were selected for analysis on 82 days. Data reduction was limited to periods in which all detectable echoes in the radar field could be individually followed, that is, during periods of scattered echoes. While the majority of echoes were associated with air mass and squall zone storms, a conscious attempt was made to select echoes associated with the onset of more organized convection, squall lines and cold fronts (Table 2). Data was generally collected between the hours of 0900 and 1900 CDT. Rain measured by raingage was recorded on 65 of the 82 analysis periods (Braham, 1981).

Table 2. First echoes observed by the university of Chicago TPS-10 cm radar located in Greenville. Radar sensitivity was 3 dbZ at 16 km and 20 dbZ at 97 km. Braham, 1981.

	# periods	# first echoes
Air mass storms	27	1129
Squall zones	24	1510
Squall lines	11	1021
Cold fronts	12	492
Other	8	401
TOTAL	82	4553

In looking at the rural sample of first echoes from METROMEX (Table 3), some similarities and differences are found in comparison with the results from the Thunderstorm and Whitetop projects. The average first echoes base is at about 2.4 km at a temperature of 10.8°C, which is similar to previous results. The mean thickness is about 2.2 km. The distributions presented in Figure 10, reflect the mean values. However, the wide range of values found is quite pronounced. It would be interesting to examine the distribution of echo characteristics - on a day to day basis, or at least stratified by synoptic type to see if the large variations still exist (see discussion).

Table 3. Summary of first echo characteristics in and around St. Louis obtained by the University of Chicago, TPS-10 3 cm radar. After Braham and Dungey (1978).

		BASE		TOP		THICKNESS
Sample	# of first echoes	km	T°	km	T°	km
All	4553	2.3	11.0	4.6	-2.1	2.2
Group 1	4175	2.5	9.9	4.7	-2.7	2.2
Group 2	1950	2.5	9.8	4.7	-2.8	2.1
Group 3	486	3.0	6.4	3.7	+2.0*	.7
Urban	432	2.2	12.6	4.5	-1.9	2.4
Rural	3413	2.4	10.8	4.6	-2.3	2.2

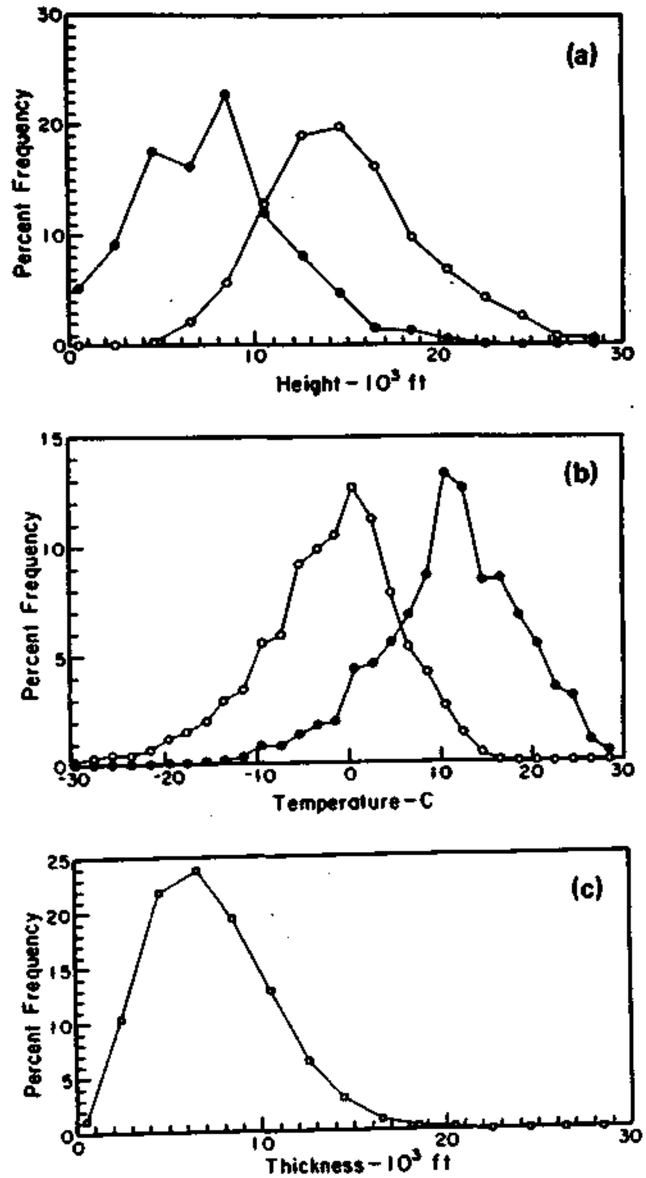
Group 1: Echoes with bases ≥ .91 km (3,000 ft).

Group 2: Echoes with bases ≥ .91 km (3,000 ft), from 44 days where the weather and cloud conditions made it very likely first echoes had roots near the surface.

Group 3: Echoes with a thickness of ≤ .91 km (3,000 ft).

* Value given in paper is -2.0°C; it is believed from examining the echo top height that an error was made in the sign of the echo top temperature.

Figure 10. Characteristics of the first echoes from Project METROMEX. a. height distribution of tops (open circles) and bases (solid circles) in total sample of 4553 echoes. b. temperature distributions. c. thickness distributions. Braham and Dungey, 1978.



The average echo top temperature, is approximately 2°C colder in the St. Louis area for both the urban and rural samples than found in earlier studies. The first echo height distribution of the METROMEX found in Johnson and Dungey (1978), are skewed by about 1 km toward higher higher tops from the Whitetop echo tops (Figure 4). The fact that the echo tops are colder also is evident in the proportion of echoes completely warmer than 0°C. In the total METROMEX sample, only 40% of the first echo tops are >0°C (1825 echoes) and 53% of the first echoes straddle the 0°C isotherm (2402 echoes). This diverges from the results of the two previous studies. However, only 7% of all echoes are found to be completely colder than 0°C (326 echoes). This is even a somewhat smaller percentage than found before.

The difference in echo top temperatures may be due in part to the age of the echo at initial detection (caused by differences in radar sensitivity as well as by lapses in time due to the mechanics of the scan mode), geographical differences, possibly to the weather systems considered, or due to climatic differences in mean frontal positions for this particular 5 year period. Differences in the age of the echo at first detection is suggested by the the observation that the smaller, probably younger echoes (group 3) had an average cloud top temperature of about 2°C. However, the cloud base temperature of group 3 is also much warmer than the older echoes. About 69% of these echoes were totally warmer than 0°C.

In METROMEX an effort was made to include synoptic types other than air mass storms and squall zones in the first echoes sample. Changnon (1978), examined 811 first echoes from July and August 1973 which were derived from another TPS-10 radar situated at Pere Marquette state park. Results were stratified by the degree of organization of the echoes (Table 4). While the results from the 2 radars can not be directly compared due to the difference in radar sensitivity (the Greenville radar would detect first echoes earlier), the difference between first echoes from isolated and more organized systems is quite marked. The bases and tops of the more organized storms are much higher (and presumably colder) than those of the isolated echoes. The echoes from the more organized systems are also deeper. This would suggest that large scale dynamic and thermodynamic differences may strongly influence variations in echo characteristics. That colder or at least taller first echo heights occur on days with more echoes was suggested by the results of Johnson and Dungey (1978), also.

Table 4. Average heights (km) of first echo tops and bases of July-August 1973 from the Pere Marquette TPS-10 3 cm radar (27 dbz = minimum reflectivity). Stratified by degree of organization of echoes. After Changnon, 1978.

First Echoes	N	Top	Base	Thickness
All	811	5.7	2.5	3.2
*Organized system	426	6.5	3.0	3.5
**Isolated system	385	4.9	2.1	2.8

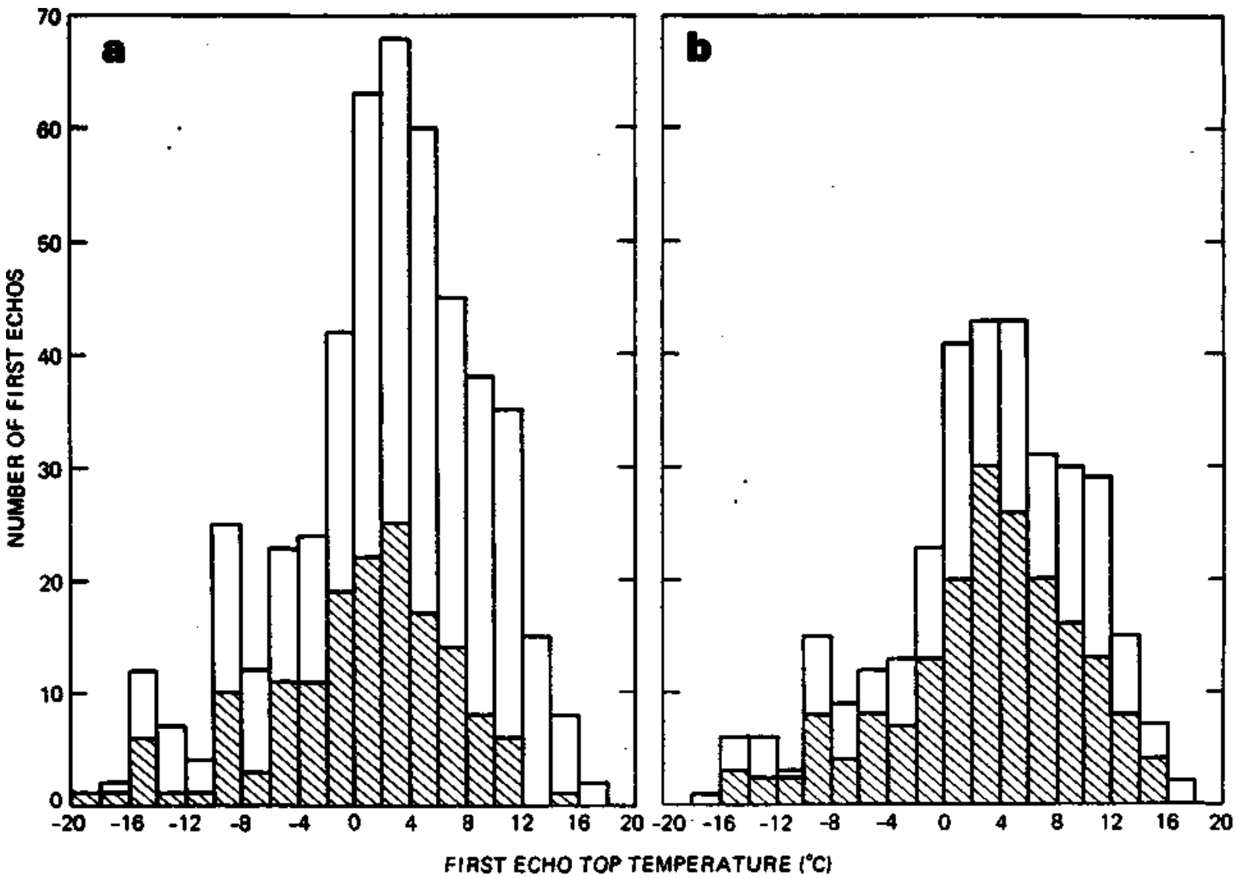
* Cold front, squall lines

** Squall zones, air mass storms, stationary fronts, warm fronts

2) Growth Characteristics

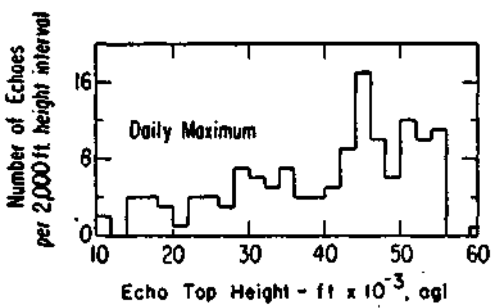
The distribution of first echo top temperature versus the first echo growth, within 3 minutes of initial detection for first echoes which were less than 1 km in depth (Figure 11), was presented by Braham and Dungey (1978). Approximately 69% of these echoes showed some growth. The distribution of echo tops stratified by echo growth are quite similar, for those which grow more than 1 km, for those which drop in height or have zero growth, and for the total sample. However, the median values are somewhat different: +4°C for the sample as a whole and for the echoes which exhibit some growth, and +2°C for the echoes which show no or 'negative' growth. The median for those which grow more than 1 km is about 5°C. The range of values is similar for each stratification, however and little predictability can be expected from the temperature of the initial echo top as an indicator of subsequent growth. No information was presented for the echoes which were presumably older (their thicknesses were greater than 1 km), nor for a cloud base temperature stratification.

Figure 11. First echo top temperature distribution for echoes with a thickness of <.91 km. a) Total sample - 486. Number of echoes with zero or no growth in first 3 minutes after detection: blue hatched, sample = 157. b) Number of echoes with positive upward growth in first 3 minutes, sample = 329. Number of echoes growing more than .91 km: red hatched, sample = 86. After Braham and Dungey, 1978.



The maximum echo top height was recorded for each day in METROMEX (Figure 12). The frequency is unimodal, with a maximum at 13.7 km (45,000 ft), a mean of 11.5 km (38,000 ft), and a median of about 13.4 km. The distribution is skewed towards values between 12.8 and 17.1 km (42,000 and 56,000 ft), while the total range spans from 3 to 18 km (10,000 to 60,000 ft). The average height of the tropopause on these days was about 15 km (50,000 ft) for St. Louis. The average daily echo top for June, July, and August were 11.1 km, 11.8 and 11.8 km, respectively (36.3, 38.8, 38.7 kft). Changnon and Morgan (1976) also examined daily maximum echo top heights but for a hail/no-hail stratification. The mean monthly values for the combined sample of days (1971-1973) were approximately: 8 km for May, 11.7 km for June, 11.0 for July and 11.9 for August. These results will be discussed further in section 2, in relation to severe weather predictability.

Figure 12. Top height distribution for the tallest echo on each day of the 140 day sample data set. Braham and Wilson, 1978.



D) DISCUSSION

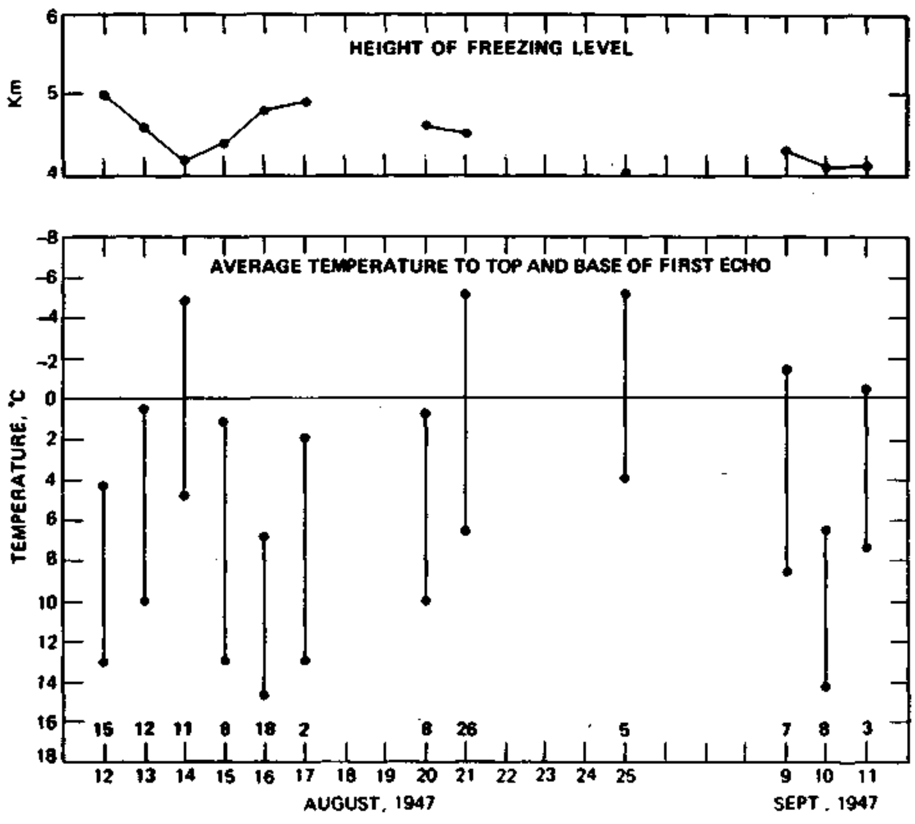
1) First Echo Daily Varibility

Common to the first echoes studies is a broad distribution of echo heights and/or temperatures at the time of initial detection. In each of the studies discussed, on the order of 7 to 11% of the first echoes formed totally above 0°C. Johnson and Dungey (1978) examined first echo top heights from days during Projects Whitetop and METROMEX when more than 20 echoes were observed (Figure 3a). The average daily first echo top heights ranged from 2.4 to 7 km with one peak at 4 km (below 0°C in the mean) and one at 5 km (above 0°C in the mean). Not only do daily mean heights (temperatures) of first echoes vary, but the values within a given day also will vary over a wide range.

This variability in first echo heights raises many questions. Is the broad distribution of echoes simply the result of the time resolution of the radar data, since the expansion of echoes both upward and downward is frequently very rapid? A subsample of first echoes were examined from METROMEX, which included only those echoes whose thickness did not exceed one kilometer. Nearly 70% of these select and probably youngest echoes formed completely below the zero degree isotherm, in contrast to 40% for the sample as a whole (Braham and Dungey, 1978). Are large scale meteorological factors controlling the first echo distribution? If so, a systematic change in the daily distribution and daily average should be present.

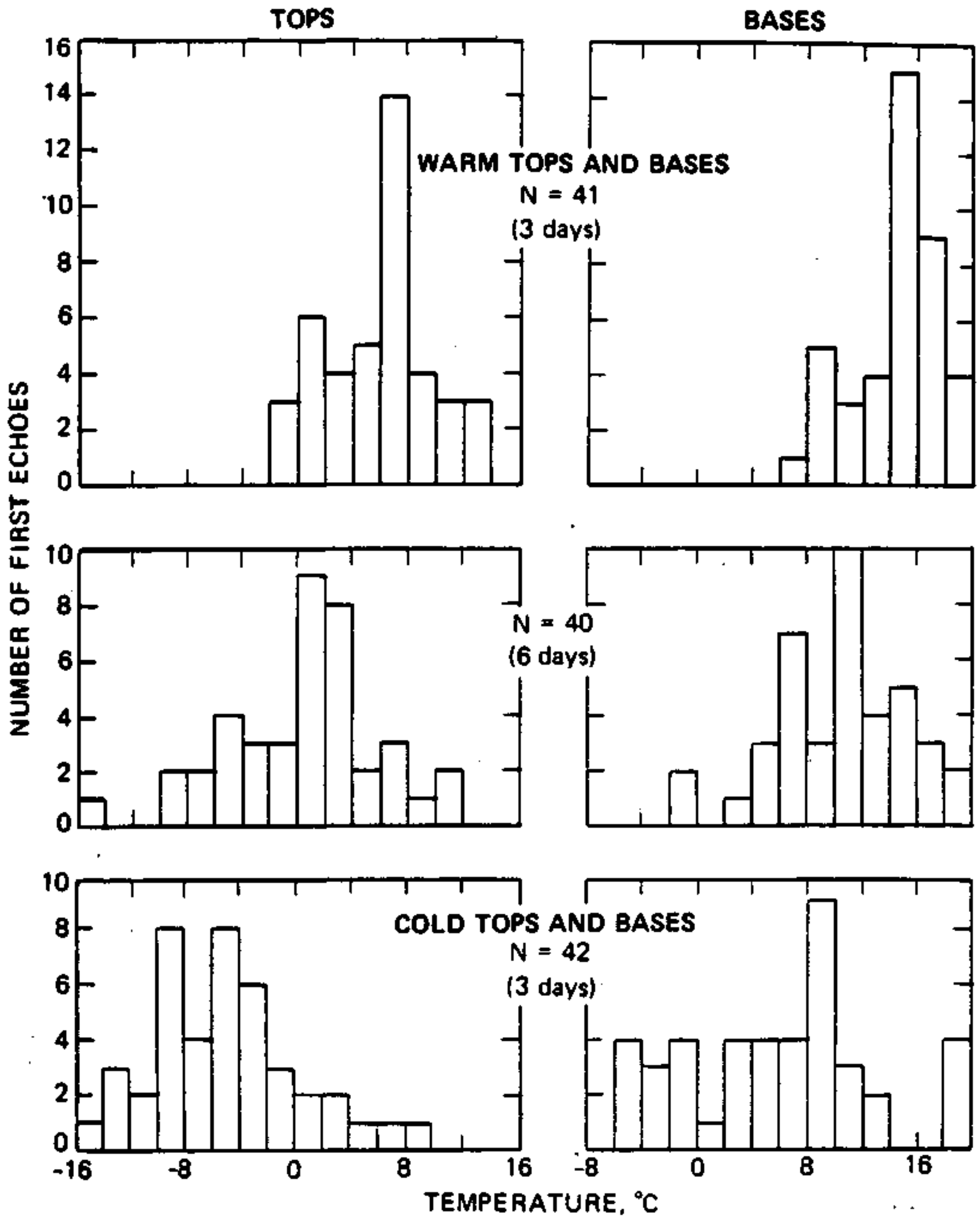
The distribution of the first echo base and top temepratures for 12 days in Ohio were tabulated by Battan (1953). The daily mean temperatures of bases and tops differed by as much as 10 to 12°C (Figure 13). Also, there was a suggestion of an inverse relationship between the height of the freezing level and the height of the echo, with the colder first echoes associated with a lower freezing level (excepting 10 September 1947). More of the echo then, was found to be colder than 0°C on average.

Figure 13. The height of the freezing level and the average temperature of the first echo top and base on 12 summer days in Ohio during the 1947 Thunderstorm project. The number of first echoes found on each day is located above the date. After Battan, 1953.



The distributions of echo bases and tops, stratified into 3 groups based on the daily mean echo base temperature, are presented in Figure 14. On days with the warmest mean echo base temperature, a much narrower distribution of bases and tops are found. Almost all of the first echoes on these days originate entirely below the freezing level. On days with the coldest mean temperatures, for both first echo bases and tops, distinctly broader distributions are found. However, only 17% of the first echoes are totally warmer than 0°C, and only 26% are totally colder. Thus, over 50% straddle the 0°C isotherm. The distribution of echo temperature is similarly broad on the 'transition' days. A closer look at the daily variation in first echo characteristics might be useful in delineating possible reasons for differences in amount of cloud growth on any particular day.

Figure 14. The distribution of first echo bases and tops, stratified by the daily mean temaperature of the first echo base. After Battan, 1953.



2) Numerical Studies

Modeling studies lend support to the importance of dynamic influences on cloud growth as suggested by the results of Changnon (1978), as well as Changncn (1976). Several numerical models of warm cloud processes have been used to simulate initial development of precipitation in urban influenced clouds Johnson and Dungey (1978), Ochs and Semonin (1979), and Johnson (1982). While these models were directed at the microphysics of urban echoes, they also showed the important effect of updraft velocity on the height of the echo. With a strong updraft, the echo top height will be increased. The bases will be increased also because of the updraft speed and because the amount of sedimentation of larger drops will be reduced. It would seem reasonable that the updraft velocities of the more organized echoes, possibly under the influence of a more organized atmosphere, would be stronger than those of isolated echoes. Also note that the difference in first echo characteristics is much greater when stratified by organization than when examined for urban-rural difference. The next section will examine more closely aggregate storms which can take the form of a line, a cluster of echoes distinctly separate from each other (an area of convective activity) or a cluster of echoes which are joined together.

E) SUMMARY

1) General Characteristics

Echoes when first detected in the midwest form near the 0°C isotherm. A summary of the percent of echoes forming above, below and stradding the freezing level is presented in Table 5, along with the first echo mean height and temperature characteristics. Differences are found to occur in the mean values, from project to project. These may be due in part to the radar sensitivity or to the manner in which the data were analyzed; and to geographic or climatological factors; and in the case of the Thunderstorm data, due to a limited number of echoes sampled.

Evidence suggests however that the thinner, probably younger echoes are more likely to form below the freezing level. Proportionally more of both the Thunderstorm clouds as a whole, and the small subsample (N=486) of METROMEX first echoes (selected with an initial thickness of less than 1 km) occur below the 0°C isotherm. The total sample of echoes observed in METROMEX are thicker, with fewer echoes totally warmer than 0°C, and with more echoes straddling the freezing level.

Table 5. a. Percent of echoes forming completely above 0°C; completely below 0°C; or with tops below and bases above 0°C from the Thunderstorm Project (TSP), Project Whitetop (WTP) and METROMEX (MMX).

	Group	N	Totally Warmer N	Totally Warmer %	Totally Colder N	Totally Colder %	Echo Base >0°C Echo Base <0°C N	Echo Base >0°C Echo Base <0°C %
TSP	A	47	26	55	7	15	14	30
	B	35	19	54	3	9	13	37
	C	30	18	60	2	7	10	33
	All	112	63	56	12	11	37	33
WTP	All	*		50*		10*		40*
MMX	All	4553	1825	40	326	7	2402	53
	Smallest	486	334	69				

Table 5. b. Mean height and temperature of first echo bases and tops from the Thunderstorm Project, estimated from growth curves and from METROMEX.

	Group	N	Tops Ht_T km	Tops T_T °C	Bases Ht_B km	Bases T_B °C	Thickness km	Ht_{max} km
TSP	A	41	4.9	-1.1	3.0	8.8	1.9	5.2
	B	30	4.3	0.8	2.7	10.2	1.6	6.4
	C	26	3.9	2.1	2.4	11.7	1.5	8.5
	All	97	4.4	0.35	2.7	10.0	1.7	
MMX	All	4553	4.6	-2.0	2.4	11.0	2.2	
	Rural	3413	4.6	-2.3	2.4	10.8	2.2	
	44 Days	1950	4.7	-2.8	2.5	9.8	2.2	
	Smallest	486	3.7	+2.0**	3.0	6.4	0.7	

* Approximate values based on 3 summers of Whitetop data (Braham, 1964).

** Value given by Braham and Dungey (1978) is -2.0°C; it is believed from examining the echo top height that an error was made in the sign of the echo top temperature.

In looking at the total distribution of values from each project, of either height or temperature of the first echo bases and tops, one is struck with the distinctively broad range of values (Figures 2, 4b, 10). In some cases, a unimodal distribution is found. Others are more multi-modal [e.g., Thunderstorm base and top temperature; Whitetop base and top height; and METROMEX base heights] or at least have more than one peak value.

In examining the Thunderstorm data on a daily basis, and stratifying the echoes by mean daily cloud base temperature, three populations of echoes seem to be distinquishable: a warm group, a transition group, and a cold group. Unfortunately little other information is readily available from these 12 days, such as the echo growth characteristics, daily rainfall, or synoptic classification. It would be interesting to examine other first echoes with supporting measurements to verify such a classification (based on daily cloud base temperatures) and to determine what impact this would have on rainfall production.

2) Growth Characteristics

A large fraction of the first echoes from these 3 studies exhibited little or no growth after initial detection. In Whitetop (Braham, 1963), only 44% of the single isolated clouds which rained, grew. Only 9% grew as much as 1.5 km and 1% as much as 3 km over their entire life. Only 6% grew for more than 9 minutes. This would seem to indicate that rain can be produced quickly from rather small echoes.

From the 3-year Whitetop sample (Johnson and Dungey, 1978), echoes were found to last from 0 to 60 minutes after detection, with 60% lasting less than 15 minutes. They in addition, estimated the proportion of total rain falling from the distribution of echoes. It appeared that 70% of the rain (time periods with rain), fell from echoes lasting more than 15 minutes. While the shorter-lived clouds most likely contribute only 30% of the total rain volume, this is still a significant amount.

From the METROMEX sample of first echoes with a thickness of less than 1 km (again presumably the youngest echoes), Approximately 68% showed some growth in the first 3 minutes after detection. Approximately 19% grew more than 1.5 km. In stratifying the echoes by amount of growth, a trend was found in the median value of cloud top temperature: +5°C for those growing more than 1 km, +4°C for those which grew; and +2°C for those showing zero or no growth. However, the distribution of cloud top temperatures were similarly shaped (uni-modal) with a common range for all stratifications. Perhaps grouping by cloud base temperature would provide more fruitful results. The results of Changnon (1976, 1978) suggesst the importance of larger scale dynamic influences on cloud growth. The numerical models of Johnson and Dungey (1978), Ochs and Semonin (1979), and Johnson (1982) indicated that effect of updraft velocity on the height of the echo. Cloud base temperature possibly reflects both scales of dynamic influences.

While there is considerable information as to the initial charzcteristics of these echoes, little information is available to distinquish which first echoes are most likely to grow and to produce the most rain. Further study of echoes stratified on a daily bases by mean daily cloud base temperature may be promising.

Multicellular Storms

Until now we hav£. looked mainly at the growth characteristics of individual cells, either isolated or adjacent to a larger storm. However, most convective rainfall is produced by more organized agglomerates of clouds, such as 'multi-celled storms' and/or 'cloud lines' or 'cloud areas'. How these storms grow and how their organization is manifested will be addressed in this section.

Changnon (1976) examined the life histories of 565 rural radar echoes, observed during the 1973 St. Louis METROMEX operations. A TPS-10, 3 cm height finding radar was employed, as in the case of the first echo studies. Photographs were taken of each RH1 sweep (approximately l/sec), for a 2° beamwidth. Three-dimensional information were derived from this data. The range resolution was .8 km; at 60 km the beam was approximately 2 km wide; at 88 km, about 3 km wide. The minimum detectable signal was 27 dbz. Of the rural echoes, 129 or 23% eventually merged into a larger mass, and 436 were 'isolated'. In this study, an echo was considered isolated, even if it embraced one or more nearby (within 4 km) echoes that grew along side it. Only if two echoes had existed at least 10 minutes, had been more than 8 km apart initially, and then joined for at least 5 minutes at the minimum detectable signal to form 1 or more cells, would they be said to have merged.

The mean heights, growths and durations are distinctly different for the 2 types of convective systems thus defined (Table 1). Echoes that later merged with another were taller at initiation, grew more and were longer-lived than those echoes which remained more isolated. Thirty-five percent of the merged echoes grew more than 3 km and only 6 percent of the more isolated echoes grew as much. The merged echoes also, lasted on average 3 times longer than the others.

Table 1. Summary characteristics of 565 rural echoes from the summer of 1973 in the St.Louis area, studied throughout their life histories, partioned into whether or not they merged. After Braham, 1981; Changnon, 1976.

	Merged	Non-merged
Sample	129	436
Avg top hts (km)		
initiation	6.7	5.8
abs. max	10.7	7.0
No. that grew		
300 m	111 (86%)	188 (43%)
3 km	45 (35%)	28 (6%)
Avg. max 5 min growth (km)	2.4	0.6
Avg. duration (min)	73	25

Due to biases caused by attenuation of the 3 cm signal, no reflectivity (or rainfall) information was derived from the data. As the height reached by the echo often reflects the strength of the convection, the amount of precipitation, and the average height of the merged echo is nearly 4 km taller than that of the non-merged echo, we can assume that the merged systems produced more rainfall than those which were more isolated. While these merged systems are considered to be more organized, no information was presented as to the shape of the storms, or their degree of organization, i.e., were the convective elements in the shape of a line or of a more amorphous agglomerate.

A. STORM GROWTH

During the Thunderstorm Project, the growth characteristics of 32 thunderstorms which initially formed near the freezing level, and reached a maximum altitude of 9 km were examined. This scale of storms would likely encompass the 'isolated' Changnon (1976) storms, and some of his 'mergers' as well. It was noted that most of these storms grew in height in a series of steps. Between these steps a short period of time elapsed during which the top of the echo either descended several thousand feet or remained constant. Some of these steps were obviously new cells growing in close proximity to the existing one. In other cases, it appeared that the updraft region of a single celled thunderstorm contained several maxima separated by either time or space. Still in other single cell cases, no large variation in ascent and descent rates could be found. Of the 32 storms, 24 had 2 or more observable turrets (Table 2). In the mean each succeeding turret was taller than the previous one: the second, 5 km taller than the first cell; and the third cell, somewhat taller than the first. The mean time between successive turrets was 17.8 minutes. This is approximately the duration of the mean growth period of a single convective cell found both by the Thunderstorm Project and Project Whitetop. It was hypothesized that the predecessors 'wet' the environment, whereby successive turrets entrain moist air. As a result, less evaporation is required to maintain saturation, so that a smaller amount of heat is removed and thereby causing less deceleration of the updraft.

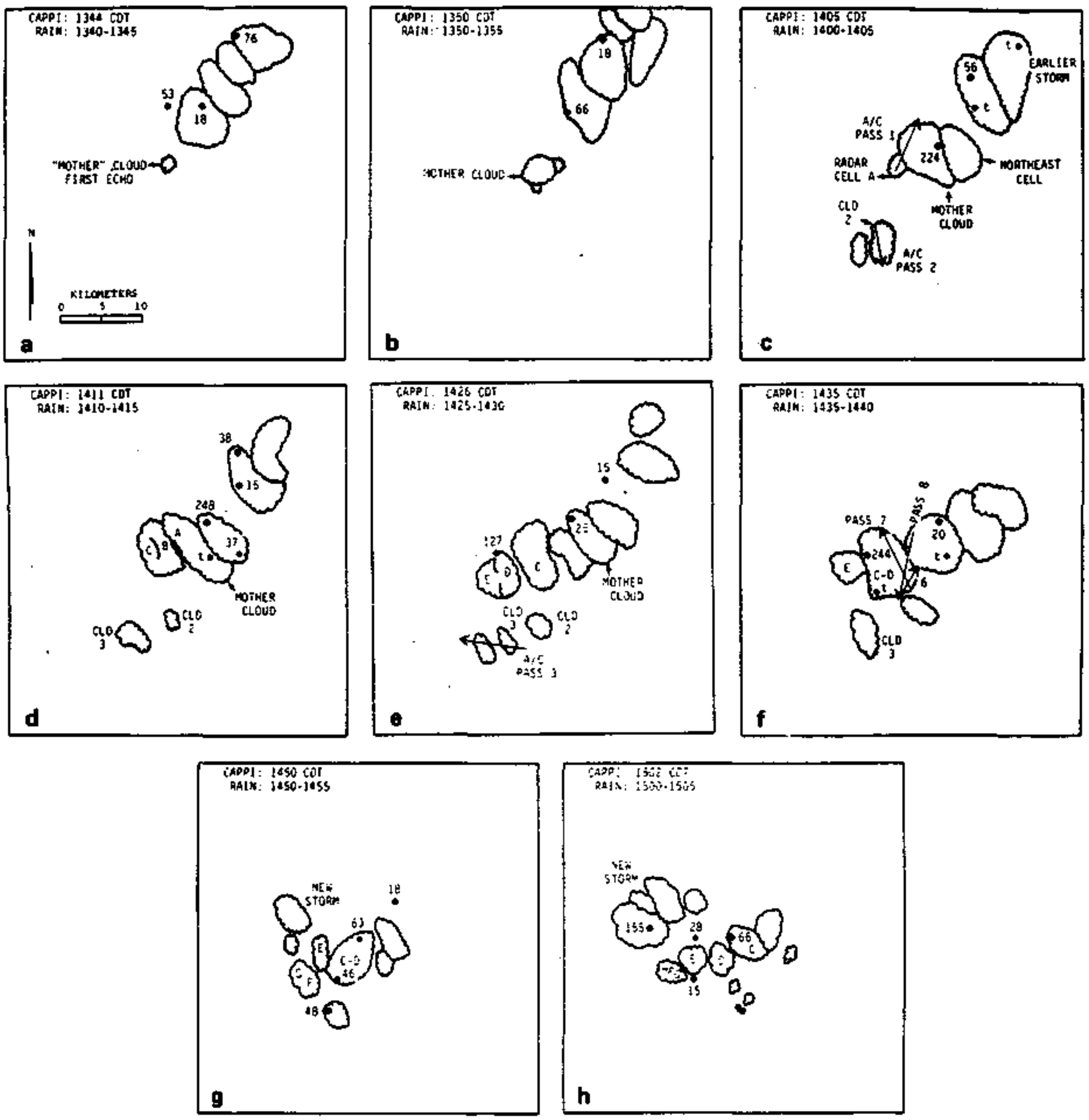
Table 2. Summary of characteristics of successive turrets of 32 multi-turreted thunderstorms. Data based on observations of Ohio thunderstorms with the AN/TPS-10 radar. Byers and Braham, 1949.

Sequence number of turret	Number of cases	Mean height above preceding maximum (km)	Mean time since preceding maximum (min)
1	32	*4.85	*17.5
2	24	1.58	17.4
3	10	.12	18.9
4	1	2.13	17.1

* height and time of maximum growth measured from level and time of initial detection of radar cloud.

An example of this type of growth was presented by Ackerman and Greenman (1978). A cloud complex that was part of a small but active line formed in SW Illinois during July of 1973. The initial echo (mother cell) of the complex was a small and rapidly growing cell, and developed a few km to the SW of an older multicellular complex. Most of the new cells occurred as a series of feeder cells forming successively on the southwest end of the mother cell. There was very little translation of the individual echoes during their development (Figure 1). The cloud complex as a whole propagated westward (up wind).

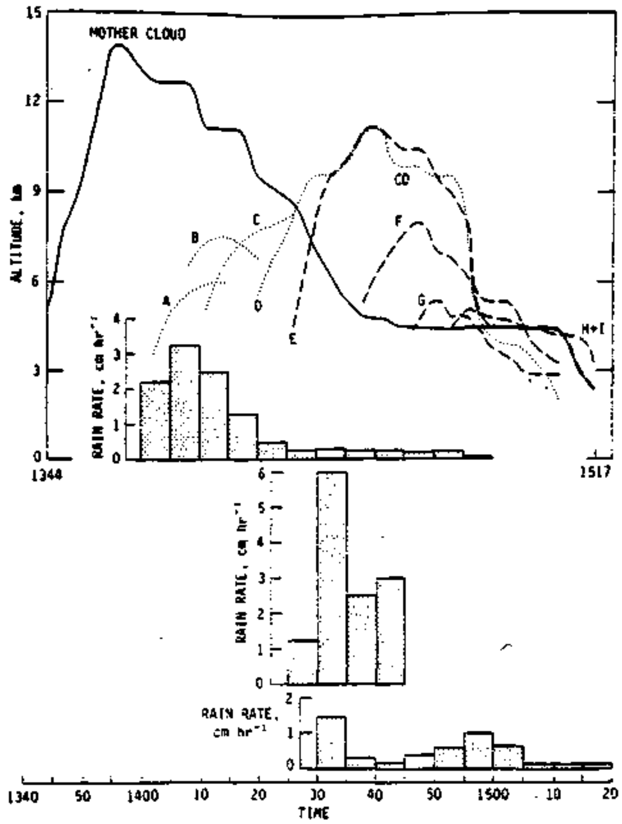
Figure 1. Radar echoes and surface rainfall at 8 times during the life cycle of the storm studied [Scalloped outline give 5000-ft CAPPI limits; rainfall is in 5-min rates (10^{-2} cm/h); airplane traverses shown by arrows in (c), (e), and (f)]. Ackerman and Greenman, 1978.



The initial echo had a top height of 4.6 km and was 3 km in diameter. Subsequent growth was explosive both horizontally and vertically. The echo expanded to 5 km in little over 5 minutes, apparently engulfing nearby smaller clouds. It reached its peak height of over 14 km in 12 minutes. Moderate to heavy rain was detected 16 minutes after initial detection (Figure 2).

Growth in height of the other radar echo cells (A - H) is viewed in Figure 2. As the feeder cells developed, they approached and then merged with the mother cloud. Although, the summits of C-D and E did not reach heights as great as the mother cell, their resultant precipitation was at least as intense (more intense in the case of C-D). Dynamic interaction between the feeder cells was suggested by the time histories of the summits of the main echo. As each new feeder cell developed (echoes A thru D), the descent of the mother cloud either decreased or slowed.

Figure 2. Radar echo tops (line graphs) and 5-min rain rates (bar graphs) versus time, CDT. Ackerman and Greenman, 1978.



The processes which initiate preferential development of new convective cells adjacent to pre-existing ones, such as in the case of successive cell growth or alternately, processes which sometimes lead to subsequent 'merging' of cells have been the subject of both observation studies and numerical simulations (Westcott, 1984).

Some 40 years ago, Byers and Braham (1949) examined both the location of new cell growth and also proposed processes which might be responsible for their formation. The probability of new cell growth around existing cells were calculated for 3 summer days in Ohio, for distances greater than 14.5 km (9 miles), in the area between 14.5 km (9 miles) and 4.8 km (3 miles) from adjacent existing cells, and in 4 quadrants within 4.8 km (3 miles) of the older cell (Figure 3). New cells were found to be 9 times more likely to form between 2 existing cells which were < 9.6 km apart, as they were when the cells were separated by more than 14.5 km (9 miles). New development was 5 times more likely to occur on the leading edge and the left lateral boundary, than beyond the 14.5 km range. On one of the 3 days, however, no cells formed between the 2 parent cells (< 9.6 km apart). The development was largely around the periphery of the parent cells. This would indicate that different mechanisms could be acting to initiate new cloud growth (Table 3).

Figure 3. "Chart shoving the relative probability of the formation of new thunderstorm cells in the vicinity of parent cells. The hatched areas represent the PPI radar echoes from the parent cells and the irregular closed curves represent the limits of the 3- and 9-mile (4.8- and 14.5-km) zones surrounding the echoes. The numbers indicate the relative probability of new echo (cell) formation in the zones and quadrants with the probability outside the 9-mile (14.5 km) zone being considered as unity." Byers and Braham, 1949.

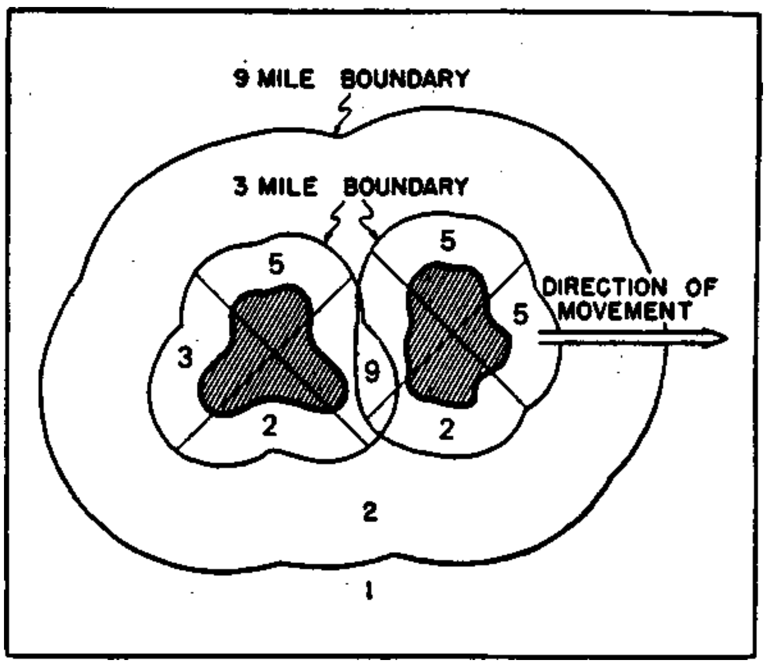


Table 3. Number of new echoes which formed per 1000 sq. mi. per 5 min in designated areas: around parent cells. Ohio 1947. After Byers and Braham, 1949.

	Aug 14	Aug 25	Sept 12	Total	Average (or Relative Probability)
Leading	9	4	2	15	5
Trailing	2	6	2	10	3.3
Rt	3	1	1	5	1.6
Lft	5	5	4	14	4.7
3 mi. band	2	4	2	8	2.7
Dual overlap	13	14	0	27	9
3-9 mi.	1	4	1	6	2
Outside 9 mi.	1	1	1	3	1
Total	36	39	13	88	

Four possible explanations for preferential development of new cells adjacent to older echoes were porposed by Byers and Braham (1949).

1. Cold outflow air underrunning and lifting neighboring warm air.
2. Mixing of saturated air entrained from the parent cell, creating a more "protected environment" than the relatively dry air surrounding and entrained by the isolated cell.
3. Addition of moisture to neighboring air by precipitation falling from an overhanging canopy created by the parent cell.
4. Local areas of surface convergence or of upper air divergence causing spontaneous generation of updrafts.

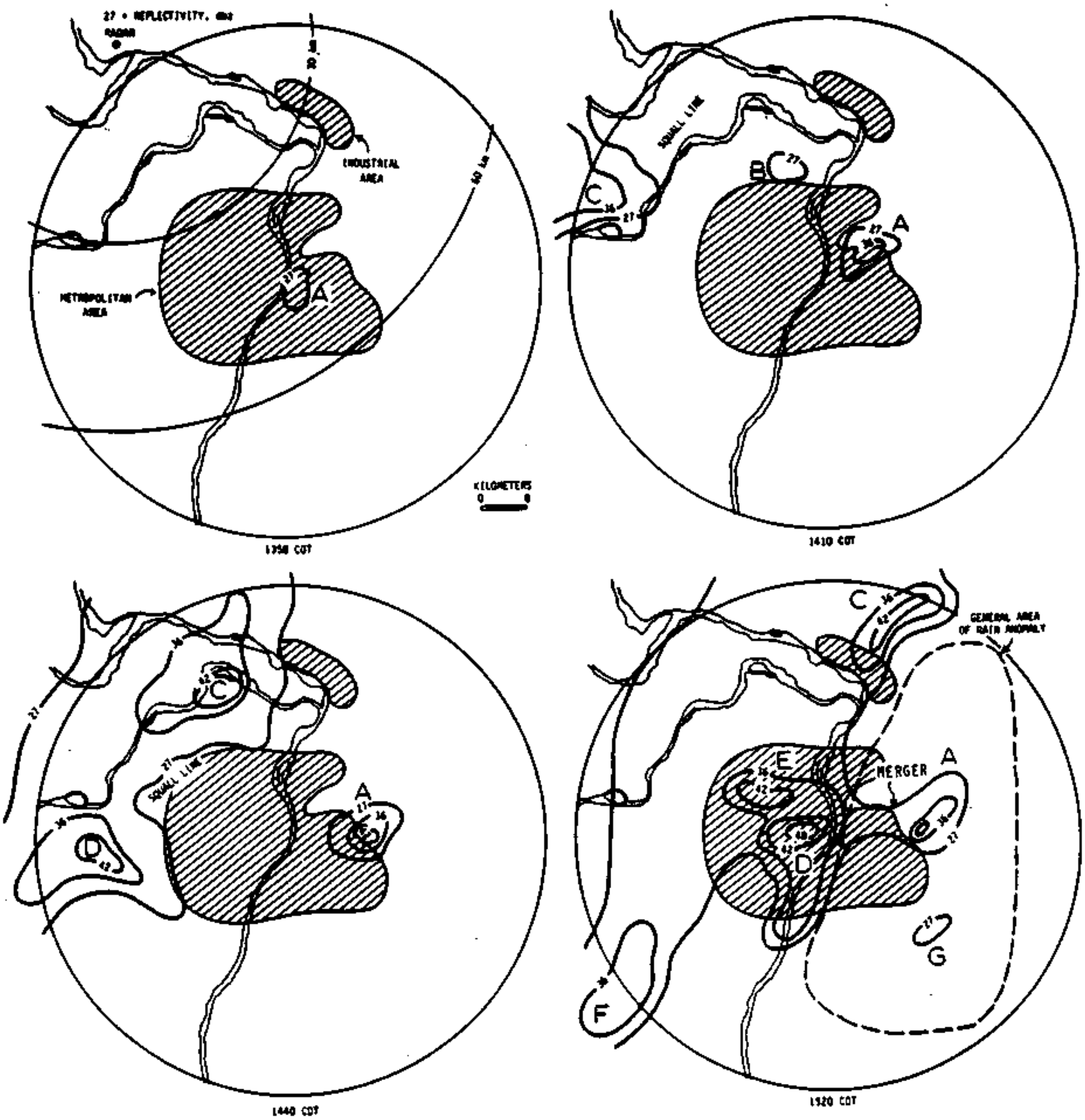
A favorable environment for neighboring convective growth likely would be an environment where cells could be "encouraged" to merge; that is, with a higher density of cells there would be a higher probability of merging. The above processes then could be acting to initiate the union of cells.

More recently, observational studies and numerical models have suggested additional processes which would lead specifically to the merger of cloud cells into a more organized larger mass. Analysis of raincells derived from a dense raingage network in St. Louis as part of METROMEX (Changnon et al., 1976) indicated that:

5. Differential motion of existing cloud entities could result in their union.

An example of a line overtaking a slower moving cloud cell is presented in Figure 4. Cunning et al (1982), also proposed that differential motion could be an important factor in promoting mergers. In this case, new growth was initiated between cells whose motions were converging.

Figure 4. Radar depiction of a line of echoes overtaking a slower moving echo (A). Changnon et al., 1976.



Another dynamic mechanism which might result in the merger of clouds cells was illustrated by the numerical models of Orvill et al. (1980), Yau (1979), and Turpeinin (1982)):

6. A favorable horizontal pressure gradient between adjacent clouds resulting in enhanced convergence.

This mechanism is particularly elusive to observe in nature because of measurement problems. However, the work of Cunning et al. (1982), suggested such a process.

Finally, a corollary to the third proposed process could be added:

7. Cooling due to the evaporation of precipitation and detrained condensate from older clouds, resulting in the destabilization of the ambient air.

Shelves or shallow extensions are commonly seen on active but mature convective clouds in the Midwest. It is hypothesized that these play an important role in cloud aggregation. These shelves by seeding from above with large water drops or ice particles, often initiate small clouds around the bases of large ones. Also, evaporative cooling at middle levels destabilizes the lower 2 or 3 km, thus encouraging new clouds to develop in the gaps between established cloud masses. Not only is the air destablized, but also is moistened such that less energy is required to maintain saturation. This mechanism and numbers 2 and 7 are indicative of microphysical processes which can lead to a dynamic change in the evolution of a cloud area. The others are considered dynamic processes which could lead to both dynamic and microphysical changes as well.

It is likely that more than one of these processes are acting in tandum with another or in response to another. The importance of cold air outflow in initiating new growth and in encouraging the union of clouds, has been well documented by a number of observational studies, (Cooper, 1982; Ackerman,. 1982; Simpson, 1980; Cunning et al., 1982), and has been investigated through numerical modeling as well (Turpeinin and Yau, 1981; Tao and Simpson, 1984). However, we have found that at least in the Midwest, surface convergence is not always the dominant triggering mechanism for cloud aggregation. In a preliminary examination of cloud development employing 3-dimension radar reflectivity fields (Ackerman and Westcott, 1984), storm outflow appeared to be the primary cause of a cloud union in only 2 of 5 'merging events'. In 2 cases, a cloud shelf extending from mid-level provided the initial impetus for cloud aggregation. In one of these cases, surface convergence also was present. In a fifth event, evaporating middle level cloud shelves preceeded the union of 2 clouds at low levels by several minutes. This preliminary study indicated that indeed different processes could be operating at any one particular time, and also that during the life of any one group of storms, all the processes could have been acting.

Cloud interactions are initiated by both microphysical and dynamic convective scale influences, and thus such interactions likely will be reflected in both the dynamic and microphysical evolution of the storm. While the physical structure and to some extent the microphysics can be obtained with comparative ease through use of 3-dimensional radar reflectivity data, to extract the vertical velocity structure still requires a mammouth effort. However, a project has been undertaken at the ISWS to do just this; to track the evolution of several merging cloud systems, to determine both the factors leading up to the merger, and what effect merging has on the subsequent evolution of the storm. It should be kept in mind that convective scale influences are only one factor in cloud organization, it also is a manifestation of or can be triggered by meso- or synoptic-scale influences concurrently operating.

B. STORM ORGANIZATION

Many of the more organized storm systems in the Midwest are observed as a line of radar echoes, often with a SW-NE orientation, moving from the west. Typically, the older cells making up the line are to the north, and developing cells to the south (or on the right flank of existing cells). Not all of the cells making up the lines are necessarily joined. While each of the 3 investigations reviewed here uses a somewhat different definition of squall line, important information can be derived from each study: Byers and Braham, 1949; Changnon and Huff, 1961; and Dzurisin and Jameson, 1980.

1) During the summer of 1947, extensive radar data was collected using a high-powered 10 cm radar in Ohio on 56 days by the Thunderstorm Project. Lines of thunderstorms were observed on 32 of these days. Squall lines generally are associated directly or indirectly with a strong surface cold front. During this summer, on 19 of the days (about 60%), the lines formed ahead of a strong surface cold front; on 6 days the lines formed along a surface front; and on 7 days, no apparent connection was found between the lines and a surface front.

Observed weather conditions associated with 27 squall lines which passed over the project micronetwork are presented in Table 4. The lines have been sorted by surface synoptic type and the pre-cold frontal lines by distance ahead of the cold front. Too few samples prevent strong conclusions from being drawn from this sample of storms, particularly in reference to the stationary front squalls. Several observations are of interest, however. First, the majority of air mass lines moved into or initiated over the micronetwork during the time of maximum heating, 1200-1800 EDT. None of these storms produced an excessive amount of rainfall. In general, air mass squall lines are typically on the order of 200 km (125 mi) in length with echoes making up the line separated by as much as 24 km (15 mi) in some areas. Most of these lines in this study however, were 120-160 km (75-100 mi) long. They tended to be parallel to the winds below 3 km, and were less well defined than the typical pre-frontal squall line.

Just less than half of the pre-cold frontal squall lines began or moved over the network between 1200 and 1800 EDT. Five out of six of the heaviest rains measured, were from this type of squall line. The mean maximum gust front wind speed was much greater from these storms 16 m/s than from the air mass ones 12m/s. In general, the pre-cold frontal squall lines were found to be longer than the other types of lines.

Table 4. Observed weather conditions associated with squall lines passing over the Thunderstorm Project micronetwork, stratified by surface synoptic type, and the pre-frontal squall lines by distance ahead of the cold front. Began and spent at least 1 hr of duration with in this 6 hour time period: EST (CDT): 0-6 A, 6-12 B, 12-18 C, 18-24 D. After Byers and Braham, 1949.

	Time of Day	Pre-Cold Frontal Dist. Ahead (km)	Max. Sta. Rain (in)	Max. Rain Dur. (min)	Dur. Over Net. (hr)	Sfc. Gust (km)	Dev. from Prev. Wind (km)
May 25	C	24.1	.16	8	1.5	15.6	13.4
June 11	C	72.4	.91	19	1.25	14.8	10.3
June 29	D	80.5	.40	10	2.5	16.5	12.0
July 31	B	80.5	.06	3	4.75	10.7	5.8
July 14	C	112.6	1.60	45	2	20.1	17.9
May 29	B	120.7	.18	30	1	19.7	14.8
July 18	D	144.8	.15	7	1	11.2	6.7
June 13	D	193.1	1.28	28	1.5	18.8	15.6
Aug 7	B	209.2	2.13	33	4.5	28.2	26.8
July 13	C	233.3	.28	155	4	23.2	19.2
Aug 14	C	249.4	.98	15	3	20.1	18.6
Sept 5	B	273.5	.30	42	1	9.8	7.2
Sept 13	A	337.9	.10	7	3	17.9	16.1
June 2	A	498.8	.14	20	.75	15.6	11.6
Sept 12	C	514.9	.50	70	.75	13.9	13.0
Sept 4	C	756.2	.04	15	1.5	9.4	8.9
Sept 11	C	772.3	.12	3	1	11.6	9.4
		Stationary					
Aug 5	B	Frontal	.37	15	1.5	21.5	20.1
Aug 6	C		.36	11	1.75	21.9	20.1
Sept 9	C		1.48	30	2	20.1	19.2
June 7	B	Air Mass	.56	11	1.25	17.4	10.3
June 27	D		.68	20	1.25	17.9	16.5
July 10	C		.46	15	1.25	9.4	6.3
July 15	C		.13	6	2.5	8.9	6.3
July 16	C		.39	15	.5	8.5	6.3
Aug 17	C		.30	9	1.25	9.8	8.5
Sept 10	C		.56	40	2	16.5	14.3

An area of convection or a "squall-line zone" often preceded a front. In the squall-line zone, several lines would be present, but were difficult to individually distinquish. Generally during the night or in the early morning, individual lines were most easily delineated. The increase in number of echoes and the rapid increase in their size at mid day likely caused by surface heating, made it difficult to distinquish separate lines. In looking at 5 cases, they found the maximum squall zone widths to vary from about 175 to 400 km (110 to 250 miles), with the ends of the squall zone extending beyond the edge of the scope, 322 km (200 miles). This is 2 to 10 times wider than the widths of the squall lines in (Table 5). The most frequent number of lines found in a squall zone was 3, with the maximum at any one time, five. Distances between adjacent lines ranged from about 15 to 300 km (10 to 185 mi). The lines tended to be parallel, though not in every case.

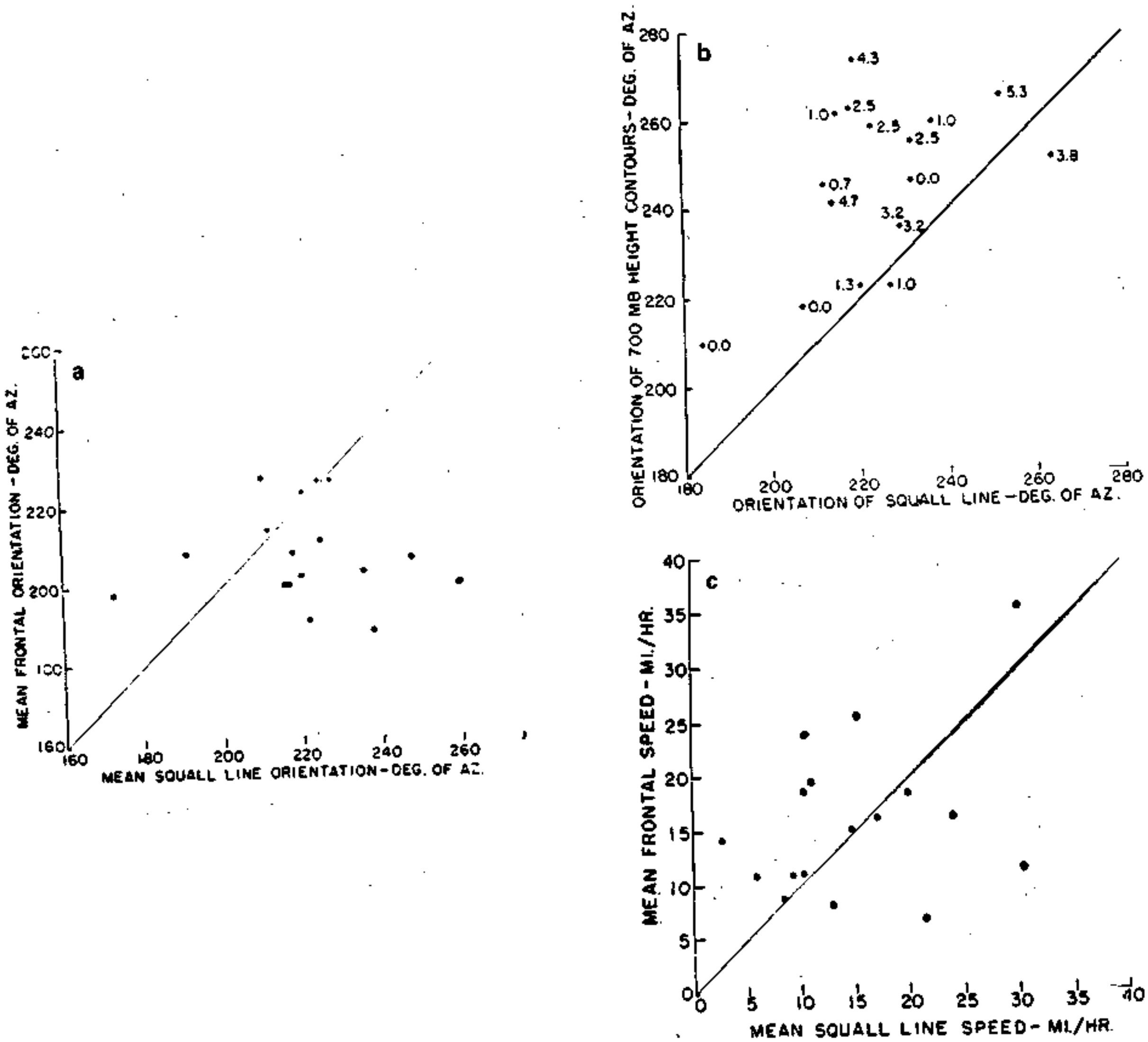
Table 5. Lengths and widths of 11 squall lines observed on the 200-mile radar scope during the 1947 Ohio operations. After Byers and Braham, 1947.

Date	Mean total length (km)	Mean solid length (km)	Mean maximum width (km)
July 14	328	134	40
July 14	282	103	76
July 14	224	69	43
July 18	253	129	48
Aug. 14	365	243	71
Aug. 14	103	77	27
Sept. 5	261	208	61
Sept. 5	253	238	56
Sept. 12-13	174	143	56
Sept. 12-13	338	282	
Sept. 12-13	299	201	101
Mean	262	167	58

Byers and Braham, (1949) in looking at individual squall lines found their mean total length - including all echoes which appeared, to be part of the line - to be 263 km and the mean solid length where all echoes associated with the line were separated by less than 16 km (10 miles) to be 167 km (Table 5). These solid lines are more similar in definition to the later studies. In general these lines were parallel to the related cold front, but there was a tendency to be oriented clockwise (+13°) to the front, and counterclockwise from the orientation of the overlying 700 mb contours (Figure 5a,b,c). They move with speeds of 1 to 13.4 m/s (2-30 mph).

In looking at the individual elements of the squall line ranging in size from 1.6-48 km (1-30 mi), it was found that they moved toward a direction clockwise to the long axis of the squall line. Elements in any one line could vary in velocity by as much as 27 and 6.3 m/s (14 mph), and averaged 12 and 2.5 m/s (5.6 mph). The number of elements in a line ranged from 4 to 5 small echoes in the early stages to as many as 40 to 50 at the time of maximum intensity. For the most part, they were found to form and dissipate on a given squall line. In a few cases isolated echoes were found to move or develop toward a line and become part of it. A new line was formed in 2 instances by the splitting of an intense line. In several cases, 2 adjacent lines having different orientations tended to merge, showing an apparent 'transfer' of echoes from one line to another.

Figure 5. In this study, the segment of the front which was used in the frontal orientations was determined by projecting the ends of the squall line back to the front along lines perpendicular to the front. The points of intersection of the perpendiculars and the front were connected with a straight line which was then considered to represent the orientation of the front. The orientation of the squall line was considered to be the orientation of the major axis of the line which, in most cases, could be determined with little difficulty. a) A scatter diagram relating the orientation of the squall line to the orientation of the associated cold front. (Based on means of hourly observations.) The correlation coefficient for this distribution is -.69. b) A scatter diagram showing the relationship between the orientations of squall lines (from radar observations) and of contour lines of the height of the 700-millibar surface. The difference between the time of the radar observation and the 700-mb chart is shown in hours beside each point. The correlation coefficient for this distribution is .49. c) A scatter diagram relating the speed of movement of the squall line to the speed of movement of the front. Based on means of speeds determined from hourly displacements. The correlation coefficient for this distribution is .58. Byers and Braham, 1949.



2) Changnon and Huff (1961) used a CPS-9, 3 cm radar located at the Champaign airport with a range of 230 km (125 nmi), and classified an echo or group of echoes as a line if the echo(es) had a rectilinear appearance, with a length of at least 92.6 km (50 n mi). Additionally, a group of small echoes were termed a line if at least 4 echoes were present within a minimum distance of 92.6 km (50 nmi), and if no more than 18.5 km (10 nmi) separated any 2 echoes. Two lines in close proximity were considered to be distinct if separated by 46.3 km (25 nmi) or more; this distance could be less if the lines formed separately. If 2 lines moved within 27.8 km (15 nmi) of each other, and the angular difference of the orientation of the major axis was 30 degrees or less, they were considered to be one line. In this case, the smaller or less intense line was terminated. In this study, analysis was limited to systems where the whole radar history was observered. One hundred ninety-six (196) radar depicted lines were examined, from August 1954 through 1955 in an area covering all of Illinois and parts of the neighboring states.

The average length and width of 196 radar lines, and a subsample of 34 associated with severe weather were measured (Table 6). The lines ranged in length from 92 to 450 km. However, 87% were less than 279 km in length, and 51% less than 168 km. . The mean average length of all lines was 187 km, and for those with severe weather, 263 km. The average width varied from 5 to 68.5 km, with a mean value of 16.7 for all lines, and a slightly larger mean value of 20.4 km for those associated with severe weather. These dimensions may be somewhat less than those found by Byers and Braham (1947), because of the difference in radar characteristics, defination of the line and possibly the actual storm sample. The lines were primarily found to be oriented from the SW to NE (Figure 6). Movement was from the west with a mean speed of 12 m/s (Table 7). Radar line durations ranged from one-half to 15 hours. Fifty-eight percent of the storms lasted less than 2 hours. The median duration for severe storms was 4 hours (Table 8a). The lifetime of each line was devided into quartiles, and the growth tendency forr each quartile recorded. From Table 8b, one can see that 58% of the lines were growing in the first quartile of their life, and the percent then decreased. The opposite trend is found for the percent of lines which were decreasing in size. By the fourth quartile, 71% of the lines were diminishing in area.

Table 6. a. Frequency of the average length of 196 radar lines and a subsample of 34 lines associated with severe weather. b. Frequency of the average width of these same lines. Widths were determined at the center and at the 2 end poinds and averaged. These means were acquired every half hour and then averaged again of the life of the line. After Changnon and Huff, 1961.

a)

Average Length (km)	Total Sample	(%)	With Severe Weather	(%)
92-130	51	(26)	1	(3)
131-167	49	(25)	3	(9)
168-204	30	(15)	10	(29)
205-241	22	(11)	5	(15)
242-278	20	(10)	3	(9)
279-315	11	(6)	2	(6)
316-352	5	(3)	4	(12)
353-389	3	(1.5)	0	(0)
390-426	3	(1.5)	3	(9)
>426	2	(1)	3	(9)

b)

Average Width (km)	Total Sample	(%)	With Severe Weather	(%)
0- 7	44	(22)	1	(3)
7-15	72	(37)	10	(29)
15-22	46	(23)	10	(29)
22-30	15	(8)	10	(29)
30-37	10	(5)	3	(9)
37-44	3	(1.5)	0	(0)
44-52	3	(1.5)	0	(0)
>52	3	(1.5)	0	(0)

	Length (km)		Width (km)	
	Total Sample	With Severe Weather	Total Sample	With Severe Weather
Mean	187	263	16.7	20.4
Median	163	231	13.0	16.7
Maximum	450	450	68.5	37.0
Minimum	91	130	5.6	7.4

Figure 6. Distribution of line orientations determined from CPS-9 images, Frequency in each 20 degree sector, expressed as a percent of total lines. Median = 255. Severe weather median = 240. Total sample =196 lines. Changnon and Huff, 1961.

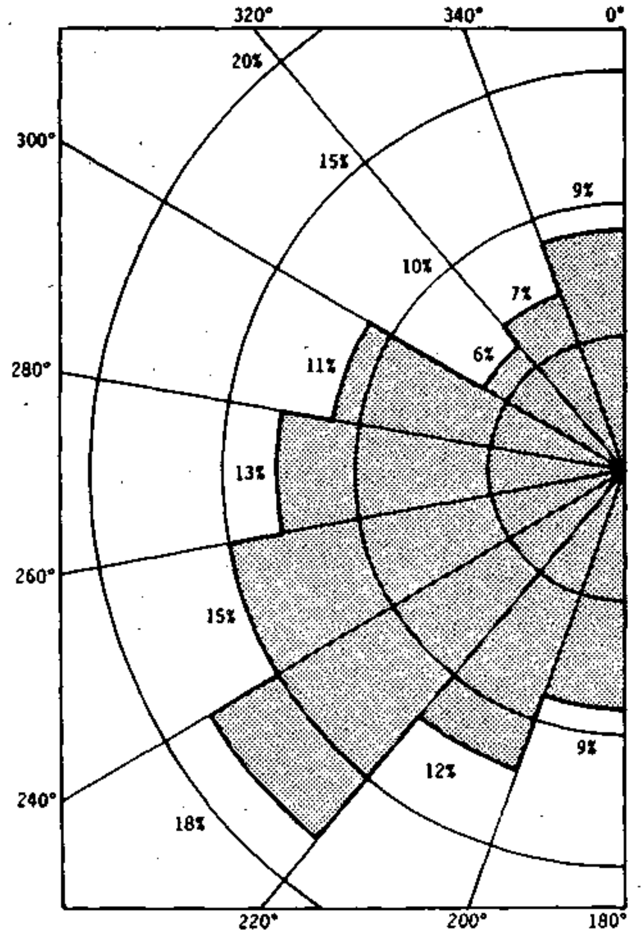


Table 7. a. Average line movement sorted by 30 degrees, expressed as percent of total lines. b. average line speed (of the center point of the leading edge), sorted by approximately 2.5 m.s (5 knot) intervals. After Changnon and Huff, 1961.

a) Direction of Line Movement

Sector (°)	% Frequency
10- 40	3
40- 70	3
70-100	3
100-130	4
130-160	4
160-190	3
190-220	9
220-250	15
250-280	22
280-310	12
310-340	15
340- 10	4
Total	196

b) Speed of Line Movement

m/s	Frequency #	Frequency %	# With Severe Weather
0.0- 2.6	9	5	0
3.1- 5.1	15	8	1
5.7- 7.7	22	11	0
8.2-10.3	36	18	3
10.8-12.9	20	10	4
13.4-15.4	27	14	5
15.9-18.0	19	10	7
18.5-20.6	16	8	3
21.1-23.1	9	5	3
23.6-25.7	6	3	0
26.2-28.3	6	3	4
28.8-30.8	4	2	2
≥31.4	7	4	2
Total		196	

Median	265°	Mean	13.9 m/s	18.5 m/s
		Median	12.3	17.5
Severe		Maximum	37.0	36.0
Weather Median	265°	Minimum	0	4.1

Table 8. a. Duration of lines sorted into one-half hour intervals, with number per interval expressed as a percent of total lines. b. Comparision of growth tendencies in each quaarter period of line duration, expressed as a percent of all 196 lines. After Changnon and Huff, 1961.

a)

Duration (hrs)	Total (%)	Lines with Severe Weather (%)
.5-1.0	26	0
1.0-1.5	20	3
1.6-2.0	12	12
2.1-2.5	7	6
2.6-3.0	9	9
3.1-3.5	5	6
3.6-4.0	4	22
4.1-4.5	5	12
4.6-5.0	2	0
5.1-5.5	2	6
5.6-6.0	2	6
6.1-6.5	1	6
6.6-7.0	1	6
>7.1	4	6
Total	195	34
Mean	2.6	4.3
Median	2.0	4.0
Maximum	15.0	8.0
Minimum	0.5	1.5

b) Growth Tendencies (% of all lines)

Tendency	1st	2nd	3rd	4th Quarter
I	58	32	26	10
N	21	37	28	19
D	21	31	46	71
	100	100	100	100
	IND	NID	DNI	DNI

The study by Changnon and Huff (1961), additionally examined the synoptic classification of 73 squall lines (Table 9), from the summer of 1955. Air mass storms and cold fronts accounted for 53% of the days with squall lines. All fronts, including: cold fronts, warm fronts, occluded fronts and stationary fronts accounted for 58% of the storms. This study also examined days with lines producing hourly rainfall amounts of greater than 1 inch during periods of radar observation. Air mass storms and cold fronts again accounted for 53% of the days, but with cold fronts being proportionally more frequent. Eighty-one percent of the heavy rain days were associated with some sort of front.

Table 9. Association of Squall Lines with Synoptic Systems. Changnon and Huff, 1961.

	a. Climatological sample (1955)		b. Heavy Rainfall sample (1955-1958)	
Synoptic Types	Number of Days	Pecent of Days	Number of Days	Percent of Days
Cold Front	21	29	14	37
Warm Front	5	7	6	16
Stationary Front	9	12	9	23
Occluded Front	7	10	2	5
Air Mass Storms	18	24	6	16
Low Center Passage	10	14	1	3
Upper Trough or Front	3	4	0	0
TOTAL	73		38	

These numbers are quite different from those of Byers and Braham (1949). Here, no storms have been classified as pre-cold frontal, while in the earlier study, 62 % if the lines were categoried as such. It is not clear if differneces in synoptic typing or in the actual difference in the storms considered from the two summers is responsible, (assuming pre-cold frontal storms were included as cold frontal, here). The summer of 1954 was one characterized by severe drought. The monthly distribution of radar lines gives an indication of how infrequent lines occurred during August and September of 1954 (Table 10).

Table 10. a. Time of line formation in the 0600 - 2300 cst period, expressed as a percent of total lines. b. Monthly line frequency data (includes data from August 1954-July 1955). After Changnon and Huff, 1961.

a) Time of Line Formation

Time of Line Formation 0600-2300 CST	Total (%)	With Severe Weather (%)
07 CST	1	6
08	7	3
09	7	3
10	8	3
11	8	6
12	7	12
13	10	17
14	8	6
15	8	6
16	9	11
17	8	6
18	8	9
19	4	0
20	2	3
21	3	3
22	1	3
23	1	3

b) Monthly Line Frequency

	# Days of Radar Oper.	# Days with Lines	Lines per Month	Ave. # Lines	Max. # Lines per Day
March	24	5	19	4	7
April	21	11	32	3	8
May	26	14	34	2+	5
June	26	20	62	3	12
July	21	18	88	5	16
August	22	3	5	2-	3
September	7	3	5	2 -	2

3) Dzurisin and Jameson (1980) in examining 35 mm photographs from a 10 cm radar, of low elevation (1-2˚) PPI images in 15 minute intervals, defined a line as a group of echoes with a length at least twice its width and extending at least 37 km (20 n mi). In examining 254 lines from central and northern Illinois, they found that relatively few occur as isolated lines. Lines occurred simultaneously with other lines, areas of echoes or isolated echoes 75% of the time. An area of echoes (119 total sample) was considered to be a group of 4 or more distinct echoes, not falling into a single line. The distance between an echo and its nearest neighbor had to be less than the maximum linear dimension across the - area, to be within the group. Isolated echoes (256 total sample) were a group of less than 4 distinct echoes. These were usually either first evidence of developing organized convection, the product of a dissipating system or the result of scattered thermally driven convection. Line6 formed from pre-existing echo systems 80% of the time: 20% from isolated echoes, 35% from areas of echoes and 25% from other lines. In addition, four out of five times, lines in the later part of their life would change into another echo system instead of dissipating at once: 40% into areas, 20% into isolated echoes, and 20% of the time into other lines.

Other line characteristics were also examined. About 60% of the lines were oriented from NNE-ENE to SSW-WSW. The motion of 44% of the lines as a Whole was to the SE, while the individual echoes within the line move to the NE 50% of the time and to the SE only 25% of the time (Figure 7). On average, a line would extend 150 km (Figure 8), and consisted of 9-10 distinct echoes. About 60% lasted less than 1 hour, and only 20% more than 2 hours (Figure 9). While this study encompassed lines smaller than observed by Changnon and Huff (1961), the mean diminsions are quite similar.

Figure 7. Normalized frequency distribution of: a. line orientation (8 directions); b. line movement (toward - 16 directions); and c. cell movement within lines (toward - 16 directions). Dzurisin and Jameson, 1980.

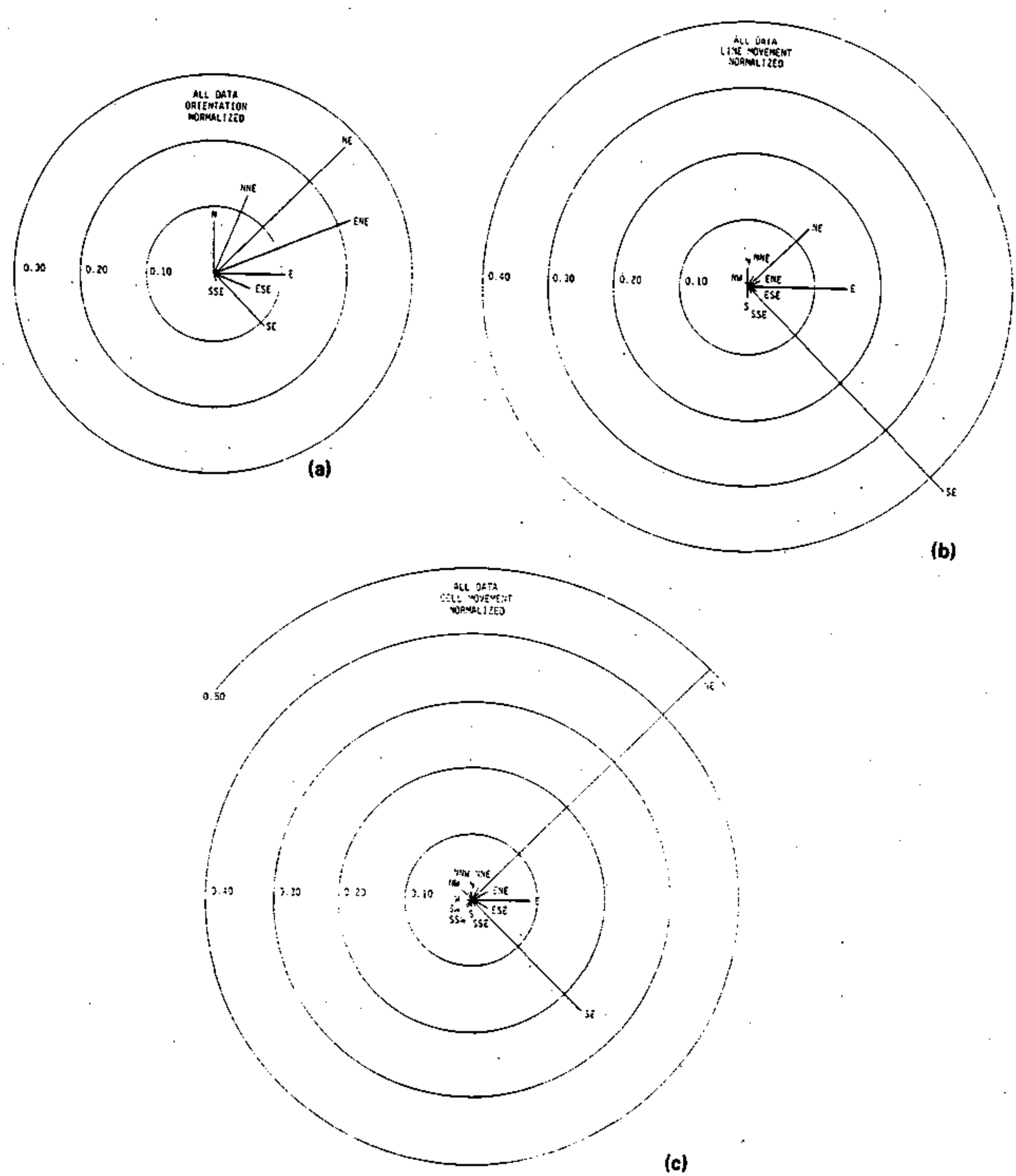


Figure 8. Normalized frequency distributions of: a. the length of lines; b. the width of lines; and c. the area of lines. Dzurisin and Jameson, 1980.

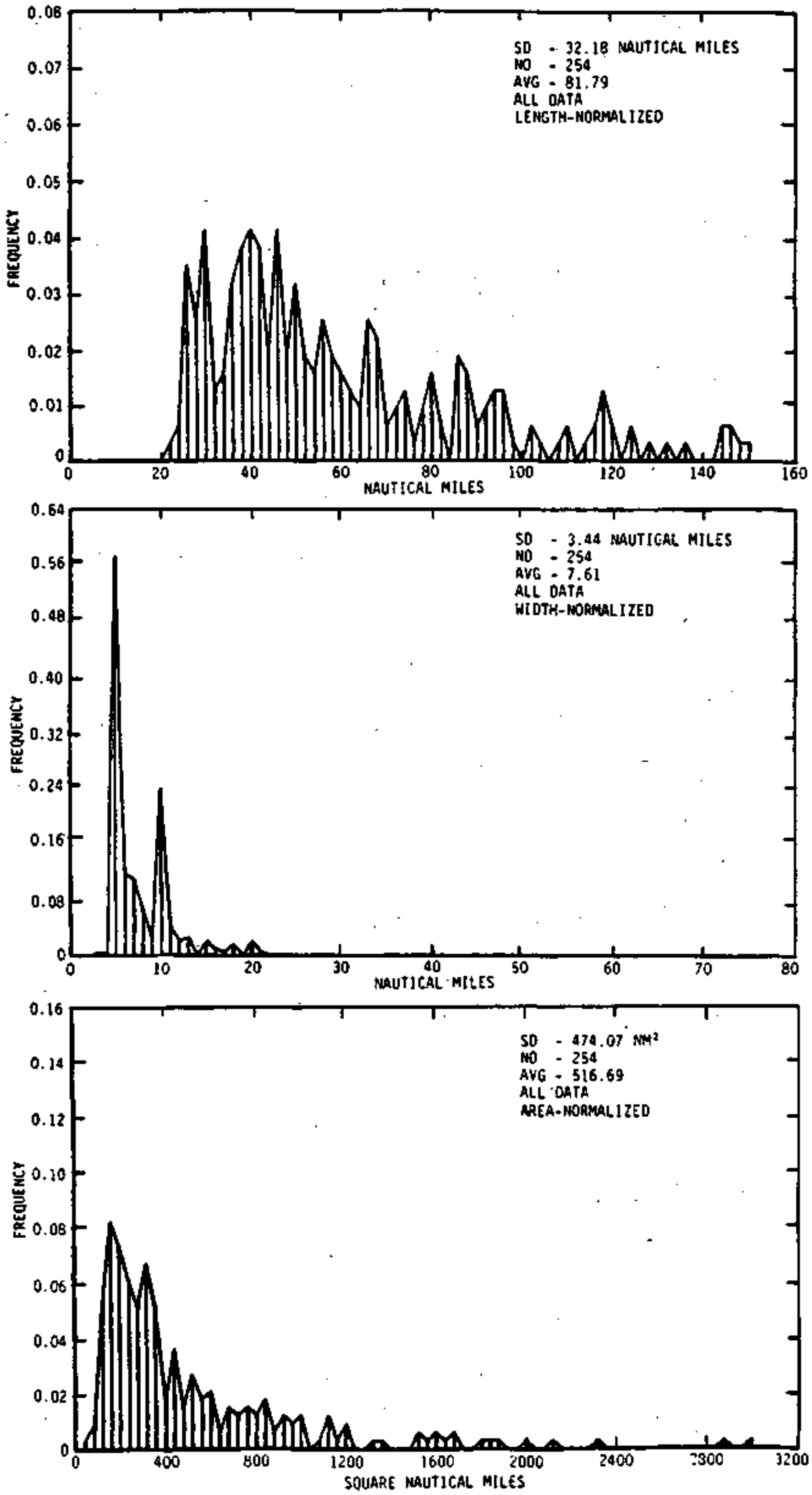
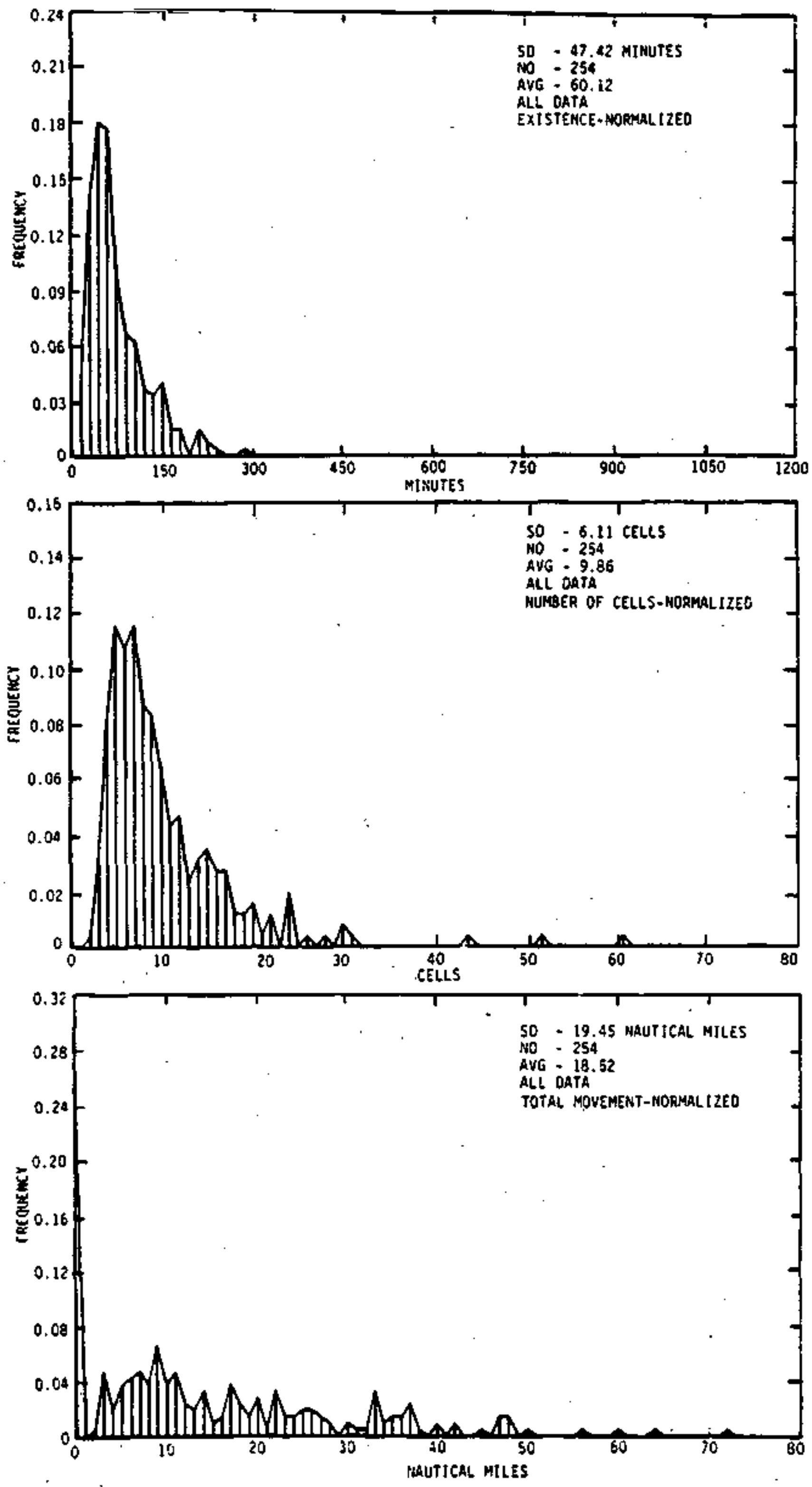


Figure 9. Normalized frequency distributions of: a. the existence time of a line; b. the number of cells in a line; and c. the total movement of a line. Dzurisin and Jameson, 1980.



In stratifying the lines into those which occurred in the evening hours (2000-0559 CDT) as opposed to those which occurred during the day (0600-2159 CDT), the only difference found was that over 80% of the first occurrences of maximum intensity happened within the first 30 minutes of the lines life during the night but only 50% appeared by 30 minutes during the day. While the daytime sample size was nearly twice that of the night lines, the average duration and maximum contour level reached, and their frequency distributions were essentially identical. This led the authors to suggest that factors other than heat-driven convective strength, such as those related to synoptic scale influences or microphysical processes could be more influential in determining the onset of convection. At least the lack of day night differences suggested that many of the properties of the lines were not controlled only by heating.

C. HAIL STORMS

Towery and Changnon (1970) undertook an extensive study of hail producing radar echoes in Illinois, for the April to September months of 1967. Using PP1 photographs from a CPS-9, 3 cm radar, the life histories of 50 hail echoes were derived. Three-dimensional radar information was available, with a volume scan completed every 10 minutes. The position of hail cells first were located and tracked from surface hail observations. The associated radar echoes were then determined and tracked. In all, 50 hail echoes from 14 days and 50 randomly chosen non-hail echoes from the same days were used in the analysis.

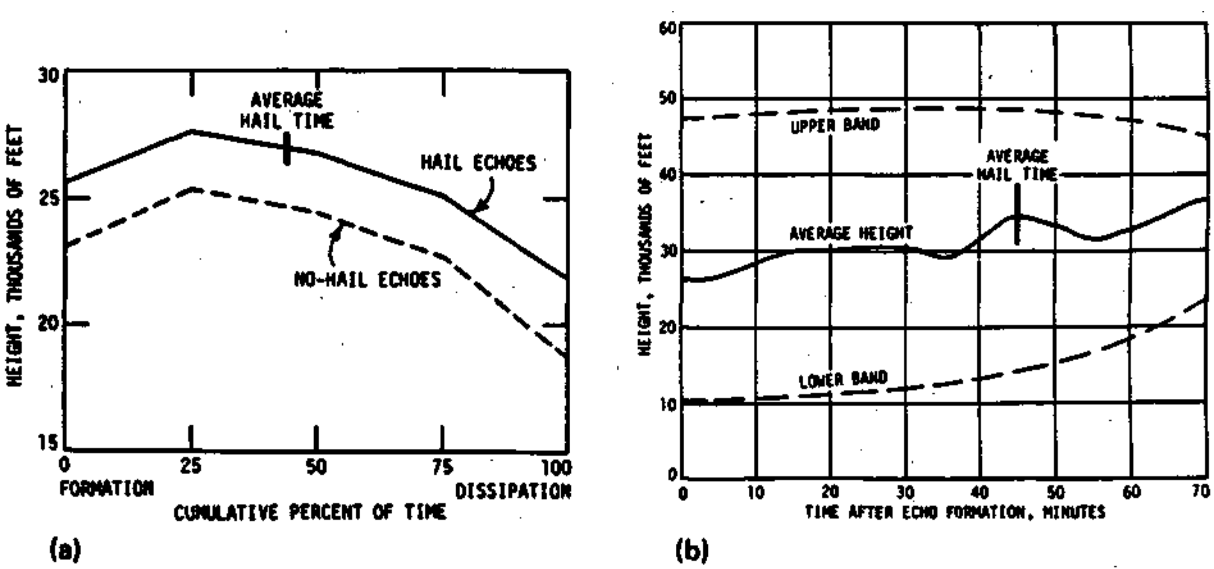
The average characteristics of the hail and no-hail echoes are presented in Table 11. Very little difference is found, except in the value of the mean height of the echo top at both the time of initiation and the time of hail formation. Figure 10a shows that the difference in mean height (.6-1.2 km) persisted throughout the lifetime of the echo. However, Figure 10b indicates that for at least hail echoes, there is a large variation in the heights of echo tops at any particular stage of a storm and especially within the first 30 minutes after detection. At the time of hail formation, the height of the echo tops ranged from 3 to 19 km. Additionally, at the time of hail formation, reflectivities ranged from 10^2 to 10^8 mm ^{6} m^{-3}. Total lifetimes varied from 30 to 197 minutes. Hail also was produced by all types of synoptic weather situations.

Table 11. Comparison between averaged hail and no hail echo characteristics. After Towery and Changnon, 1970.

	Hail	No Hail
Sample size	50	50
Preferred time of occurrence, CST	1200-1800	1200-1800
Direction of movement from, degrees	262	266
Speed, m/s	12.2	12.4
Reflectivity at formation, mm^6/m^3	6.1×10^2	5.5×10^2
Reflectivity at hail time*, mm^6/m^3	7.3×10^4	1.6×10^4
Height at formation, km	7.8	7.0
Height at hail time*, km	8.2	7.5

*Average hail time was 44 minutes after formation

Figure 10. a) Height curves for all hail and no-hail echoes as determined for the indicated percent of time from formation to dissipation in range. b) Average height curves and 90 percent envelope curves (made by upper and lower bands) for hail echoes for time after echo formation. Ten-minute intervals after formation were used to prepare the curves. Towery and Changnon, 1970.



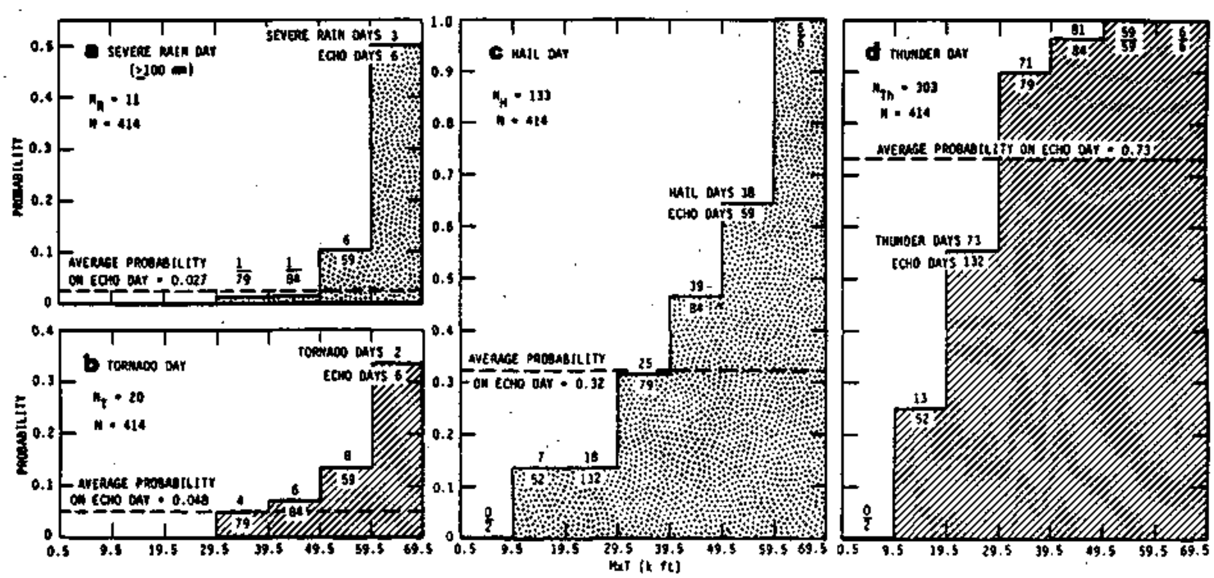
Rinehart et al. (1968) found too, that damaging hail fell from echoes with reflectivities as low as 10^3 mm^6 m^3. Refectivity-height profiles of hail and no-hail storms were similarly shaped as well, with a peak in the 6-7.5 km (20-25 kft) level. Also, only 2-3% of the echoes with Z of $10^{5.5}$ mm^6 m^3 at 5.5- 6 km (18-20 kft) above the freezing level were associated with damaging surface hail. No other reflectivity-height combination showed a better hail relationship. Poor correlations between hail, reflectivity and height of the maximum reflectivity may have been caused by a sparcely sited hail network, the use of a 3 cm radar which was somewhat affected by attenuation and also by the evolving nature of the storms themselves.

Poor predictability of the presence of hail by reflectivity magnitudes encouraged investigations into the realm of dual-wavelength measurements (e.g., Eccles and Atlas, 1973; Jameson and Heymsfield, 1980; Johnson et al. 1983). Recent observations have proven the usefulness of dual-wavlength measurements in detecting large hail (Westcott et al., 1984). However, the analysis tehcniques are not at a point where they can be preformed in real time.

Other studies have suggested that the maximum daily echo top height is related to the occurrence of severe weather on a given day (Grosh and Morgan, 1975; Changnon and Morgan, 1976; Grosh, 1977). The probability of various severe weather events occurring as a function of maximum daily echo top height is presented in Figure 11 (Grosh, 1977). The height data were based on NWS RADU charts, from March through August of 1971-1973. Tornadoes and severe rain storms occurred on days with the maximum echo height as low as 94 km (30 kft). On days with a maximum height of 18 km (60 kft), there was a 50% chance of severe rain occurring sometime on that day. Even with tops as tall as 18 km (60 k ft), the 50Z probability level was never attained for tornado days.

Thunder and hail on the other hand, occurred on days with much lower maximum echo tops, as low as 2 km (10 kft) in fact. Storms reaching 6 km (20 kft) had a 50% chance of producing thunder, and on days reaching 15 km (50 kft), a 100% probability. For hail, the daily maximum echo top had to be 15 km (50 k ft) for a 50% chance and 18 km (60 k ft) for a 100% chance. While these data point out the relationship between echo height and severe weather, little predictability was found (Changnon and Morgan, 1976). Again, the broad distribution of even daily values of height are troublesome.

Figure 11. Probability of severe weather as a function of M x T (maximum top height) for a) severe rain days, b) tornado days, c) hail days, and d) thunder days. Grosh, 1977.



D. SUMMARY

1) Storm Growth

This section largely dealt with multicellular clouds. These clouds were found to have higher tops at the time of their first detection, and subsequently grew taller and lasted longer than the more isolated cells (Changnon, 1976). Multicellular storms appear to grow in a series of steps, often with these steps representing the growth of new adjacent cells.

Seven possible explanations were presented which could lead to both the preferential development of new cells adjacent to older ones, and to the merger of cloud cells into a more organized larger mass (Table 12). A preliminary study by Ackerman and Westcott (1984) indicated that different processes could be operating at any one particular time, and that during the life of the storm, all of the processes could have been acting. These are both microphysical and dynamic convective scale processes, and both could lead to either microphysical or dynamic changes. However, convective scale influences are only one factor in cloud organization. Mesoscale and synoptic scale processes could be acting concurrently to trigger or drive convective scale circulations.

Table 12. Possible explanations for preferential cloud grew adjacent to older clouds, and for the union of cloud cells.

1. Cold outflow air underrunning and lifting neighboring warm air.
2. Mixing of saturated air entrained from the parent cell, creating a more "protected environment" than the relatively dry air surrounding and entrained by the isolated cell.
3. Addition of moisture to neighboring air by precipitation falling from an overhanging canopy created by the parent cell.
4. Local areas of surface convergence or of upper air divergence causing spontaneous generation of updrafts.
5. Differential motion of existing cloud entities could result in their union.
6. A favorable horizontal pressure gradient between adjacent clouds resulting in enhanced convergence.
7. Cooling due to the evaporation of precipitation adn detrained condensate from older clouds, resulting in the destabilization of the ambient air.

2) Storm Organization

Radar lines have been extensively studied in the midwest. These lines often are observed with a SW-NE oreintation, moving from the west at 3 to 20 m/s. Typically the older cells making up the line are to the north and the developing cells to the south. Not all of the cells in the line are necessarily joined. The specific dimensions of the storms vary from project to project. This is most likely a function of the range of view, the resolution and the sensitivity of the radars employed. A summary of mean line characteristics is present in Table 13.

Table 13. Summary table of radar squall line characteristics from Byers and Braham, 1949 [B and B]; Changnon and Huff, 1961 [C and H]; and Dzurision and Jameson, 1980 [D and J].

	B and B	C and H	D and J
Sample size	12-17	196	254
Mean length (km)	167	187	152
Mean width (km)	58	17	14
Mean duration (hr)	—	2.6	1.0
Median direction of movement (from °)	—	265°	225°
Mean speed (m/s)	7	14	—
Median orientation (from °)	220°	255°	236°

Dzurisin and Jameson (1980) examined lines in relation to other nearby convection. They found that lines formed from pre-existing echo systems 80% of the time and occurred simultaneously with other lines 75% of the time. Also, four out of five times, lines in the later part of their life changed into other echo systems instead of dissipating. Isolated storms were found to usually be either first evidence of developing organized convection, the product of dissipating systems or the result of scattered isolated thermally driven convection. Byers and Braham (1947) examined squall line zones as well as squall lines. The squall line zones were areas where multiple lines occurred but were difficult to distinquish. Squall lines were most easily delineated during the night and early morning hours when the effects of surface heating are not present.

Dzurisin and Jameson (1980) found little difference between the characteristics of lines formed in daylight hours (0600-2159 CDT) and those formed at night. The only difference determined was that the first occurrence of the maximum intensity was within 30 minutes of first detection 80% of the time for night echoes, and only 50% of the time for daylight echoes. The means and distributions of the other echo characteristics examined were essentially the same. Changnon and Huff however, found that more lines associated with severe weather occurred between 1300 and 1800 CDT (50% for all lines, 58% for lines with severe weather).

3) Hail Storms

The mean height and reflectivity characteristics of hail storms were examined. While in the mean, hail storms are significantly different from non-hail storms, too broad a distribution of values prevents a large degree of predictibility. More sophisticated radar techniques to identify large hail are available for analysis purposes, but are not yet suitable for real time predictions.

References

Ackerman, B. 1982. Low Level Convergence and the Prediction of Convective Precipitation. Final Report for Grant NSF ATM 73-08865, ISWS Contract Publication 316, p. 128.

Ackerman, B., and Greenman. H. A. 1978. The Evaluation of a Multicellular Convective Cloud Mass: A Case Study. In Preprint Conf. on Cloud Phusics and Atmospheric Electricity, Issaquah; AMS, Boston, pp. 655-660.

Ackerman, B., and Westcott, N. E. 1984. The morphology of merging clouds. In Proceedings of the 9th International Cloud Physics Conf., Tallinn; BIT, U.S.S.R., pp. 403-406.

Battan, L. J. 1953. Observations on the formation and spread of precipitation in convective clouds. J. Meteor. 10(5): 311-324.

Battan, L. J., and Braham, R. R., Jr. 1956. A study of convective precipitation based on cloud and radar observations. J. Meteor. 13(6):587-591.

Braham, R. R., Jr. 1956. The physics of precipitation in cumulus clouds. Geofis. Pura Appl. 35:126-138.

----. 1963. Project Whitetop, April 4, 1962 to April 3, 1963; Final Report to National Science Foundation, Grant NSF G-22419. Univ. Chicago Cloud Physics Lab., p. 36. Chicago, .

----. 1964. What is the role of ice in summer rain-showers?. J. Atmos. Sci. 21(6): 640-645.

---- 1981. Urban precipitation processes. In MHTRQMEX: A Review and Summary, ed. Changnon SA Jr. pp. 75-116. Boston: Amer. Meteor. Soc. Meteor. Monogr. 18(40)

Braham, R. R., Jr., and Dungey, M. J. 1978. A study of urban effects on radar first echoes. J. Appl. Meteor. 17(5):644-654.

Braham, R. R., Jr., and Wilson, D. 1978. Effects of St. Louis on convective cloud heights. J. Appl. Meteor. 17(5):587-592.

Byers, H. R.; Sattan, L. J.; and Braham, R. R. - Jr. 1953. Observations and measurements on natural and artificial rain from convective clouds. In Proceedings of the Toronto Meteorological Conf., pp. 262-268.

Byers, H. R., and Braham, R. R., Jr. 1949. The Thunderstorm: Report of the Thunderstorm Project. Washington, D.C. U.S. Government Printing Office.

Changnon, S. A., *Jr.* 1976. Effects of urban areas and echo merging on radar echo behavior. J. Appl. Meteor. 15(6):561-570.

---- 1978. Vertical characteristics and behavior of radar echoes. In Summary of METROMEX, Vol. 2: Causes of Precipitation Anomalies; ISWS Bulletin 63, pp. 274-279.

---- 1980. Evidence of Urban and Lake Influences on Precipitation in the Chicago Area. J. Appl. Meteor. 19(10):1137-1159.

Changnon, S. A.- Jr., and Huff, F. A. 1961. Studies of Padar-Depicted Precipitation Lines. Scientific Report 2 for Contract AF 19(604)-4940, ISWS Contract Publication 21, p. 63.

Changnon, S. A. , Jr. , and Morgan, G. M. , Jr. 1976. Design of an Experiment to Suppress Hail in Illinois. ISWS Bulletin 61, p. 194.

Changnon, S. A. , Jr. ; Semonin, R. G.; and Huff, F. A. 1976. A Hypothesis for Urban Rainfall Anomalies. J. Appl. Mateor 15(6): 544-560.

Changnon, S. A., Jr., and Stout, 0. E. 1964. A Detailed Investigation of an Illinois Hailstorms on August 8,1963. CHIAA Research Report 18, ISWS Contract Publication 45, p. 33.

Cooper, H., and Garstang, M. 1981. The Behavior of Surface Wind and Thermodynamic Fields in the Presence of Deep Convection. Technical Report 5, NSF Grant ATM 78-08865, Low Level Convergence and the Prediction of Rainfall, p. 240.

Cunning, J. B. ; Holle, R. L.; Gannon, P. T.; and Watson, A. I. 1982. Convective evolution and merger in the FACE experimental area: Mesoscale convection and boundary layer interactions. J. Appl. Meteor. 21:953-977.

Dzurisin, G. L. , Jameson, A. R. 1980. Chapter 2: Echo systems: Initial analysis oF echo lines. In Precipitation Augmentation for Crops Experiment (PACE) - Pre-Experiment Studies, ISWS Contract Publication 245, pp. 28-39.

Grosh, R. C. 1977. Relationships between Severe Weather and Echo Tops in Central Illinois. In Preprint Tenth Conf. on Severe Local Storms, Omaha; AMS, Boston, pp. 231-238.

Grosh, R. C. , and Morgan, G. M. , *Jr.* 1975. Radar-Thermodynamic Hail Day Determination. In Preprint Ninth Conference on Severe Local Storms, Norman; AMS, Boston, *pp.* 454-459.

Johnson, D. B. 1982. The role of giant and uitragient aerosol particles in warm rain initiation. J. Atmos. Sci. 37:448-460.

Johnson, D. B., and Dungey, M. J. 1978.'Microphysical interpretation of radar first echoes. In Preprint 18th Conf. on Radar Meteor., Atlanta; AMS, Boston, pp 117-120.

Ochs, H. T., III, and Semonin, R. G. 1979. Sensitivity of a Cloud Microphysical Model to an Urban Environment. J. Appl. Meteor. 18(9):1118-1129.

Orville, H. D. ; Kuo, Y-H. ; Farley, R. D. ; and Hwang. C. S. 1980. Numerical simulation of cloud interactions. J. Rech. Atmos. 14:499-516.

Rinehart, R. E. ; Staggs, D. W. ; and Changnon. S. A., Jr. 1968. Identification of hail and no-hail echoes. In Preprint 13th Radar Meteorology Conference, Montreal; AMS, Boston, pp. 422-427.

Simpson, J. 1980. Downdrafts as linkages in dynamic cumulus seeding effects. J. Appl. Meteor. 19:477-487.

Tao, W-K., and Simpson, J. 1984. Cloud interactions and marging: numerical simulations. J. Atmos. Sci. 41(19): 2901-2917.

Towery. N. G., and Changnon, S. A., Jr. 1970. Characteristics of Hail Producing Radar Echoes in Illinois. Mon. Wea. Rev. 98(5):346-353.

Turpeinen. O. 1982. Cloud interactions and merging on jay 261 of GATE. Mon. Wea. Rev. 110:1238-1254.

Turpeinen, O., and Yau, M. K. 1981. Comparison of results from a 3-dimensional cloud model with statistics of radar echoes on day 261 of GATE. Mon. Wea. Rev. 109:1495-1511.

Westcott, N. E. 1984. A historical perspective on cloud mergers. Bull. Amer. Meteor. Soc. 65(3):219-226.

Yau, M. K. 1980. The effects of evaporation, water load, and wind shear on cloud developments in a 3-dimensional numerical model. J. Atmos. Sci. 37:488-494.

PART 3.

PART 3

Chin-Fei Hsu

Appendix: Details of Projects Reviewed

Project: Australian Isolated Cumulus Clouds Project

1. Purpose of the project, questions to be investigated — 1) to provide statistically acceptable evidence of the effect of seeding on the amount of rain which fell from the clouds under various conditions, 2) to ascertain the effects of varying the quantity of silver iodide used

2. Where and when (special terrain feature)— an area within 1800 km of Sydney; October 1962 to February 1965

3. Parameters of cloud physics — cloud-top temperature (5 minutes before, and 10 minutes after seeding), cloud height, cloud depth, life after seeding

   3.1. Definition of single cloud — single isolated (dense and compact) cumulus cloud with flat and substantial base, having depth larger than 1000 m, the cloud-base height did not exceed 3500 m, no visible rain fell from the clouds within 30 km prior to seeding, and the cloud had to be at least 30 km from other cloud with visible signs of glaciation

   3.2. Cloud temperature - top, middle, base levels — cloud-top temperature had to be -5C or colder for more than 30 minutes

   3.3. Definition of 'equivalent" clouds — none, the unseeded clouds occurred in different time period from seeded clouds

   3.4. Aircraft measurement — cloud-top temperature and height were measured to decide seeding suitability (if the cloud height was more than 6000 m, the temperature was extrapolated), then the aircraft descended to cloudbase to decide suitability; after seeding, the aircraft flew at cloudbase to measure rain with an impactor (fitted at the nose of the aircraft), estimated the cloudtop height and observed adjacent clouds

4. Radar — none

5. Seedability criterion (who decide, how) — 'experimenter' on board the seeding aircraft decided the suitability of cloud

6. Seeding method (agent and rate, how and by whom) — the 'randomizer' operated a burner which released either 20 gm or 0.2 gm of Agl/Nal in acetone solution at rate of 0.15 gm/sec during two aircraft passes under cloud for approximately two minutes

7. Design — unrestrictly randomized

   7.1. Sampling unit — 12 minutes to more than 2 hours after seeding

   7.2. Experimental unit — single cloud

   7.3. Numbers of seeded and unseeded units — 36 seeded clouds, 33 unseeded cloud, 4 clouds were excluded from analysis because of merging

7.4. Time relation between seeding and data recording — none

7.5. Randomization procedure — the decisions were made in advance of the project

7.6. Implementation of design — the 'randomizer' open an envelope with a decision according to a per-determined random series

7.7. Person knows the randomization decision, and when — the 'randomizer' on board the aircraft know the decision, the others were not advised until the measurement, recording and computation were completed

7.8. Other decisions made in the field and by whom —

7.9. Target and control spacing and area sizes — no control area was used

7.10. Change of design in progress — the smaller burner was not used after October 1964

8. Response variables and quality of data — rainfall under cloudbase was recorded for each cloud using an impactor

9. Statistical analysis — mean, median of seeded and unseeded; Wilcoxon-Mann-Whitney test

9.1. Transformation of data — none

9.2. Stratification of data — by cloudtop temperature and by type of burners

9.3. Estimated seeding effect and significance — 1) mean seeded rainfall was greater (significant at 5%) than unseeded using larger burner; 2) mean seeded rainfall was more (but not significant) than unseeded using smaller burner; 3) lifetime of seeded cloud exceeded that of unseeded (not significant); 4) seeding did not affect maximum cloud height; 5) when cloudtop temperature was warmer than -10C, or when rain fell within 30 km of the seeded clouds, no effects of seeding were detected

9.4. Covariates used — synoptic types

9.5. Problem of multiplicity — possible

9.6. Re-analyses —

9.7. Statistical criticism — none

10. Extra-area effect — not studied

11. Key questions unanswered, major problems, methodology criticism — one unseeded cloud had an unusually long life

12. Special features of the project — though no rainfall were measured, adjacent clouds (within 30 km) were observed for rain or glaciation to offer insight into analysis of the seeded clouds; concluded that effect of seeding on cloudtop height was not great

13. Reference — Bethwaite et al. (1966)

Project: Florida Cumulus Projects

1. Purpose of the project, questions to be investigated — to study the dynamic effects of massive seeding on cumulus clouds and the subsequent precipitation enhancement, single clouds

2. Where and when (special terrain feature) — south Florida, May-June 1968

3. Parameters of cloud physics —

   3.1. Definition of single cloud —

   3.2. Kind of clouds used —

   3.3. Cloud temperature - top, middle, base levels —

   3.4. Definition of 'equivalent' clouds —

   3.5. Aircraft measurement —

4. Radar — 10-cm University of Miami radar

   4.1. Definition of echo —

   4.2. Echo parameters — duration, area

5. Seedability criterion (who decide, how) — The EML cumulus computer model was used in conjunction with objective forecast by laboratory personnel to define the experimental unit

6. Seeding method (agent and rate, how and by whom) — airborne seeding using pyrotechnic Agl flares, 20 flares per cloud in two passes, at approximately 20,000 m (-10 C); seedable clouds existed for up to 6 hours per day, any seeded cloud took about 10 minutes to seed

7. Design — block randomized design of 200 unit (single clouds), 2/3 were seeded

   7.1. Sampling unit —

   7.2. Experimental unit — single cloud, determined by radar echo 10 minutes prior to seeding

   7.3. Numbers of seeded and unseeded units — 14 seeded clouds, 10 unseeded clouds

7.4. Time relation between seeding and data recording —

7.5. Randomization procedure —

7.6. Implementation of design—

7.7. Person knows the randomization decision, and when —

7.8. Other decisions made in the field and by whom —

7.9. Target and control spacing and area sizes — 100 naut. mile radius of Miami radar, 30,000 sq naut. miles; no control area

7.10. Change of design in progress —

8. Response variables and quality of data — rain estimated by a 10-cm radar, and was compared to rain recorded in 150 randomly distributed raingages over south Florida

9. Statistical analysis — (1) pooled student t test with assumed equal variance, doubled rainfall, significant at < .10 level; (2) normal scores test, doubled rainfall, significant at < .05 level; (3) Wilcoxon-Mann-Whitney test, doubled rainfall, significant at < .10 level

9.1. Transformation of data — none

9.2. Stratification of data — using radar echo coverage, on "fair" days the rainfall was increased by seeding, while on "rainy" days the rainfall may have been decreased (MS, 1973)

9.3. Covariates used — none

9.4. Problem of multiplicity —

9.5. Re-analyses —

9.6. Statistical criticism—

10. Extra-area effect —

11. Key questions unanswered, major problems, methodology criticism — it was observed that the merger of 2 medium-sized cumulonimbi resulted in the formation of a giant cumulonimbus complex with at least an order of magnitude more precipitation than the two separate clouds combined, however, the cases were too few

12. Special features of the project —

13. Reference — Simpson et al. (1970); Woodley (1970a)

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Project: FACE-1

1. Purpose of the project, questions to be investigated — exploratory rain enhancement experiment to study the dynamic effect of seeding supercooled cumulus clouds with silver iodide pyrotechnics over a single area

2. Where and When (special terrain feature) — south central Florida, summers of 1970, 1971, 1973, 1975, and 1976

3. Parameters of cloud physics — liquid water content, ice particle concentration, updraft velocity (Sax, 1974; Sax et al, 1979), tracer study (Wisniewski et al., 1974; Wisniewski and Sax, 1979)

   3.1. Definition of single cloud —

   3.2. Kind of clouds used — multiple supercooled cumulus clouds

   3.3. Cloud temperature - top, middle, base levels —

   3.4. Definition of 'equivalent' clouds — see Simpson et al., 1975

   3.5. Aircraft measurement — silver tracer at cloudbase (Wisniewski and Sax, 1979)

4. Radar — a 10-cm radar from the University of Miami was used in 1970-1971; a WSR-57 digitized radar from the National Hurricane Center was used in 1973, 1975, and 1976

   4.1. Definition of echo —

   4.2. Echo parameters — echo motion (Woodley et al, 1977)

5. Seedability criterion (who decide, how) — daily seedability criteria derived from cloud model at 0700 EST was used to screen out days too dry or too wet

6. Seeding method (agent and rate, how and by whom) — a DC-6 and B-57 were used for seeding in 1970-71, a C-130 in 1973, and a C-130 and DC-6 were used in 1975, 3 Piper Navajo aircraft in 1976; pyrotechnic Agl flares released from the rear of an aircraft, and was monitored by the "randomization officer"; no flares were fired on unseeded days in 1970-1975; placebo flares were fired on unseeded days in 1976; scientists could not see the firing of flares, but might be able to detect it on lighter aircraft; types of flares used varied from time to time, a new flare type (NE1) was used in and after August 1975; cloudtop seeding at altitudes between 18000 and 21000 ft MSL; 100-1000 gm of Agl per cloud

7. Design — complete randomized design was used in 1970, 1971, 1973; randomized block design was used in 1975, block length was variable but no greater than 5; restricted randomization was used in 1976, of a character unknown to the decision makers

7.1. Sampling unit — 24 hour

7.2. Experimental unit — day

7.3. Numbers of seeded and unseeded units — 53 seeded days and 51 unseeded days; of them, 29 were A days and 75 were B days

7.4. Time relation between seeding and data recording —

7.5. Randomization procedure — the complete schedule was determined in advance of the season

7.6. Implementation of design — decision for day of seeding was made by an airborne "randomization officer" by opening a sealed envelop in 1970-1975; in 1976 the treatment decision was determined on the ground before takeoff; placebo flares were used in 1976

7.7. Person knows the randomization decision, and when — airborne randomization officer in 1970-1975; in 1970-1971, the scientists were told by the end of each experimental day whether the day had been selected for seeded; in 1972-1976, the schedules of seeding were not revealed to scientists until after the end of the season; however, there existed the risk that the scientists were able on some days to predict the seeding decision before deciding whether that day was suitable for an experimental day or not (STF, 1978); in 1976, both randomizer and flare loader knew the seeding decisions

7.8. Other decisions made in the field and by whom — airborne assessment of the field of clouds in the target area prior to treatment initiation; updraft exceeding 0.5 g per cubic m

7.9. Target and control spacing and area sizes — a fixed target area, of size 9200 sq km in 1970 and 13000 sq km after 1970; no control area was used

7.10. Change of design in progress — (1) complete randomized design in 1970-1973, changed to randomized block design in 1974-1976, (2) Olin flares were used in 1975, NE1 flares were used in 1976, (3) seedability criteria was change from 1.00 to 1.50 after 1971,

8. Response variables and quality of data — 24-hour rain volume in the total target and in the floating target, estimated by radar (Cunning, 1976) — in 1970, rainfall estimates were manually generated from radar without adjustment; in 1971, rainfall estimates were manually generated from radar with adjustment by raingage measurements; in 1973, 1975, 1976, rainfall was estimated from digitized radar data with daily adjustment by raingage values; the primary observational period was the 6 hour after initiation of

treatment

9. Statistical analysis — Bayesian inference assuming gamma distribution for rainfall (Simpson et al., 1973, 1975), modified t-test, Wilcoxon test, F test, modified Siegel-Tukey test, Spearman rank correlation coefficient

   9.1. Transformation of data — 4-th root (Simpson et al., 1975)

   9.2. Stratification of data — analyses were made for (1) A and B days combined, or B days only, (2) over a fixed target, or a floating target, (3)1970-1973, or 1975-1976, (4) light wind vs strong wind, (5) undisturbed vs disturbed days, (6) days with echo motion vs no echo motion (Woodley et al., 1976; Woodley et al., 1979), (7) large vs small expenditure of flares (8) stratification by time after treatment showed that seeded rain was substantially more (P-value less than .001) than unseeded in the period 2 to 5 hours after treatment, with the seeded rain peaking about 1.5 hour later than the unseeded rain (Woodley et al., 1982)

   9.3. Estimated seeding effect and significance — results over all years and conditions showed a slight but nonsignificant increase in mean rainfall on seeded days; stronger results were reported for B days only, and for the floating target (50%); results suggested the possibility of a seeding effect

   9.4. Covariates used — pre-wetness, model predicted rainfall, mean vector wind speed, large square rainfall (Woodley et al., 1982)

   9.5. Problem of multiplicity — there were numerous stratifications which could give rise to problems of multiplicity

   9.6. Re-analyses — Nickerson (1979) used hourly rainfall in a control area to re-analyzed the data, and found that natural variability appeared to account for statistically significant differences between area-wide rainfall on seed and no-seed days. Flueck et al. (1981) responded that Nickerson's raingage density was sparse, did not handle meteorological variability and the control area might be contaminated.

   9.7. Statistical criticism — a few days (5-6 days) made a large contribution of apparent seeding high success (STF, 1978), may need to extend the experiment duration (STF, 1978)

10. Extra-area effect — area outside the target might have been contaminated (Flueck et al., 1981)

11. Key questions unanswered, major problems, methodology criticism — every component of the definition of floating target depends on subjective judgement (STF, 1978); useful estimates of cloud-top height were not obtained as originally planned because of operational difficulties

12. Special features of the project — airborne scientists were able to correctly guess whether the day was seeded or unseeded about 80% out of the 50% total number of days they were willing to guess, based on the changed in cloud appearance

13. Reference — Woodley et al. (1982)

Project: FACE-2

1. Purpose of the project, questions to be investigated — confirmation of the FACE-1 rainfall results

2. Where and when (special terrain feature) — south central Florida, 15 June to 31 August in 1978 and 1980 and 1 July to 31 August in 1979

3. Parameters of cloud physics — the cloud physics aircraft measured air vertical velocity, ice concentrations and habits, and cloud droplet spectra; however, informative cloud physics data were collected only on about half of the FACE-2 GO days due to either need to seed additional clouds or mechanical failure

   3.1. Definition of single cloud —

   3.2. Kind of clouds used — suitable clouds were those that had a hard cauliflower head appearance, a strong updraft (more than 5 m/sec) concurrent with at least 1.0 g per cubic meter of cloud water as measured by Johnson-Williams instrumentation, and a top height between 18000 and 23000 ft (Barnston et al., 1983)

   3.3. Cloud temperature - top, middle, base levels —

   3.4. Definition of 'equivalent' clouds — none

   3.5. Aircraft measurement — one of the Aero Commander aircraft served as the cloud physics aircraft at the seeding level near -10 C.

4. Radar — (1) a S-band 10-cm NOAA WSR-57 radar, operated by National Hurricane Center personnel in Coral Gables, was used to monitor cloud over the target and was the principal mean of the evaluation, the radar was operated mainly in PPI mode at an elevation of 0.5 degree; (2) a digitized, narrow (0.8 degree vertical beamwidth C band radar was operated in a CAPPI mode with full 360 degree scanning at 15 tilt angles to acquire echo coverage information, the data was of high quality in 1980, marginal quality in 1978, and no data in 1979

   4.1. Definition of echo —

   4.2. Echo parameters — mean echo height and thickness for floating and total target areas were measured by C-band radar in CAPPI mode, growth rates,

5. Seedability criterion (who decide, how) — a S-band radar was used to continuously monitor the morning convective precipitation of a potential operational day, the suitability index had to be at least 1.50, suitable weather conditions must be found upon flight into target area and before 1600 EDT

6. Seeding method (agent and rate, how and by whom) — seeding always began before 1600 EDT and was carried out by 3 seeding aircraft (2 Aero Commander and 1 Cessna 421 in 1978; 1 Aero Commander and 2 Cessna 421 in 1979-1980); Nuclei Engineering Company pyrotechnic flares (with a TB-1 mixture) containing 70 g of Agl or 70 g of sand was released from aircraft at an average rate of about 1 flare per 100-200 m; seeding was conducted at 18000-21000 ft (5.49-6.40 km); if echo coverage at 1400 EDT within 100 mi of Miami was less than 13%, seeding was stopped; seeding was always completed before 2100 EDT

7. Design — four restricted randomization schemes were used depending on the mean layer vector wind conditions, which was observed from the West Palm Beach morning sounding (Woodley et al. 1978; Woodley et al., 1983)

7.1. Sampling unit — 24-hour

7.2. Experimental unit — day, seeded day was declared as "A" day if less than 60 flares were used, otherwise it was declared as "B" day

7.3. Numbers of seeded and unseeded units — 51 B days and 10 A days

7.4. Time relation between seeding and data recording —

7.5. Randomization procedure — 2500 randomization plans, each of length 75, were prepared such that there were not more than two seed or two no-seed days in a row within any of the blocks, the plans were randomly selected for use in the experiment

7.6. Implementation of design — after a day was declared as suitable, a decision of treatment was randomly determined and then transmitted to the airport to launch the aircraft

7.7. Person knows the randomization decision, and when — the treatment decisions were withheld from all scientists until the field experiment was completed and all of the data fully reduced and verified on Nov. 30, 1981

7.8. Other decisions made in the field and by whom —

7.9. Target and control spacing and area sizes — target area was of size 13000 sq km, no control area was employed

7.10. Change of design in progress — none

8. Response variables and quality of data — radar-estimated rainfall, adjusted by measurements from a network of dense raingages (3.2 km spacing); a less dense network of raingages (10.8 km spacing) was used an independent means of rainfall evaluation and as a tool for assessment of the validity of the gage-adjustment technique for the target radar rainfall; considerable amount of effect was spent in the verification of various data (Barnston et al., 1983)

9. Statistical analysis —

9.1. Transformation of data — logarithmic

9.2. Stratification of data — B days vs A+B days; total target vs floating target

9.3. Estimated seeding effect and significance — non-significant 20% rain increase for floating target and 17% for total target using unweighted equations (Woodley, et al., 1983)

9.4. Covariates used — prewetness, large square rainfall, lower level wind speed, and model-predicted rainfall (Barnston et al., 1983)

9.5. Problem of multiplicity —

9.6. Re-analyses —

9.7. Statistical criticism —

10. Extra-area effect —

11. Key questions unanswered, major problems, methodology criticism —- problems with the WSR-57 radar range and the ascribed azimuths were discovered in 1979 and were adjusted thereafter by using the University of Miami's MPS-4 research radar; the southeast corner of the target was too close to the radar ground clutter, an adjustment procedure was employed to compensate for the zero-out rain in the area; on some GO days, there were problems with the radar scan recording process; false radar rainfall returns, usually caused by anomalous propagation, were sometimes present in the final hour or two of the 6 hour after treatment, they were manually adjusted by person not otherwise involved with the seeding; there was a single unseeded day (29 July 1978) which had rainfall more than two times of any other days; the FACE-2 failed to confirm the results of FACE-1 (Voodley et al., 1983)

12. Special features of the project —

13. Reference — Woodley et al. (1978); Barnston et al. (1983); Woodley et al. (1983)

Project: HIPLEX-1

1. Purpose of the project, questions to be investigated — to reduce the scientific uncertainties concerning both natural and artificially modified precipitation processes in warm season convective clouds of the High Plains

2. Where and when (special terrain feature) —— pre-experimental phase started in 1976 till earlier 1979 at Montana, Kansas, and Texas; phase 1 experiment was conducted during the periods of 22 June-31 July 1979 and 1 May-31 July 1980 at Miles City, Montana, in a circle of 150 km diameter

3. Parameters of cloud physics — see Smith et al. (1984)

   3.1. Definition of single cloud — 3 classes (A-1, A-2, B) of clouds were defined using measurements of average liquid water contents, ice crystal concentrations, vertical velocity, cloud horizontal extent, cloud base and top temperature, and others (Smith et al., 1984) taken by a King Air aircraft, these measurement were used to initiate a real time computer algorithm which objectively determined if the candidate cloud qualified for treatment (Smith et al, 1984)

   3.2. Kind of clouds used — individual, small, semi-isolated cumulus congestus cloud (TCU) that fulfilled microphysical and dynamic criteria measured by a King Air aircraft (see Table 1 in Smith et al. (1984) for details); the cloud selected must not have radar-detectable echo by the aircraft weather radar

   3.3. Cloud temperature - top, middle, base levels — clouds selected must have cloudbase temperature > 0 C and cloudtop temperature be between -6 to -20 C at the time of selection

   3.4. Definition of 'equivalent' clouds — none

   3.5. Aircraft measurement — before seeding, the King Air aircraft (cloud physics aircraft) measured or derived values, at -8 C level, of cloudtop temperature and rate of growth, liquid water content, ice crystal concentration, size and habit (Lawson, 1981), while the Learjet (seeding aircraft) measured the cloudtop temperature; both King Air and Learjet systematically penetrated seeded clouds to take measurements (Smith et al., 1984)

4. Radar — SWR-75 radar (5-cm, 1 degree beamwidth) conducted a continuous series of 3-min volume scans beginning at an elevation angle of 0.7 degree, then 1.0 degree, and incremented subsequently at either 1.0 (near) or 0.5 (far) degree

4.1. Definition of echo —

4.2. Echo parameters — time to first echo was defined as the time to the first 15 dBZ echo using a C-band radar having a 1 degree beam width and a 1 km range resolution

5. Seedability criterion (who decide, how) — in addition to (1) cloudtop and cloudbase temperature requirement, clouds selected required, (2) to have a 1-km-average liquid water content exceeding 0.5 g per cubic meter, (3) to have a vertical air velocity exceeding 1 m/s in the cloud region selected as the target for seeding

6. Seeding method (agent and rate, how and by whom) — static seeding; within 2 minutes of declaration of an experimental cloud unit, a Learjet aircraft delivered dry ice pellets (1.5 cm in diameter and 0.5-2.5 cm long) or placebo into the cloud at about the -10 C level (Lawson et al., 1981); at the intended rate of 0.1 kg per km of flight path

7. Design — double-blind randomized block design (see below for block size)

7.1. Experimental unit — small, semi-isolated cumulus congestus cloud (TCU) that fulfilled microphysical and dynamic criteria measured by a King Air aircraft

7.2. Sampling unit — single cloud

7.3. Numbers of seeded and unseeded units — 12 clouds were seeded with dry ice, 8 clouds were seeded with placebo; among them, 7 were class A-1 clouds, and 13 were class 8 clouds

7.4. Time relation between seeding and data recording — data were collected immediately after seeding

7.5. Randomization procedure — a randomized block design of size 2 was used in 1979; a two-stage randomized block design of size 4/6 was used in 1980, the first stage randomly selected a block size of either 4 or 6, the second stage randomly selected a random sequence from a fixed collection of sequences with the selected size; separate random sequences were prepared for each cloud class

7.6. Implementation of design — a double blind procedure was implemented — both seeding and dispenser randomization sequences were determined before the seeding operation

7.7. Person knows the randomization decision, and when — one of the 2 identical dispensers on the seeding aircraft (Learjet) was disabled, as determined by the dispenser random sequence, by (ground) personnel not otherwise involved in the operation, the dispensers were then sealed and locked; after a unit was declared for seeding, dispenser selection was accomplished via radio transmission of a coded message from ground to the Learjet crew immediately prior to the treatment pass; during actual seeding operation, a noise device was installed to prevent crew from differentiation between the seed and placebo dispensers; the information of seed/no-seed decision was not available until after each flight.

7.8. Other decisions made in the field and by whom — two person manually checked some of the measurement collected by the cloud physics aircraft and made correction if necessary

7.9. Target and control spacing and area sizes — the target location for seeding was determined to be the center of the 1 km region of maximum average liquid water content found on the pre-seeding flight pass by the onboard computer; no control was used; minimum separation between tested clouds must be at least 15 km

7.10. Change of design in progress —

8. Response variables and quality of data — 12 primary, 7 secondary response variables measured by an aircraft and a 5-cm radar, as well as 4 final test statistics were used (Smith et al., 1984): (1) for microphysical hypothesis, ice crystal measurements using an oil slide exposed in the seed plum within 6-9 minutes of seeding were used for testing seeding signature; (2) for "ice-embryo" hypothesis, concentration of ice crystals 2 minutes after seeding (CIC2) and 5 minutes after seeding (CIC5) were used, both measured at -8 C level by a PMS 2D-C probe; (3) time to first echo was used; (no measurement of rain at the ground was available for HIPLEX-1)

9. Statistical analysis — multi-response permutation procedures (Mielke et al., 1984), specified before the seeding operation

9.1. Transformation of data — normalization individually

9.2. Stratification of data — by various cloud physics variables

9.3. Estimated seeding effect and significance — (1) using criteria based on the spreading of ice crystal plume resulting from dry ice seeding, the data collected by the King Air indicated that an identifiable seeding signature was present in 9 of 12 of seeded clouds (two of the 3 exceptions were cases in which the cloud dissipated or fell below the aircraft sampling level prior to the scheduled sampling time); none of the 8 un-seeded clouds showed a seeding signature; (2) the use of "time to first echo" did not show any seeding effect (Cooper et al., 1981); (3) rainfall measured at +10 C level using a FMS 2D-P imaging probe on the King Air showed that the seeded clouds had more than 3 times of rainfall than unseeded (significant at .19 level using Wilcoxon-Mann-Whitney test); (4) seeding increased the l-km-average ice crystal concentration by a factor of 100 (Cooper, 1981); (5) cloud ice concentration at both 2-minutes and 5-minutes after seeding showed significant additional values for seeded clouds for both warmer (A-1) and colder (B) clouds (Mielke et al., 1984)

9.4. Covariates used — numerous

9.5. Problem of multiplicity — the experiment is exploratory

9.6. Re-analyses — none

. 9.7. Statistical criticism — none

10. Extra-area effect —

11. Key questions unanswered, major problems, methodology criticism — (1) the operational considerations of selecting growing clouds with warm cloudtops led to selection of clouds with relatively low updraft speeds (Cooper, 1981), (2) the entrainment in the clouds selected for seeding proceeded so rapidly that the cloud liquid water was depleted just as the ice crystals produced by seeding had grown to sizes where timing cloud be effective (Cooper, 1981), (3) the precipitation development occurred as hypothesized for the first 8 minutes, but at that time a majority of the clouds have insufficient supercooled water remaining for continued precipitation growth (4) one cloud (16 June 1980) was erroneously selected for seeding because of equipment failure in measuring vertical air motion, the case was included in the evaluation anyway

12. Special features of the project — atmospheric soundings at Miles City around 1200 CUT each operational days during 1979-1980 were used (1) to discriminate between days having suitable clouds (TCU) and days not having suitable clouds and (2) to discriminate between TCU days with seeded clouds and TCU days without (Hartzell and Jameson, 1981); a very detailed physical hypothesis of seeding class A clouds was stated for the experiment (Smith et al., 1984)

13. Reference — Silverman (1979); Smith et al. (1984); Mielke et al. (1984); Cooper and Lawson (1984)

Project: Israeli I

1. Purpose of the project, questions to be investigated — to study the effect of seeding on areal precipitation

2. Where and when (special terrain feature) — winters (mid-October to mid-April) of 1961-1967; semi-orographic

3. Parameters of cloud physics — cloud thickness was used in seedability

    3.1. Definition of single cloud — none

    3.2. Kind of clouds used — cold continental cumulus clouds

    3.3. Cloud temperature - top, middle, base levels — cloudtop

    3.4. Definition of 'equivalent' clouds — none

    3.5. Aircraft measurement —

4. Radar — none

    4.1. Definition of echo — none

    4.2. Echo parameters — none

5. Seedability criterion (who decide, how) — cloud-top temperature was less than or equal to -5 C and cloudbase height was less than 2 km

6. Seeding method (agent and rate, how and by whom) — static seeding, airborne seeding at cloud base (3000 ft), 0.55 kg/hour of AgI in aceton, flying track was parallel to and upwind of target

7. Design — two fixed targets, unrestricted randomized crossover design; evaluation was restricted to those days in which a measurable rainfall fell at least at one of three predesignated stations in the Buffer zone

    7.1. Sampling unit — 24 hours

    7.2. Experimental unit — weekly (0800 Sunday to 0800 Sunday from Feb. 19 1961 to Nov. 5 1961), and 24 hours (2000-2000 from Nov. 7 1961 to Jan. 8 1964, changed to 0800-0800 from Jan. 9 1964 to Feb. 2 1967)

    7.3. Numbers of seeded and unseeded units — 197 seeded, 167 unseeded days

    7.4. Time relation between seeding and data recording —

7.5. Randomization procedure —

7.6. Implementation of design— days were selected for seeding after passing seedability criterion

7.7. Person knows the randomization decision, and when —

7.8. Other decisions made in the field and by whom —

7.9. Target and control spacing and area sizes — 10 miles between the 2 fixed targets — North Target (1400 sq. miles), Center Target (1500 sq. miles)

7.10. Change of design in progress — first used crossover randomization of weeks, then used crossover randomization of days; daily schedule for seeding and recording was changed during the course of the study

8. Response variables and quality of data — rainfall estimated by raingages, 27 gages in North Target, 18 in Center Target

9. Statistical analysis — Wilcoxon-Mann-Whitney test was chosen in advance of the analysis, square root of double ratio (Gabriel, 1967b)

9.1. Transformation of data — none

9.2. Stratification of data — (1) by the amount of rain in the buffer, (2) by 700-mb temperature (Gabriel, 1967b)

9.3. Estimated seeding effect and significance — (1) Wilcoxon-Mann-Whitney test, rain increase was significant at .054 level (Gabriel, 1967a), (2) re-randomization test using single ratio, 15.3% (standard error 6.5 %) rain increase in the target, significant at .009 level (Gabriel, 1967a), (3) normal two-sample test, significant at .025 level, (4) regression analysis, 23% rain increase, significant at .01 level

9.4. Covariates used — wind speed, wind direction, total precipitable water, 700 and 500 mb temperatures

9.5. Problem of multiplicity — many stratification of data posed the possibility of multiplicity (Calvin, 1969)

9.6. Re-analyses —

9.7. Statistical criticism — Neyman (1977) raised the question on the change of 24-hour periods that the precipitation was measured, and was rebutted by Gabriel (1978)

10. Extra-area effect — serious remote effects between the area pairs of target and control were quite unlikely (STF, 1978), there may have been some contamination of the North target during some Center seeding days (Wurtele, 1971)

11. Key questions unanswered, major problems, methodology criticism —

12. Special features of the project — no "persistence" of seeding effects was found either from day to day, within seasons, or from season to season (Gabriel et al., 1967)

13. Reference — Gabriel (1970); Gagin and Neumann (1974)

Project: Israeli II

1. Purpose of the project, questions to be investigated — a confirmatory project to study the effect of seeding on areal precipitation

2. Where and when (special terrain feature) — winters (Nov.-Apr.) of 1969-1975, over the catchment area of Lake Kinneret, semi-orographic

3. Parameters of cloud physics — cloud thickness was used in seedability, cloudtop height

   3.1. Definition of single cloud — none

   3.2. Kind of clouds used — cold continental cumuliform clouds, associated mostly with cold fronts and post-frontal bands

   3.3. Cloud temperature - top, middle, base levels — cloudtop

   3.4. Definition of 'equivalent' clouds — none

   3.5. Aircraft measurement —

4. Radar — none

   4.1. Definition of echo — none

   4.2. Echo parameters — none

5. Seedability criterion (who decide, how) -- cloud-top temperature less than or equal to -5 C, and cloudbase height less than 2 km

6. Seeding method (agent and rate, how and by whom) — 1) airborne seeding at cloud base (3000 ft), 0.55 kg/hour of AgI, (flying track parallel to and upwind of the Target), and 2) 42 ground generators in mountain (4000 ft) unreachable by air generators,

7. Design — fixed target, unrestrict simple randomized target-control design, 50% randomly selected for seeding in the North Target, with a west control area and a buffer to the south, in addition, the target was extended into the South Target (but without control)

   7.1. Sampling unit — rainy days, i.e., days on which at least 0.1 mm of rain was recorded in a buffer zone south of and adjacent to the target area

   7.2. Experimental unit — 24 hours

7.3. Numbers of seeded and unseeded units — 209 allocated seeded (rainy) days (174 actually seeded days), 179 unseeded (rainy) days

7.4. Time relation between seeding and data recording —

7.5. Randomization procedure — seed and no-seed days were selected randomly prior to each season

7.6. Implementation of design — days were selected for seeding after passing seedability criterion

7.7. Person knows the randomization decision, and when — both decision making and operational personnel knew (or could discover) whether a given day was to be seeded or not (STF, 1978), but not the rainfall observers

7.8. Other decisions made in the field and by whom —

7.9. Target and control spacing and area sizes — 20 miles between the 2 fixed targets, North Target 3775 sq. km (including 2080 sq km of Lake Kinneret), South Target 4000 sq. km; one control west to the target

7.10. Change of design in progress — no important experimental decisions were allowed during the course of an experimental day

8. Response variables and quality of data — rainfall estimated by raingage, 49-69 gages in the North Target, 22-25 in the Control, 3 in the Buffer, and 76 in the South Target

9. Statistical analysis — randomization double ratio, comparing seeded target rain with unseeded target rain, and rainfall in an upwind control area under seeding and nonseeding (Gagin and Neumann, 1981) showed 13% rain increase, significant at .028 level

9.1. Transformation of data — none

9.2. Stratification of data — (1) cloud-top temperature stratification indicated very large (46% at .005 level) seeding effect in the -15 to -20 C range (2) stratification by daily rain in the control area indicated that larger rain increases for smaller rainfall

9.3. Estimated seeding effect and significance — estimated mean rainfall increase of 13% in the North and 18% in the Catchment areas, significant at 2.8 and 1.7% respectively.

9.4. Covariates used — cloudtop height and cloudtop temperature

9.5. Problem of multiplicity —

9.6. Re-analyses —

9.7. Statistical criticism — there remains some concerns over the extent to which data-handling personnel were aware of seeding decisions (STF, 1978)

10. Extra-area effect — an area in the south was seeded on days when the main target was not seeded, the effect was not serious (STF, 1978)

11. Key questions unanswered, major problems, methodology criticism — a control area was added to the South Target and will be used in Israeli III experiment

12. Special features of the project — all days selected for seeding were included in the evaluation even though they were not actually seeded; the effect of seeding is most pronounced and consistent on most of the days (82%) when the daily rainfall is less than or equal to 15 mm (mean was 8 mm)

13. Reference — Gagin and Neumann (1981)

Project: North Dakota Pilot Project

1. Purpose of the project, questions to be investigated — to assess effects of seeding for both rainfall enhancement and hail suppression

2. Where and when (special terrain feature) — summers (1 Hay to 15 August) of 1969 through 1972 in western North Dakota

3. Parameters of cloud physics — ice nucleus count, cloud depth

   3.1. Definition of single cloud —

   3.2. Kind of clouds used —

   3.3. Cloud temperature - top, middle, base levels — cloudbase

   3.4. Definition of 'equivalent' clouds —

   3.5. Aircraft measurement —

4. Radar — 10-cm and 3-cm M-33 radar system (manual), and NCAR's 10-cm NCPR-1 radar (digitized)

   4.1. Definition of echo — the 1972 radar data were analyzed (Miller at al., 1975 (M-33); Koscielski and Dennis, 1976 (NCPR-1))

   4.2. Echo parameters — first echo was closer to cloud base on seeded days, additional parameters were echo height, diameter, duration (Miller et al., 1975)

5. Seedability criterion (who decide, how) — radiosondes and one-dimensional steady-state cloud modeling were introduced in 1971 for seedability decision

6. Seeding method (agent and rate, how and by whom) — silver iodide crystals (10 or 20 g) were released from acetone generators on aircraft operating in updrafts below cloud base; a 3% silver iodide-sodium iodide in acetone solution was burned in the generators during 1969 and 1970, ammonium iodide was substituted for sodium iodide in 1971 (10% solution of Agl) and 1972 (4% solution); the seeding operation was directed by the project meteorologist using ground-to-air communications, radar and an aircraft tracking system

7. Design — periodic random target-only, each season was divided into 8-day time blocks, each of which was further divided into 4 two-day blocks, one of the two-day block was selected at random from each 8-day block as no-seed days

7.1. Sampling unit — 12 hour of rainfall ending at 2200 CDT

7.2. Experimental unit — two-day

7.3. Numbers of seeded and unseeded units — 277 declared seeded days (113 days were actually seeded), 91 unseeded days

7.4. Time relation between seeding and data recording —

7.5. Randomization procedure — random selection of seed/noseed days was made in advance of the season

7.6. Implementation of design —

7.7. Person knows the randomization decision, and when — all personnel knew in advance the seeding schedule except possibly the volunteer rainfall observers (Dennis et al., 1975)

7.8. Other decisions made in the field and by whom — the project meteorologist judged an approaching storm to be seeded for rain or hail on the basis of hail reported on the ground or radar reflectivity beyond a predetermined threshold

7.9. Target and control spacing and area sizes — no control area was used

7.10. Change of design in progress — no change of operational design occurred

8. Response variables and quality of data — rainfall estimated by radar and raingages; data were of good quality (Biondini, 1977)

9. Statistical analysis — chi-square test, ratio, Wilcoxon 2 sample test, permutation test, employed gamma distribution

9.1. Transformation of data — logarithmic

9.2. Stratification of data — 500 mb temperature, precipitable water, 850 mb wind, cloud types, cloudbase temperature, year, and dynamic seedability

9.3. Estimated seeding effect and significance — results for some stratifications were significant, but analyses for all days were far from significance; results showed significantly less rainfall under seeding on days with 500 temperature between -15 and -20 C

9.4. Covariates used —

9.5. Problem of multiplicity — possible

9.6. Re-analyses —

9.7. Statistical criticism — main statistical technique was not chosen in advance; too many analyses resulted from stratification of the data; the decision for rain or hail seeding was subjective; the knowledge of seeding schedule may consciously or unconsciously influenced procedures in both rainfall measurement and in collecting and recording hail insurance claims; Biondini (1977) raised the question on using the 8-day block in the project design

10. Extra-area effect — none, except from other seeding operations

11. Key questions unanswered, major problems, methodology criticism— no evidence for confirmation of seeding effect (STF, 1978); some results that approach nominal levels of statistical significance seemed to be perplexing from a meteorological perspective (STF, 1978); Biondini (1977) questioned the Monte Carlo method used in the evaluation

12. Special features of the project — analysis showed little evidence of bias in selecting unseeded days (Dennis et al., 1975)

13. Reference — Dennis et al. (1974); Dennis et al. (1975)

Project: Santa Barbara II

1. Purpose of the project, questions to be investigated — confirmatory study on the effects of seeding on precipitation in the main target area, and exploratory study of rain enhancement in the extended (downwind) area

2. Where and when (special terrain feature) — Santa Barbara County, California; phase 1 from winters of 1967 to 1971, phase 2 from 1971 to 1974, orographic

3. Parameters of cloud physics — none

   3.1. Definition of single cloud — none

   3.2. Kind of clouds used — convective rain band

   3.3. Cloud temperature - top, middle, base levels —

   3.4. Definition of 'equivalent' clouds — none

   3.5. Aircraft measurement —

4. Radar —

   4.1. Definition of echo —

   4.2. Echo parameters —

5. Seedability criterion (who decide, how) — experimental unit defined by radar observation of trackable band and/or by raingage telemetry in a western control area

6. Seeding method (agent and rate, how and by whom) — in phase 1 a single high output ground generator of Agl (1.6 kg/hour, LW83 pyrotechnic, one pyro every 15 minutes) was used, generator was on a 1650 m ridge; in phase 2 airplane (6000-10000 ft, north-south 25 miles long track, approximately 2 hours) as well as one ground generator (.425 kg/hour, approximately 4 hours) were use,

7. Design — unrestricted randomized design

   7.1. Sampling unit — convective rainband

   7.2. Experimental unit — convective rainband in phase 1; storm in phase 2

   7.3. Numbers of seeded and unseeded units — in phase 1, 56 seeded and 51 unseeded rainbands; in phase 2, 18 seeded and 27 unseeded rainbands

7.4. Time relation between seeding and data recording —

7.5. Randomization procedure — unrestricted randomization on rainband (phase 1) or storm (phase 2)

7.6. Implementation of design —

7.7. Person knows the randomization decision, and when — seeding schedule was not revealed to neither the scientific director nor to the analysis staff until after completion of the post-season analysis

7.8. Other decisions made in the field and by whom — a meteorologist determined the time rainband passing over raingages

7.9. Target and control spacing and area sizes — fixed target (2100 sq miles) and control (1000 sq miles) were used in phase 1 with 50 statute miles between center of control and target; variable target (depending on wind) with no control in phase 2

7.10. Change of design in progress — ground based seeding only was used in phase 1, while airborne and ground seeding were used in phase 2

8. Response variables and quality of data — rainfall and band duration time estimated at 60 gages in the target and 6 gages in the control; there were missing data at many gages

9. Statistical analysis — single and double ratios were used for phase 1, single ratio was used for phase 2; Wilcoxon-Mann-Whitney test

9.1. Transformation of data — none

9.2. Stratification of data — by stability indices, 500 mb temperature, day vs night seeding

9.3. Estimated seeding effect and significance — in phase 1 seeding was ineffective when the base of convection was at or above 3000 feet (500 mb temperature colder than -22 C); various analyses of phase 1 showed rain increases more than 50% (significant around 5%); phase 2 was suspended before completion; positive conclusions do not seem to be justified (STF, 1978)

9.4. Covariates used — 12 covariates derived from radiosondes at Santa Barbara Airport (in the target) and Vandenberg Air Force Base for each rainband (Gleeson, 1977)

9.5. Problem of multiplicity — possible

9.6. Re-analyses — phase 1 data were re-summarized by response surfaces (Bradley et al., 1977), using covariates (Gleeson, 1977), and using principal component analyses (Scott, 1978); regression analyses (Bradley et al., 1979) without using covariates generally confirmed the results of Elliott and Brown (1971)

9.7. Statistical criticism — a major source of variation may be caused by the subjective definition of rainband as experiment unit, and the independence of observations was doubtful (Bradley et al., 1979) phase 2 was terminated prematurely;need (but did not) do re-randomization analysis

10. Extra-area effect — the control in phase 1 was far enough (it was not used in the data analysis), there existed a possible upwind effect in the control area (Elliott and Thompson, 1970)

11. Key questions unanswered, major problems, methodology criticism — there may exist persistence effect of seeding into unseeding bands (Elliott and Thompson, 1970); the covariates collected in phase 1 were not useful (Bradley et al., 1979)

12. Special features of the project — rainband was used as experimental unit, which increased the total number of e. u.'s; in phase 2 seeding was conducted 60 miles further west (off the Coast) due to safety consideration

13. Reference — Elliott and Thompson (1970); Elliott et al (1971); Elliott and Brown (1971); Thompson et al. (1975)

Project: Project Sierra Cumulus

1. Purpose of the project, questions to be investigated — to study the effects of seeding on precipitation and runoff from watersheds

2. Where and when (special terrain feature) — Sierra Nevada of California, summers of 1966-1968, orographic; in 1966, inside the upper portion of Kings, in 1967-68, over Bear Creek Watershed, both near San Joaquin River

3. Parameters of cloud physics —

   3.1. Definition of single cloud —

   3.2. Kind of clouds used —

   3.3. Cloud temperature - top, middle, base levels —

   3.4. Definition of 'equivalent' clouds — criteria for similarity of clouds was based on visual observations of cloud size, growth, and physical separation

   3.5. Aircraft measurement —

4. Radar —

   4.1. Definition of echo —

   4.2. Echo parameters —

5. Seedability criterion (who decide, how) — forecast and occurrence by 1400 PDT of cumulus clouds with depths exceeding 5500 ft

6. Seeding method (agent and rate, how and by whom) — airborne seeding at -5C level in updraft on individual clouds for Agl flares (.02-.2 kg/hour), and on-top seeding for dry ice (2 to 6 pounds per mile); at 12000-20000 ft level; only Agl was used in 1967-68; seeding lasted 1-6 hours per day

7. Design — cloud pairs (north or south) were used, restricted randomized, 50% seeding; besides, fixed historical target-control design was used in 1967-68 for runoff study

   7.1. Sampling unit — single cloud in 1966-68; in addition, seasonal (areal) runoff in 1967-68

   7.2. Experimental unit — single cloud

7.3. Numbers of seeded and unseeded units — 45 pairs of seeded and unseeded clouds; in addition, 7 seeded days (3 in 1967, 4 in 1968) were selected in the runoff study

7.4. Time relation between seeding and data recording —

7.5. Randomization procedure —

7.6. Implementation of design —

7.7. Person knows the randomization decision, and when —

7.8. Other decisions made in the field and by whom—

7.9. Target and control spacing and area sizes — 20-70 miles; in runoff study, target was 53 sq miles with 4 control areas north and south to the target

7.10. Change of design in progress — cloud pair was used, day (storm) was used in runoff study

8. Response variables and quality of data — radar echo was used in pair cloud study, seasonal runoff was used in target-control study

9. Statistical analysis — chi-square and McNemar tests were used in cloud pair study; t-test on regression in the runoff study

9.1. Transformation of data — none

9.2. Stratification of data — AgI vs dry ice (no significant difference); by wind speed and direction, precipitable water, temperature, cloud-base temperature, cloud-top temperature, cloud depth, streamflow

9.3. Estimated seeding effect and significance — in cloud pair study, out of the 45 seeded clouds, 21 yielded rain, 13 yielded virga, and 11 gave none, out of the 45 unseeded clouds, 3 yielded rain and 42 gave none, overall, there was significantly (at .001 level) more precipitation in seeded clouds; in runoff study, +34% (not significant) to +266% (.005 significant) for seasonal runoff

9.4. Covariates used —

9.5. Problem of multiplicity —

9.6. Re-analyses —

9.7. Statistical criticism — the selection of days used in runoff study was subjective and not adequate to reduce possible bias (NAS, 1973); there was concern on the use of historical data in the regression

10. Extra-area effect —

11. Key questions unanswered, major problems, methodology criticism —

12. Special features of the project —

13. Reference — Williams and Lehman (1970)

Project: Project Stormfury

1. Purpose of the project, questions to be investigated — 1) to develop and test cumulus cloud models, 2) to determine to what extent and under what conditions cumulus processes may be altered artificially, 3) to serve as a proving ground for storm modification techniques

2. Where and when (special terrain feature) — Bravo Missile area, Caribbean sea, July 28 to August 10, 1965 (a total of 9 days)

3. Parameters of cloud physics —

   3.1. Definition of single cloud —

   3.2. Kind of clouds used — tropical clouds with tops 17-26000 feet, clouds were selected by combined visual and RHI radar information

   3.3. Cloud temperature - top, middle, base levels —

   3.4. Definition of 'equivalent' clouds — none; however, 6 of the 7 unseeded clouds were close in time (one hour) and space (in 50 miles) to a seeded cloud, and 5 of them were paired with seeded clouds that grew above 31,000 feet, the other one was paired with a seeded cloud which did not grow

   3.5. Aircraft measurement — 4 instrument aircraft penetrated the chosen cloud from cloudbase to 31,000 feet before seeding; during seeding a WC-121 aircraft circled the cloud at a distance of 2-5 miles to observed cloud details and detect any visible smoke trails of the falling pyrotechnics; a C-130 made frequent dropsounds from 30,300 ft; the command-and-control aircraft made a series of radar, still and time-lapse photographs to determine the radius of the cloud tower; the seeder aircraft recorded maximum cloud height.

4. Radar — 10-cm radar at University of Miami (Simpson, 1967)

   4.1. Definition of echo —

   4.2. Echo parameters — PPI and RHI

5. Seedability criterion (who decide, how) —

6. Seeding method (agent and rate, how and by whom) — sixteen (8 for the last 2 clouds) Alecto units were released into each selected cloud within 1000 feet of cloudtop at 100 m interval by the pilot of seeding aircraft, each generator produced a little over 1 kg of AgI

7. Design — randomized block design, block size 5, 3 seeded, 2 unseeded; no fixed target and control areas

    7.1. Sampling unit — none was used

    7.2. Experimental unit — single clouds

    7.3. Numbers of seeded and unseeded units — 15 seeded clouds, 7 unseeded clouds

    7.4. Time relation between seeding and data recording —

    7.5. Randomization procedure —

    7.6. Implementation of design — 200 randomization decisions (numerically orered) were contained in sealed envelops prepared before seeding operation began by W. J. Youden and G. W. Brier

    7.7. Person knows the randomization decision, and when — the pilot of seeding aircraft opened the sealed envelop after cloud was selected, no other persons knew the decision

    7.8. Other decisions made in the field and by whom —

    7.9. Target and control spacing and area sizes — less than 50 miles between clouds; no control area was used

    7.10. Change of design in progress — none

8. Response variables and quality of data — mainly cloutop heights measured independently by aircraft, radar and photogrammetry; relative humidity at 3 layers (cloudbase-700, 700-500, 500-400 mb), static stability at 4 layers (cloudbase-700, 700-500, 500-400, 400-200 mb)

9. Statistical analysis — compared observed cloudtop heights with model predicted heights

    9.1. Transformation of data —

    9.2. Stratification of data — two groups—cloud grew above 31,000 feet (8 clouds), and clouds grew little or not at all (4 clouds).

    9.3. Estimated seeding effect and significance — two-third of properly seeded clouds underwent marked vertical growth, while 6/7 of the unseeded clouds did not

    9.4. Covariates used — none

9.5. Problem of multiplicity — none

9.6. Re-analyses —

9.7. Statistical criticism —

10. Extra-area effect —

11. Key questions unanswered, major problems, methodology criticism — out of 15 seeded clouds, the Alectos missed 1 cloud, two clouds were seeded by accident with tops near freezing, or considerably warmer than -5C

12. Special features of the project —

13. Reference — Simpson et al. (1966); Simpson (1967); Simpson et al. (1967)

Project: Tasmania

1. Purpose of the project, questions to be investigated — rain enhancement

2. Where and when (special terrain feature) — central Tasmania, Australia; year-rounding seeding in 1964, 1966, 1968, 1970; target area was mainly on a plateau of 2500 to 3000 feet with peaks to 5000 feet in the western part

3. Parameters of cloud physics —

   3.1. Definition of single cloud — cloudtop must contain supercooled water, cloud must have a depth exceeding half the terrain clearance, cloud must solid and compact (Smith et al., 1977)

   3.2. Kind of clouds used — cumulus, altostratus or altocumulus when deep enough, and nimbostratus and stratocumulus when cold enough

   3.3. Cloud temperature - top, middle, base levels — cloudtop temperature must be colder than -5 C (stratus) or -10 C (cumulus)

   3.4. Definition of 'equivalent' clouds — none

   3.5. Aircraft measurement —

4. Radar —

   4.1. Definition of echo —

   4.2. Echo parameters —

5. Seedability criterion (who decide, how) — reconnaissance flights were made to decide seedability — cloudtops must contain supercooled water and cooler than -5 C (stratus) or -10 C (cumulus), cloud depth must exceed half the terrain clearance of the base, clouds must be "solid" and "compact" (Smith et al., 1977)

6. Seeding method (agent and rate, how and by whom) — aircraft fitted with 2 smoke-generators burning Agl and Nal solution directly into cloud at rate of 2 gallons per hour

7. Design — periodic random target-control design, time was divided into periods of about 12 days, and one of the 2 consecutive 12-day periods was randomly selected for seeding

   7.1. Sampling unit — day

7.2. Experimental unit — period of approximately 12 days

7.3. Numbers of seeded and unseeded units — 202 seeded days, 211 unseeded days, 191 suspended days

7.4. Time relation between seeding and data recording —

7.5. Randomization procedure —

7.6. Implementation of design —

7.7. Person knows the randomization decision, and when — "cloud-seeder" on board the aircraft, who also selected clouds for seeding

7.8. Other decisions made in the field and by whom — "cloud-seeder" on board the aircraft decided how to seed, when to fly, observed clouds in the target and control areas; if the wind was such that the silver iodide might pass over one of the control areas, then no seeding was carried out, but still recorded as seeded; the results might thus be conservative

7.9. Target and control spacing and area sizes — 1 target area, 1 subsidiary area, 3 control areas, all of dimension 30-100 miles

7.10. Change of design in progress — the north-west control area was added at end of 1966

8. Response variables and quality of data — daily rain read at 0900 from a network of gages, 16 in the target, 18, 8, and 12 in the north, north-west, and south control areas

9. Statistical analysis — double ratio and regression (in the content of randomized block design)

9.1. Transformation of data — untransformed, square-root, or cube-root transformation

9.2. Stratification of data — by season

9.3. Estimated seeding effect and significance — mean rainfall in "autumn" was increased 30% (significant at .05 level); and mean rainfall in "summer" was decreased 5-10%

9.4. Covariates used —

9.5. Problem of multiplicity — the analysis of the four "Seasons" suggested the existence of multiplicity

9.6. Re-analyses —

9.7. Statistical criticism — there remained the question of multiplicity (STF, 1978)

10. Extra-area effect — the possibility existed (STF, 1978)

11. Key questions unanswered, major problems, methodology criticism — issues of multiplicity in data analysis leave question unsettled

12. Special features of the project — in advance of the experiment five circumstances were defined for suspending unsuitable day from being used in analyzing the experimental results (Smith et al., 1977), one of them is that the rain in the north and south controls has to satisfy certain relationship

13. Reference — Smith et al. (1971), Smith et al. (1977)

Project: Whitetop

1. Purpose of the project, questions to be investigated — to study the effects of seeding upon summertime rain

2. Where and when (special terrain feature) — around West Plains, Missouri, summers of 1960-1964, seeding was done inside an circular area with a 60-miles radius in south-central Missouri and north-Central Arkansas

3. Parameters of cloud physics —

   3.1. Definition of single cloud — none

   3.2. Kind of clouds used — summertime, non-orographic, convective clouds

   3.3. Cloud temperature - top, middle, base levels —

   3.4. Definition of 'equivalent' clouds — none

   3.5. Aircraft measurement — a Beechcraft D18C was used for cloud physics measurements

4. Radar — AN/TPS-10 3-cm radar located at West Plains, Missouri

   4.1. Definition of echo — radar scope was photographed using a 16-mm movie camera

   4.2. Echo parameters —

5. Seedability criterion (who decide, how) — determined by whether wind direction at 400 feet msl was from the sector between 170 and 340 degree or not, precipitable water, and probability of afternoon precipitation, based on the radiosonde data at 0600 CST at Little Rock, Arkansas and Columbia, Missouri

6. Seeding method (agent and rate, how and by whom) — airborne seeding (using three Cessans 172) at cloud base (between 3000-5000 feet msl), AgI at rate of 2.7 kg/hour, along a 30 miles long line perpendicular to the wind and upwind of the experimental area, 3 planes were used for seeding for 6 hours (1100-1700 during 1960-1961, 1000-1600 during 1962-1964), 6 silver iodide-in-aceton Australian-type generators were used

7. Design — unrestricted randomized design on days, moving target-control based on locally measured winds and starting and stopping of seeding

   7.1. Sampling unit — 14 hours (1000-2400)

7.2. Experimental unit — day

7.3. Numbers of seeded and unseeded units — 102 seeded, 96 unseeded days

7.4. Time relation between seeding and data recording —

7.5. Randomization procedure —

7.6. Implementation of design — days were selected for seeding before the decision on seedability was made

7.7. Person knows the randomization decision, and when —

7.8. Other decisions made in the field and by whom —

7.9. Target and control spacing and area sizes — 0 miles between target and control; variable area sizes, target and control combined to equal 11300 sq miles; Decker and Schickedanz (1967) found that plume widths of as much as 60 miles and plumes covering the entire target were observed on occasion

7.10. Change of design in progress —

8. Response variables and quality of data — rainfall total estimated by 49 recording raingages and 3-cm radar

9. Statistical analysis — (1) Wilcoxon-Mann-Whitney test, (2) Taha-Mielke squared rank test, and (3) t-test, all the tests indicated 30-40 % less rainfall on seeded days than on unseeded days in the target, some were significant at .05 level; and significantly 25% (.04-.09 levels) less echos in the target when comparing seeded periods to unseeded periods, however, there were more echo in target when maximum echo height was between 20000-40000 feet

9.1. Transformation of data — logarithmic (Decker and Schickedanz, 1967)

9.2. Stratification of data — 1) by 'plume area' - Missouri plume area (narrower), Chicago plume area (wider), and out-of-plume area (complement of Chicago plume area); 2) by 'time' - during seeding hours (-10% rain, nonsignificant) and 5 hours immediately after seeding (-42% rain, nonsignificant; -74% radar echo, significant at .027); 3) by low level wind - southerly winds showed negative effect (-15 to -30%), westerly winds showed weak positive effect (as much as 30%) (Braham and Flueck, 1970); (4) by echo height - days with maximum echo heights between 20,000 and 40,000 ft msl showed substantial positive effect (>100%), days with maximum echo heights above 40,000 ft msl showed negative effect

9.3. Covariates used —

9.4. Problem of multiplicity — numerous a priori and a posteriori analyses have been published

9.5. Re-analyses — Neyman et al. (1969a) and Lovasich et al. (1969) examined rainfall over much large area than those of either Chicago or Missouri plume

9.6. Statistical criticism — 1) part of the conclusion by Decker and Schickedanz (1967) might be due to the 'area-to-area' comparison, Neyman and Scott (1967) preferred 'seeded day vs un-seeded day' comparison

10. Extra-area effect — control area sometimes had been partially seeded (as noticed by project scientist); Lovasich et al. (1971) found the seeding decreased precipitation over the area 180 miles in radius; however, Schickedanz and Huff (1970) found the evidence for downwind effects to be very weak.

11. Key questions unanswered, major problems, methodology criticism — non-seeded days were favored with more rain, despite randomization (Decker and Schickedanz, 1967)

12. Special features of the project — 'plume areas' defined by wind direction between 14000 ft and seeding level were used in the analyses

13. Reference — Final Reports of Project Whitetop, Part 1 and II (Braham, 1966), Part IV (Decker and Schickedanz, 1966), Part V (Flueck, 1971), Decker and Schickedanz (1967)

PART 4.

PART 4

Appendix 1. Characteristics of Rain Events (Storms), CHAP 1977-79.

Storm No.	Date	Begin Time	End Time	Motion (from)	Synop Type	No. Miss	Comments
1	6/01/77	1232	1256	W	AM		
2	6/01/77	1625	2112	NW	CF		time gaps
3	6/08/77	1502	1721	NW	LW		
4	6/16/77	1945	2020	NW	AM		bad date
5	6/17/77	1302	1532	W	SF		
6	6/17/77	1907	0105	W	SL		some bad data, bad time, time gaps
7	6/23/77	1630	1821	SW	WF	8	
8	6/28/77	1522	1623	W	CF		
9	6/28/77	1833	2012	W	CF	1	
10	6/30/77	1204	1409	W	SL		
11	7/03/77	1034	1249	W	WF	1	
12	7/07/77	0720	0921	W	CF		
13	7/08/77	1315	2128	W	SZ		
14	7/15/77	1521	2309	W	SF	4	
15	7/17/77	0050	0357	W	SL		
16	7/18/77	0652	1113	W	SZ	37	
17	7/20/77	1754	1857	W	AM		
18	8/05/77	1106	2033	SW	SZ		many gaps, bad times
19	8/06/77	1024	1216	W	SF		
20	8/06/77	1306	2113	W	SF	1	time gaps
21	8/07/77	0642	0914	W	SZ		time gaps
22	8/08/77	0223	0251	W	SL		
23	8/09/77	0957	1036	W	SL		
24							non-existing
25	8/10/77	0244	0421	W	SL		
26	8/11/77	0814	1749	SW	SF	3	time gaps
27	8/12/77	1623	1785	W	SL		time gaps
28	8/16/77	0529	0948	W	SL	1	bad time
29	8/16/77	1459	1556	W	CF		
30	8/19/77	1230	1256	NW	AM	3	bad time
31	8/19/77	2220	1025	NW	SF		
32	8/20/77	1535	2207	NW	SZ	2	
33	8/21/77	0749	1445	NW	SZ		
34	8/21/77	1709	2159	NW	AM		
35	8/23/77	1425	2305	W	CF		
36	8/28/77	1142	1656	SW	CF		
37	6/07/78	0135	0605	SW	SZ	1	
38	6/07/78	2039	2315	SW	SL	1	
39	6/12/78	0410	0823	SW	SL		
40	6/12/78	1235	1527	W	AM		time gaps
41	6/14/78	1330	0305	NW	AM		time gaps
42	6/16/78	0050	1251	W	SZ	7	time gaps
43	6/16/78	1351	2130	W	SZ	1	not in order, time gaps
44	6/17/78	0418	0745	NW	SL		

Storm No.	Date	Begin Time	End Time	Motion (from)	Synop Type	No. Miss	Comments
45	6/17/78	0833	1415	NW	SZ		
46	6/17/78	2003	2254	SW	SL	3	
47	6/18/78	0455	0650	W	SF		
48	6/20/78	1235	0010	W	SZ	1	time gaps
49	6/23/78	1005	1919	W	SZ		time not in order, gaps
50	6/25/78	0457	2151	W	SZ	27	extreme heavy rain, time gaps
51	6/25/78	2201	1040	SW	SZ	4	time gaps
52	6/27/78	0133	1145	SW	CF		bad EOF
53	6/29/78	2206	0030	NW	AM		
54	6/30/78	0033	1239	W	CF	3	time gaps
55	6/30/78	1323	2230	W	SF	2	
56	6/30/78	2235	0255	W	SF		time gaps
57	7/01/78	0300	1154	W	WF	2	
58	6/29/79	0240	0845	NW	SZ	1	
59	6/30/79	1840	2325	NW	SZ	1	bad times
60	7/13/79	1240	1855	SW	SF	1	time gaps
61	7/03/79	1900	0100	NW	CF		
62	7/04/79	0105	0620	NW	CF	1	
63	7/10/79	1630	2130	SW	AM	1	
64	7/11/79	1350	1945	SW	SZ		bad time, time gaps
65	7/14/79	0050	1025	NW	SZ	2	
66	7/14/79	1030	1710	W	SF	3	time gaps
67	7/24/79	1105	1640	SW	SZ		time gaps
68	7/24/79	1645	2310	SW	SL	2	
69	7/25/79	0330	0945	SW	SZ		time gaps
70	7/27/79	2030	0100	SW	SF		time gaps
71	7/28/79	0810	1050	SW	SF		
72	7/29/79	2315	0220	SW	SF		time gaps
73	7/30/79	0300	1200	SW	SZ		
74	7/30/79	1800	0235	SW	AM	1	time gaps
75	8/01/79	0848	1654	SW	POSF	2	time gaps
76	8/03/79	0200	0339	SW	SZ		
77	8/04/79	1505	2155	NW	SZ		
78	8/05/79	0955	1425	NW	SZ		
79	8/05/79	1425	1715	NW	SZ		time gaps
80	8/05/79	1814	2354	NW	CF		time gaps
81	8/08/79	0720	0916	W	SF		
82	8/08/79	2140	0340	SW	SF		
83	8/09/79	2200	0945	W	SL		time gaps
84	8/10/79	1535	1840	NW	CF		
85	8/10/79	1845	2100	SW	SF		
86	8/13/79	0238	0825	NW	SZ		
87	8/13/79	1546	2025	SW	PRCF	1	time gaps

PART 5.

PART 5
Philip Garcia

****

February 15, 1932

DATA BASE FORMAT FOR NCDC ELEMENT ARCHIVES

FILE INFORMATION:

File format	: Variable length blocked
Block size	: 12000 Characters
Media	: ANSI Quarter-word mode mag tape
Tape file structure	: 1 Data file

For IBM equipment specify JCL as:

```
LRECL   = 1230+4= 1234
RECFM   = DB
OPTCODE = Q
```

There are different Element Archive files corresponding to different families of data, such as Daily Data (Summary of the day) or Monthly Data. Information about the arrangement of records within a file is contained in an appendix for each of the different element files. However, all Element Archive files share the same record structure.

****

RECORD INFORMATION:

Each logical record contains a station's data for a specific meteorological element over a specific time interval. The form of a record is:

ID PORTION (30 characters)

RECORD-TYPE	STATION-ID	ELEMENT-TYPE	ELEMENT-UNITS	YEAR	MONTH	DAY	NUM-VALUES
X(3)	X(8)	X(4)	X(2)	9(4)	9(2)	9(4)	9(3)

DATA PORTION (12 characters repeated NUM-VALUES times)

TIME-OF-VALUE	DATA-VALUE SIGN	DATA-VALUE VALUE	FLAG-1	FLAG-2
9(4)	X(1)	9(5)	X(1)	X(1)

The first eight fields, the ID PORTION of the record, describe the characteristics of the entire record (station, time interval, element type). The last five fields, the DATA PORTION of the record, contain information about each element value reported. This portion is repeated for as many values as occur in the given time interval. As an example, one record might contain one month of daily maximum temperatures, or one day of hourly temperatures, etc.

****

FIELD INFORMATION:

RECORD-TYPE: The type of data stored in this record.
HLY = one day's worth of hourly element values
DLY = one month's worth of daily element values
MLY = one year's worth of monthly element values
LTM = one year's worth of long term monthly means of element values
U-A = element values for a single upper air sounding

STATION-ID: 8 character station identifier assigned by the National Climatic Center. The meanings of the individual characters varv according to which type of data the record contains (see Appendix for your file).

ELEMENT-TYPE: The type of data element stored in this record (see the ELEMENT-CODE TABLE in Appendix for your file).

ELEMENT-UNITS: The units and decimal position of the data value for this record (See the ELEMENT-UNITS TABLE for codes).

YEAR: Year of the record.

MONTH: Month of the record when applicable. See Appendix for your file for the exact meaning.

DAY: Day of the record when applicable. See Appendix for your file for the exact meaning.

NUM-VALUES: The actual number of data entries in the record.
NOTE: a record may contain fewer or more data values than what YOU might expect. A monthly record of daily values may contain as few as 1 data values or as many as 62. This is primarily due to missing or-edited data. If a particular data value was not taken or is unavailable there is no entry for it. Also, when erroneous data are encountered during quality control the original values are flagged and are followed by replacement values (see FLAG-2 TABLE for details).

TIME-OF-VALUE: Actual time or level of the data value. See Appendix for your file for the exact meaning.

DATA-VALUE: Actual data value including leading sign position. The SIGN portion of the field contains either a blank or a minus sign (never a plus sign). The VALUE portion of the field is a five digit integer. Units and decimal position are indicated in the ELEMENT-UNITS field described above.

FLAG-1: Data measurement flag. See the FLAG-1 TABLE for details.

FLAG-2: Supplementary flag. See the FLAG-2 TABLE for details.

****

The following statements may be used to read a logical record in COBOL or FORTRAN.

Typical ANSI COBOL Data Description.

```
FD  INDATA
    LABEL RECORDS ARE STANDARD
    RECORDING MODE D
    BLOCK CONTAINS 12000 CHARACTERS
    DATA RECORD IS DATA-RECORD.
01  DATA-RECORD.
    02 RECORD-TYPE              PIC X(3).
    02 STATION-ID  .            PIC X(3).
    02 ELEMENT-TYPE             PIC X(4).
    02 ELEMENT-UNITS            PIC XX.
    02 YEAR                     PIC 9(4).
    02 MONTH                    PIC 99.
    02 DAY                      PIC 9(4).
    02 NUM-VALUES               PIC 9(3).
    02 DAILY-ENTRY
        OCCURS 1 TO 100 TIMES DEPENDING ON NUM-VALUES.
       04 TIME-OF-VALUE         PIC 9(4).
       04 DATA-VALUE            PIC S9(5) SIGN LEADING SEPARATE.
       04 FLAG-1                PIC X.
       04 FLAG-2                PIC X.
```

Typical FORTRAN 77 Data and File Description.

```
      DEFINE FILE 10(ANSI,VB,1230,12000)
      CHARACTER*3 RECTYP
      CHARACTER*8 STNID
      CHARACTER*4 ELMTYP
      CHARACTER*2 EUNITS
      CHARACTER*1 FLAG1, FLAG2
      DIMENSION ITIME(100), IVALUE(100), FLAG1(100), FLAG2(100)
      READ(10,20,END=?99) RECTYP,STNID,ELMTYP,EUNITS,IYEAR,IMON,IDAY,NUMVAL
     +                  ,(ITIME(J),IVALUE(J),FLAG1(J),FLAG2(J) , J=1,NUMVAL)
   20 FORMAT(A3,A8,A4,A2,I4,I2,I4,I3,100(I4,I6,2A1))
```

NOTE: If YOU do not have FORTRAN 77 YOU can read the character data described above into integer variables.

ELEMENT-UNITS TABLE

D	Whole Fahrenheit degree days
F	Whole degrees Fahrenheit
I	Whole inches
M	Whole miles
CM	Centimeters
HI	Hundreths of inches
ME	Whole meters
MH	Miles per hour
MM	Millimeters
TC	Tenths of degrees Celsius
TD	Tenths of Fahrenheit degree days
TF	Tenths of degrees Fahrenheit
TI	Tenths of inches
TM	Tenths of millimeters
NA	No units applicable (Non-dimensional)
N1	No units applicable - element to tenths
N2	no units applicable – element to hundreths

NOAA Form 34-326 (3-82)

THIS IS A TRANSMITTAL; PAYMENT IS NOT REQUESTED

09441

SF /E/CC423 01775

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Environmental Satellite, Data, and Information Service
National Climatic Data Center
Asheville, North Carolina
28801-2696
FEDERAL TAX ID 52 0821608

REFERENCE YOUR CUSTOMER NO. WHEN CONTACTING US ABOUT THIS OR FUTURE ORDERS

ORDER NO.	COMPLETED	CUSTOMER NO.	REFERENCE	PAGE
54111867000	85/02/21	61801970		1

ATTACHMENT

SHIPPING INFORMATION EFFECTIVE 1/1/85 ALL ORDERS MUST BE PREPAID. MC/VISA ACCEPTED

BILL TO :

UNIV. OF IL/URBANA-CHAMPAIGN
252 ADMINISTRATION DIVISION
506 SOUTH WRIGHT ST.
URBANA, IL 61801

DESCRIPTION	AMOUNT
DIGITAL SERVICE AND HANDLING CHARGE	10.00
01 MAG TAPE TD3220 - MONTHLY SURFACE DATA ELEMENT	375.00
9 TRACK 6250 BPI DENSITY ASCII	
SELECT STATES	
VARIABLE LENGTH RECORDS	
ON THE ATTACHED PAGE READ PARAGRAPHS NO(S): 01	

Charge for late payment will be assessed at the rate of 1.068 %(13.000 *% annual rate) of the overdue balance for each 30 day period or portion thereof that payment is delayed.*

TOTAL	385.00
LESS PREPAID	385.00
BALANCE	.00

PLEASE DETACH AND RETURN WITH YOUR REMITTANCE. ADDRESS ANY QUESTIONS OR COMMENTS ON A SEPARATE CLOSURE. WRITE ORDER NUMBER ON YOUR CHECK.

To assure continued service payment should be received by
%%%%%%%%%%%%%%%%%%%%

PAY THIS AMOUNT .00

MAKE CHECK PAYABLE TO COMMERCE, NOAA, NCDC

AMOUNT ENCLOSED ~~NONE DUE~~

ORDER NO.	COMPLETED	CUSTOMER NO.	REFERENCE	PAGE
54111867000	85/02/21	61801970		1

ATTACHMENT

AFTER PROCESSING THIS ORDER, YOU HAVE A ZERO ACCOUNT BALANCE = $0.00

UNIV. OF IL/URBANA-CHAMPAIGN
252 ADMINISTRATION DIVISION
URBANA, IL 61801

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** O.K. TO PAY BY MASTERCARD OR VISA **

If necessary forward this statement to your paying agency

NATIONAL CLIMATIC DATA CENTER-FEDERAL BUILDING-ASHEVILLE, N.C. 28801-2696 PHONE (704) 259-0682

1 Tape readability is guaranteed to original purchaser provided that National Climatic Data Center furnished the blank tape and the user attempts to read the tape within 60 days of receipt.

2 The program you are receiving is a copy of an active piece of software on the UNIVAC 1100 System used by the National Climatic Data Center for its internal use and as such is in the public domain. The fee paid to receive this program covers only the cost of transfer of the source code to your desired output medium. Since this center is not a software broker, we do not:

a. Provide support in making the program run on your system.
b. Automatically provide possible changes or updates made to enhance the program.

3 Technical questions regarding these data should be sent to:

Dr. Larry Rothman
AFGL/OPI-Mail Stop 30
Hanscom AFB, MA 01731

4 The National Climatic Data Center considers that, in some cases, the reported values on Cooperative Climatological Observation forms, January 1982 and later, are questionable due to recording errors. The best estimates of observed values may be obtained from our Climatological Data publication or from our digital data files.

5 The National Climatic Data Center considers the accuracy of the solar radiation data you have requested to be questionable. The best estimates of observed solar radiation may be obtained from our magnetic tapes in the SOLMET format.

6 If payment is made by check, it must be drawn on a United States bank or a U. S. branch of a foreign bank, payable in United States currency. International money orders or UNESCO coupons also are acceptable as payment.

7 Since no weather records are received for your specified area, we are substituting available data of the type desired from the nearest reporting station. Because of the distances involved or differences in terrain features, these data may not be completely representative.

8 If assistance is needed in the application of the data on these records, obtain a list of addresses for private consulting meteorologists from:

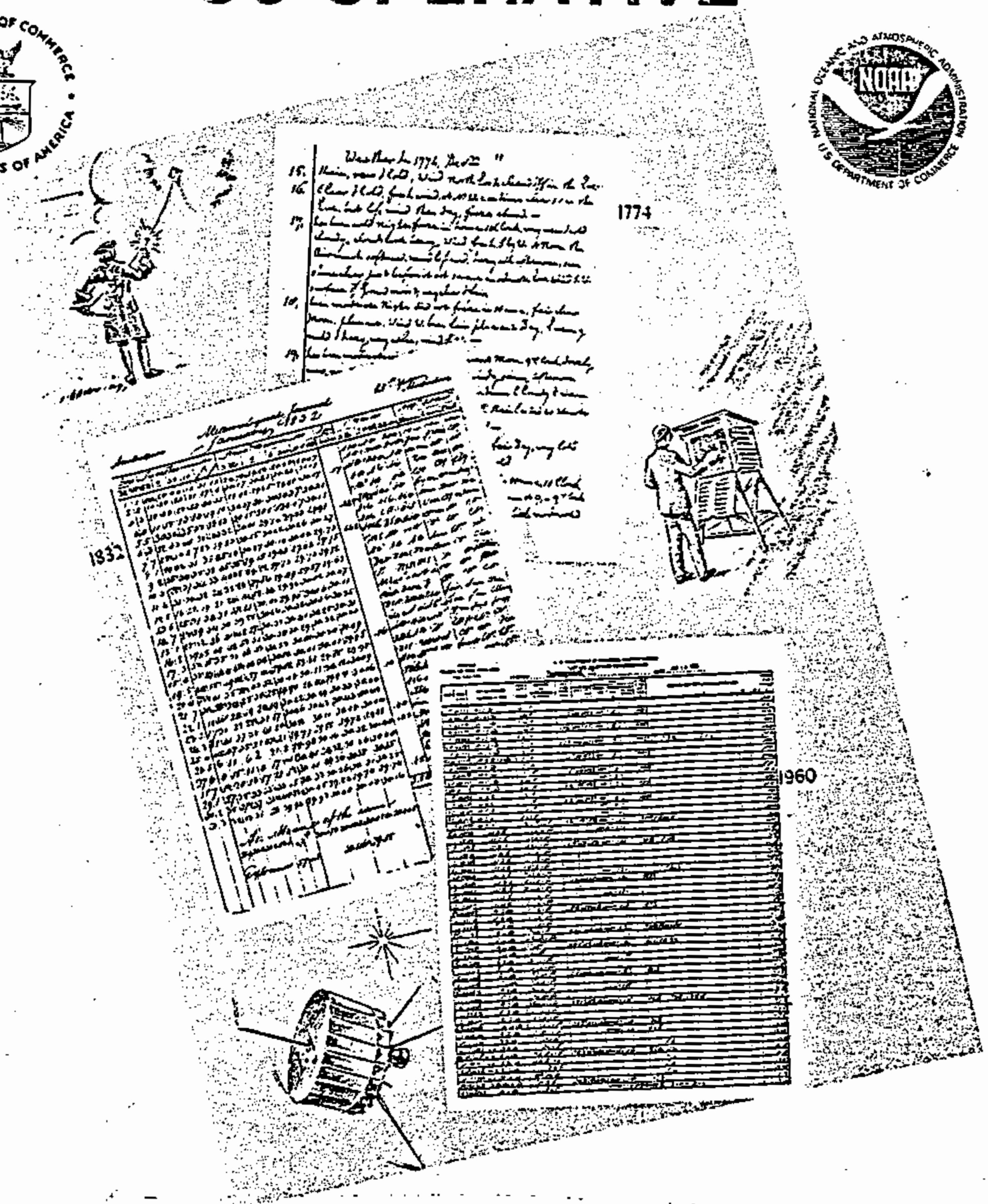
The American Meteorological Society
45 Beacon Street
Boston, MA 02108

9 URGENT

Regulations will not permit the National Climatic Data Center to absorb cost for services provided customers on a reimbursable basis. UNTIL WE RECEIVE PAYMENT, OR JUSTIFICATION FOR NON-PAYMENT WE WILL NOT BE ABLE TO HONOR FUTURE REQUESTS FOR DATA. Should your records show that payment has been made for this invoice, please send proof of payment. We prefer to remove your name from our past-due accounts RATHER THAN TURN IT OVER TO THE NOAA OFFICE OF GENERAL COUNSEL FOR COLLECTION.

10. Excess payment less than $10.00 may be used as credit on future orders. Please indicate your desire to use this credit on the order to which you want it applied. Excess payment of $10.00 or greater will be refunded upon written request only.

TD - 3220
SUMMARY OF MONTH
CO-OPERATIVE



noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / NATIONAL ENVIRONMENTAL SATELLITE, DATA, AND INFORMATION SERVICE / NATIONAL CLIMATIC DATA CENTER ASHEVILLE, N.C.

SUMMARY OF THE MONTH
COOPERATIVE
TD-3220

Prepared by
National Climatic Data Center
Federal Building
Asheville, North Carolina

October 1984

This document was prepared by the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite Data and Information Service, National Climatic Data Center, Asheville, North Carolina.

This document is designed to provide general information on the content, origin, format, integrity and the availability of this data file.

Errors found in this document should be brought to the attention of the Data Base Administrator, NCDC.

INTRODUCTION

SOURCE

Observations of daily weather have been recorded in the United States since the first settlers arrived, but systematic development of a climatological network didn't begin until the mid-1800s. It was soon realized that volunteer observers, using approved instruments and observing techniques, would be the only way to achieve an adequate network density. Cooperative observers remain the backbone of the climatological observation program to this day.

Information contained in this monthly data file are primarily those from the cooperative network, augmented by observations from principal climatological stations operated by the National Weather Service and other sites having highly trained observers.

The primary thrust of the cooperative observing program today is the recording of 24-hour precipitation amounts, but about 55% of the stations also record maximum and minimum temperatures. Principal stations are usually fully instrumented and therefore record a more complete range of meteorological parameters.

The Summary of the Month (SOM) data file is a product of editing and summarizing' of the Summary of the Day (SOD) TD-3200 daily data file (reference documentation TD-3200). Current SOM data are produced in format TD-3220.

Through the years more than 23,000 stations have recorded observations in this program but seldom were there more than 12,000 in operation at any one time. In the 19.84 data approximately 9,000 active stations are included in the digital data base.

The major effort toward automatic processing began in 1948 when punched cards were first used to help summarize climatological data. Data from that time onward comprise the majority of the total file. Data for earlier periods were placed on punched cards as a result of cooperative agreements with various State universities. Initially, not all the 3tates participated in this program so the number of stations as well as the period of record is varied.

During the late 1960's the 136 character data set TD-9924 was transferred to magnetic tape to form the SOM digital data base. This 136 character format remained in effect until the current element file structure was developed in 1982. At that time the historical files were converted to TD-3220 and processing of current data was completely revised.

Areal coverage includes the contiguous U.S., Alaska, and Hawaii with some Pacific and Caribbean Islands. Selected Central American Stations (1960-1967 only).

The digital file contains Record type, Station Identification, and Element types:

Temperature Data: Mean monthly maximum, mean monthly minimum, mean for month, departure from normal (in effect at the time data were processed). Highest and lowest with dates, frequency of maximum and minimum within categories, heating and cooling degree days (Base 65°F).

Precipitation Data; Total for month, departure from normal, (in effect at the time data were processed). Greatest observed daily amount and date, total snowfall for month, greatest depth of snow and date, and the number of days of the occurrence of precipitation within specified limits. (Example: Number days with > or = 0.5 inches of precipitation.)

Evaporation Data; Total monthly wind mileage, total monthly evaporation and mean maximum and minimum pan water temperature.

Freeze Data: Annually only. Lowest temperature and date of occurrence. Date of last spring minimum freezing temperatures and date of first fall minimum freezing temperatures occurring within five categories (less than or equal 32 deg, 28 deg, 24 deg, 20 deg, 16 deg). Number of days between occurrences of freezing temperatures within the five categories.

Soil Temperature Data; Soil Type, soil depth, temperature data for various soil types and depths (mean monthly minimum and maximum, mean monthly at observation time, lowest and highest at observation time, lowest monthly minimum, highest monthly maximum).

Divisional Average Data: Temperature and precipitation monthly departures from normals (in effect at the time the data were processed). Number of days with rain, monthly means (temperature, precipitation, and snowfall).

Annual totals and means are derived at the end of each year. The values are present in the 13th value. The first 12 values represent the 12 months of the year.

Soil data were added in Jan. 1982 with approximately 250 stations reporting soil data. Soil data prior to 1982 are available in TD-9639.

Some 285 principal climatological stations report most of the elements listed above. The remainder of the stations usually report a lesser number of elements.

Cooling Degree Day and Divisional Values are available only from 1980 forward. Divisional data prior to 1980 are available in TD-9640 Divisional Averages Temperatures, Precipitation, and Normals.

Caribbean stations are recorded in metric units, except for Puerto Rico and the Virgin Islands.

Beginning with the data for January 1982 Cooperative data: were processed through a completely revised system. Relying heavily on new computer editing procedures, data are subjected to internal consistency checks, compared against climatological limits, checked serially, and evaluated- against surrounding station observations.

The historical data were converted from existing digital files and structured into the element structure format. These data were processed through a gross value check and not the new edit syseem. It is the goal of the NCDC that these historical files will be brought up to the same level of quality as those from 1982 onward as resources become available.

SPECIAL NOTES

QUALITY

It must be understood that at the onset of punched card processing of climatological observations the primary goal was the publication of the monthly climatological summaries. The conversion from manual to automated systems meant that more work could be done faster with fewer people and at less cost. Even though the punched cards were retained, it was never envisioned that 20 to 30 years from then a great number of users would be seeking large data files for retrospective studies using high speed computers.

Benign neglect, state of the art processing (CIRCA 1952), and limited money/people resources all contributed toward less than optimum conditions in maintaining integrity of the digital files. Many of these shortcomings are now recognized and efforts are underway to upgrade the principal data sets.

FILE STRUCTURE

The element file structure is designed to allow maximum flexibility in requesting data. Only those elements or groups of elements of particular . interest need be ordered. End user input programs can be modified easily to operate on different sets of elements.

LOGICAL REFERENCE TO ELEMENT TYPES

(Note: Element descriptions begin on page 11)

Logically grouped Element types are as follows:

1. Degree Days - CLDD, HTDD
2. Normals - DPNP, DPNT
3. Number of days Precipitation and or Snow occurred: DPOl, DPO3 DPO5, DOPH, DPOQ, DP10, DP25, DP50, DSNW, and MDRN.
4. Number of days temperature occurred within a specified threshold: DT00, DT15, DT30, DT32, DT60, DT70, DT90, DX15, DX32 and DX60.
5. Temperature: EMNT, EMXT, MMNT, MMXT and MNTM.
6. Precipitation and/or Snow: EMXP, MXSD, TSNW, and TPCP.
7. Evaporation Data: MMNP, MMXP, TEVP, TPCP, and TWND.
8. Soil Data: NMyz, HNyz, LNyz, MOyz, HOyz, LOyz, MXyz, HXyz, and LXyz.
9. Divisional Data: DAPT, DPNP, DPNT, MDRN, NNTM, TPCP, and TSNW.

USE OF THE MANUAL

This manual was designed so that reference to other reference material should be unnecessary. Inventories, station listings, or any additional information may be obtained if necessary by writing or calling:

National Climatic Data Center E/CC42
ATTN: USER Services Branch
Federal Building
Asheville, North Carolina 28801-2696

Telephone inquiries may be directed to:

Commercial 704-259-0682
FTS 672-0682

Care should be taken to read carefully the "Manual and Tape Notations" and 'Code Definitions and Remarks" sections.

TAPE FORMAT

MANUAL AND TAPE NOTATIONS

1. FILE (NCDC Variable Length Storage Structure)

   A. Physical Characteristics

This primary data file contains monthly data through 1983 as of Oct. 1984. Current data are available in a yearly file that is appended as each month is processed. Example: After the first 3 months processing are complete, the current file would contain JAN, FEB, and MAR. The annual data files are then merged each year until five years of data are accumulated, at which time the five years of data are merged with the primary data file. Divisional data available from 1980 forward only. Divisional data are maintained as a separate file within TD-3220. Current year divisional data are stored in a year of record file only. (Current monthly divisional data are available by special request only.)

2. RECORD

   A. Physical Characteristics

Each logical record contains one year of one station's monthly data values for a specific meteorological element. The record consists of a control word and identification portion, and a data portion. The control word is used by the computer operating system for record length determination. The identification portion identifies the observing station, year and record element codes. The data portion contains the meteorological observation for the monthly values and flags. The data portion is repeated for as many values as occur in the given time interval.

NOTE: Freeze data is an exception as it pertains to annual values and does not contain 12 monthly values. See Code Definitions and Remarks on 'FRZD'.

Data in this set are retained in chronological order by station. Divisional data are filed on separate tapes in State and division order. Although library tapes are normally maintained as described below, different characteristics including fixed length records can be furnished on request. Additional charges may be accrued for special processing.

NCDC Library Tapes are structured as follows:

Record length	:	Variable with maximum of 1230 characters
Blocked	:	12000 characters maximum
Media	:	ASCII 9 Track
Density	:	6250 BPI
Parity	:	Odd
Label	:	ANSI Standard Labeled
File	:	1 File per tape

B. FORMAT (VARIABLE RECORD)

1. The first eight tape fields, the ID PORTION of the record, describe the characteristics of the entire record. The DATA PORTION of the record contains information about each element value reported. This portion is repeated for as many values as occur in the yearly record of monthly values.

Each logical record is of variable length with a maximum of 1230 . characters. Each logical record contains a station's data for a specific meteorological element over a one year interval. The form of a record is:

ID PORTION (30 characters) Fixed length

	REC TYP	STATION ID	ELEM TYPE	UNT	YEAR	FILL	FILL	NO. VAL
	XXX	XXXXXXXX	XXXX	XX	XXXX	XX	XXXX	XXX
TAPE FIELD	001	002	003	004	005	006	007	008

DATA PORTION (12 Character Data Portion repeats the number of times indicated by the data value stored in Tape Field 008)

	MO	DY	DATA ELEM S	DATA ELEM VALUE	FL 1	FL 2	MO	DY	DATA ELEM S	DATA ELEM VALUE
	XX	XX	X	XXXXX	X	X	XX	XX	X	XXXXX
TAPE FIELD	009	010	011	012	013	014	015	016	017	018

	DATA ELEM S	DATA ELEM VALUE	FL 1	FL 2
	X	XXXXX	X	X
TAPE FIELD	197	198	199	200

TAPE FIELD	TAPE RECORD POSITION	ELEMENT DESCRIPTION
001	001-003	RECORD TYPE
002	004-011	STATION I.D.
003	012-015	METEOROLOGICAL ELEMENT TYPE
004	016-017	MET. ELEMENT MEASUREMENT UNITS
005	018-021	YEAR
006	022-023	FILLER = 99 ONLY
007	024-027	FILLER = 9999 ONLY
008	028-030	NUMBER OF DATA PORTION GROUPS THAT FOLLOW
009	031-032	MONTH OF OBSERVATION (13 = ANNUAL)
010	033-034	DAY OF OBSERVATION (WHERE APPLICABLE)
O11	035	SIGN OF METEOROLOGICAL VALUE
012	036-040	VALUE OF METEOROLOGICAL ELEMENT
013	041	QUALITY CONTROL FLAG 1
014	042	QUALITY CONTROL FLAG 2
(015-020)	(043-054)	DATA GROUPS IN THE SAME FORM AS TAPE FIELDS
(021-026)	(055-066)	009-014. REPEATED AS MANY TIMES AS NEEDED
(027-032)	(067-078)	TO CONTAIN ONE YEAR OF RECORD.
(195-200)	(1219-1230)	

The following statements may be used to read a logical record in COBOL or FORTRAN for variable length.

Typical ANSI COBOL Data Description.

```
FD   INDATA
     LABEL RECORDS ARE STANDARD
     RECORDING MODE D
     BLOCK CONTAINS 12000 CHARACTERS
     DATA RECORD IS DATA-RECORD.
01   DATA-RECORD.
     02 RECORD-TYPE              PIC X(3).
     02 STATION-ID               PIC X(8).
     02 ELEMENT-TYPE             PIC X(4).
     02 ELEMENT-UNITS            PIC XX.
     02 YEAR                     PIC 9(4).
     02 FILLER                   PIC 99.
     02 FILLER                   PIC 9(4).
     02 NUMBER-VALUES            PIC 9(3).
     02 DAILY-ENTRY
          OCCURS 1 to 100 TIMES DEPENDING ON NUMBER-VALUES.
        04 MONTH                 PIC 99.
        04 DAY                   PIC 99.
        04 DATA-VALUE            PIC S9(5) SIGN LEADING SEPARATE.
        04 FLAG-1                PIC X.
        04 FLAG-2                PIC X.
```

Typical FORTRAN 77 Data and File Description.

```
DEFINE FILE 10 (ANSI, VB, 1230, 12000)
CHARACTER*3 RECTYP
CHARACTER*8 STNID
CHARACTER*4 ELMTYP
CHARACTER*2 EUNITS
CHARACTER*4 IYEAR
CHARACTER*6 IFIL
CHARACTER*3 NUMVAL
CHARACTER*1 FLAG1, FLAG2
DIMENSION IMON(100), IDAY(J), IVALUE(100), FLAG1(100),
FLAG2(100)

READ (10,20,END=999) RECTYP, STNID, ELMTYP, EUNITS, IYEAR,
IFIL, NUMVAL, (IMON(J), IDAY(J), IVALUE(J), FLAGl(J),
FLAG2(J), J=1, NUMVAL)

20 FORMAT (A3, A8, A4, A2, I4, A6, I3, 100(2I2, I6, 2A1))
```

NOTE: If you do not have FORTRAN 77 you can read the character data described above into integer variables.

3. IBM JCL NOTES.

1. For ASCII Variable specify:
   LRECL = 1234
   RECFM - DB
   OPTCODE - Q

2. For EBCDIC Variable specify:
   LRECL - 1234
   RECFM - VB

TAPE FIELD	TAPE RECORD POSITION	ELEMENT NAME	CODE DEFINITIONS AND REMARKS
001	1-3	Record-Type	The type of data stored in this record. Value is "MLY."
002	4-11	Station-ID	This 8 character station identifier is assigned by the National Climatic Data Center.

TAPE FIELD	TAPE RECORD POSITION	ELEMENT NAME	CODE DEFINITIONS AND REMARKS
	4-5	State-Code	STATE CODE Range of values is 01-91.

01 Alabama	43 Vermont
02 Arizona	44 Virginia
03 Arkansas	45 Washington
04 California	46 West Virginia
05 Colorado	47 Wisconsin
06 Connecticut	48 Wyoming
07 Delaware	49 Not Used
08 Florida	50 Alaska
09 Georgia	51 Hawaii
10 Idaho	60 Bahamas
11 Illinois	61 Turks & Caicos Islands
12 Indiana	62 Cuba
13 Iowa	63 Jamaica
14 Kansas	64 Haiti
15 Kentucky	65 Dominican Republic
16 Louisiana	66 Puerto Rico
17 Maine	67 Virgin Islands
18 Maryland	68 Netherlands Antilles,North
19 Massachusetts	69 Antigua, Leeward Islands
20 Michigan	70 Guadeloupe
21 Minnesota	71 Martinique
22 Mississippi	72 Grenada, Windward Islands
23 Missouri	73 Tobago
24 Montana	74 Trinidad
25 Nebraska	75 Netherlands Antilles,South
26 Nevada	76 British Guiana
27 New Hampshire	77 Surinam
28 New Jersey	78 Venezuela
29 New Mexico	79 Colombia
30 New York	80 French Guiana
31 North Carolina	81 British Honduras
32 North Dakota	82 Costa Rica
33 Ohio	83 E1 Salvador
34 Oklahoma	84 Guatemala
35 Oregon	85 Honduras
36 Pennsylvania	86 Nicaragua
37 Rhode Island	87 Panama Canal Zone
38 South Carolina	88 Mexico
39 South Dakota	90 Barbados
40 Tennessee	91 Pacific Islands
41 Texas	96 Canada
42 Utah	

SPECIAL NOTE:

STATE NUMBER	PERIOD OF RECORD
60	1960-1967
61-65 & 68-88	1960-1964 (overall)

TAPE FIELD	TAPE RECORD POSITION	ELEMENT NAME	CODE DEFINITIONS AND REMARKS
002	6-9	Cooperative Network Index	Cooperative Network Index Number assigned by NCDC. Range=0000-9999. 0000 = Divisional Data.
	10-11	Cooperative Network Division Number	Cooperative Network Division Number assigned by NCDC. (Station List). Range of values 01-10, 99 (99=Missing Division Number)-

NOTE: The division number for a station can change through time.

HAWAII (STATE 51)*

ISLAND NAME	DIVISION
Kauai	01
Oahu	02
Molokai	03
Lanai	04
Maui	05
Hawaii	06

*Note: Hawaii (State 51) division numbers were changed during the initial conversion of this file. Divisions within islands no longer exist. Division numbers now represent each island.

PACIFIC (STATE 91)

Division

02 - East of 180th Meridian - Phoenix Islands, Line Islands, and American Samoa
03 - Western Pacific Islands, North of 12N.
04 - Caroline and Marshall Islands

TAPE FIELD	TAPE RECORD POSITION	ELEMENT NAME	CODE DEFINITIONS AND REMARKS
003	12-15	Element-Type	The type of data element stored in this record. Range of values are listed below.

NOTE: Metric units were used by most of the Caribbean countries except for Puerto Rico and the Virgin Islands.

CLDD Monthly cooling degree days - base 65 degrees F. from 1980 onward.

TAPE FIELD	TAPE RECORD POSITION	ELEMENT NAME	CODE DEFINITIONS AND REMARKS	
003			DP01	Number days with > or = 0.1 inches precip. from 1954 onward.
			DP03	Number days with > or = 3.0 millimeters precip. for metric stations only.
			DP05	Number days with > or = 0.5 inches precip. from 1951 onward.
			DPOH	Number days with > or = 0.01 inches precip. available only prior to 1954.
			DP0Q	Number days with > or = 0.25 inches precip. available only prior to 1951.
			DP10	Number days with > or = 1.0 inches precip.
			DP25	Number days with > or = 25.0 millimeters precip. for metric stations only.
			DP50	Number days with > or - 50.0 millimeters precip. (for metric stations only.)
			DPNP	Departure from normal monthly precip.
			DPNT	Departure from normal monthly temp.
			DSNW	Number days with snow depth > or = 1 inch.
			DT00	Number days with minimum temp. < or = 0 degrees F.
			DT15	Number days with minimum temp. < or = 15 degrees C. (For Metric Stations only.)
			DT30	Number days with maximum temp. > or = 30 degrees C. (for Metric Stations only.)
			DT32	Number days with minimum temp. < or = 32 degrees F.

TAPE FIELD	TAPE RECORD POSITION	ELEMENT NAME	CODE DEFINITIONS AND REMARKS
003			DT60 Number days with minimum temp. < or = 59 degrees F. (Puerto Rico, Virgin Islands only.)
			DT70 Number days with maximum temp. > or = 70 degrees F. (Alaska Stations only.)
			DTSO Number days with maximum tempo > or = 90 degrees F.
			DX15 Number days with maximum temp. < or = 15 degrees C. (Metric Stations only.)
			DX32 Number days with maximum temp. < or = 32 degrees F.
			DX60 Number days with maximum temp. < or = 59 degrees F. (Puerto Rico, Virgin Islands only.)
			EMXP Extreme maximum daily precip. in the month. (Contains the day of occurrence in the Day-of-Observation Tape Field 010.)
			EMNT Extreme minimum temp. for the month. (Contains the day of occurrence in the Day-of-Observation Tape Field 010.)
			EMXT Extreme maximum temp. for the month. (Contains the day of occurrence in the Day-of-Observation Tape Field 010.)

TAPE FIELD	TAPE RECORD POSITION	ELEMENT NAME	CODE DEFINITIONS AND REMARKS
003			FRZD Freeze Data

FREEZE DATA TABLE

Freeze data do not contain 12 monthly values. Instead it contains the date of occurrence and the actual temperature observed within 10 specified threshold positions. (See table below.) Tape Field 009 contains the date of occurrence (month/day) and Tape Field 010 contains the actual temperature. One threshold position is represented by Tape fields 009, 010, 011, and 012.

Example: The first threshold position which represents the last occurrence of a temperature < or = 16 Degrees F in the spring might appear as 00207 00016 (Feb. 7th, Temp was 16 DEG. F.) Spring occurrences period is from 1 January thru 30 June and fall occurrences period is from 1 July thru 31 December.

Threshold Position	Meaning (values in degrees F)	
1	Temp < or = 16 DEG	Last occurrence in the Spring
2	Temp 17, 18, 19, or 20 DEG	
3	Temp 21, 22, 23, or 24 DEG	
4	Temp 25, 26, 27, or 28 DEG	
5	Temp 29, 30, 31, or 32 DEG	
6	Temp < or Equal 16 DEG	First occurrence in the Fall
7	Temp 17, 18, 19, or 20 DEG	
8	Temp 21, 22, 23, or 24 DEG	
9	Temp 25, 26, 27, or 28 DEG	
10	Temp 29, 30, 31, or 32 DEG	

For no occurrences TIME-OF-VALUE = 9999
DATA-VALUE = -99999
FLAG-1 = M

HTDD Monthly heating degree days - base 65 degrees F. (From July 1950 onward.)

TAPE FIELD	TAPE RECORD POSITION	ELEMENT NAME	CODE DEFINITIONS AND REMARKS
003			MMNP Monthly mean minimum tempo of evaporation pan water.
			MMNT Monthly mean minimum temp.
			MMXP Monthly mean maximum temp. of evaporation pan water.
			MMXT Monthly mean maximum temp.
			MNTM Monthly mean temp.
			MXSD Maximum snow depth during the month. (Contains the day of occurrence in the Day-of-Observation Tape Field 010.)
			TEVP Total monthly evaporation.
			TPCP Total monthly precip.
			TSNW Total monthly snowfall.
			TWND Total monthly wind movement in miles over evaporation pan.
			ELEMENT CODE TABLE (DIVISIONAL DATA)
			NOTE: Divisional Data records from 1980 onward. Data are part of the SOM file but are maintained on separate digital tapes. Station Index Number will always be '0000' for All Divisional Data.
			DAFT Divisional average total monthly precip. for stations that take both temp. and precip.
			DPNP Departure from normal monthly precip. (thru 1981 only)
			DPNT Departure from normal monthly temp.
			MDRN Number of days in the month with rain. (from 1982 onward.)
			MNTM Monthly Mean temp.
			TPCP Mean monthly precip.
			TSNW Mean monthly snowfall.

TAPE FIELD	TAPE RECORD POSITION	ELEMENT NAME	CODE DEFINITIONS AND REMARKS
003			ELEMENT CODE TABLE (SOIL DATA)

ELEMENT CODE TABLE (SOIL DATA)

Soil records from 1982 forward only. The last 2 digits on soil element names represent codes for soil cover and soil depth. Example: MN11 represents the element name for mean monthly soil temperature of grass cover at 2 inches and/or 5 cm. There is no distinction whether the depth reading is actually read in inches or centimeters.

MNyz Monthly mean minimum soil temp.

HNyz Highest minimum soil temp. for the month.

LNyz Lowest minimum soil temp. for the month.

MOyz Monthly mean soil temp. at observation time.

HOyz Highest soil temp. at observation time.

LOyz Lowest soil temp. at observation time.

MXyz Monthly mean maximum soil temp.

HXyz Highest maximum soil temp. for the month.

LXyz Lowest maximum soil temp. for the month.

CODE (y = Code for soil cover)
(z = Code for soil depth)

Y = 1	Grass
2	Fallow
3	Bare ground
4	Brome grass
5	Sod
6	Straw mulch
7	Grass muck
8	Bare muck
0	Unknown

CODE	Depth (inches)	Depth (cm)
Z=l	2	5
2	4	10
3	8	20
4	20	50
5	40	100
0	Unknown	

TAPE FIELD	TAPE RECORD POSITION	ELEMENT NAME	CODE DEFINITIONS AND REMARKS
004	16-17	Element-Units	The units and decimal position of the data value for this record. Range of values are listed below. C Whole degree Celsius D Whole fahrenheit degree days F Whole degrees fahrenheit HI Hundredths of inches I Whole inches M Whole miles MH Miles per hour MM Millimeters NA No units applicable (non-dimensional) TC Tenths of degrees celsius TF Tenths of degrees fahrenheit TI Tenths of inches TM Tenths of millimeters
005	18-21	Year	This is the year of record. Range of values is 1800-current year processed.
006	22-23	Filler	Filler value is 99.
007	24-27	Filler	Filler value is 9999.
008	28-30	Number reported Values	This denotes the actual number of values Range of values is 1-13. NOTE: A record may contain fewer or more data values than you might expect. A yearly record of monthly values may contain as few as 1 data value or as many as 13. This is primarily due to missing data. If a particular data value was not taken or is unavailable there is no entry for it.
009	31-32	Month	Contains the month of the element value. Range of values 1-13. 13 = Annual value.
010	33-34	Day	Contains the day of the element value, if applicable.

TAPE FIELD	TAPE RECORD POSITION	ELEMENT NAME	CODE DEFINITIONS AND REMARKS
011	35	Sign of Meteor-ological Value	This is the "SIGN" of the meteorological data value (Tape Field 012.) This field contains either a blank or a minus sign (never a plus sign.)
012	36-40	Data-Value	Actual data value including leading sign portion. The SIGN portion of the field 011 contains either a blank or a minus sign (never a plus sign). This field is a five digit integer. Units and decimal position are indicated in the ELEMENT-UNITS field described in Field 004.

TAPE FIELD	TAPE RECORD POSITION	ELEMENT NAME	CODE DEFINITIONS AND REMARKS
013	41	FIAG1	The Data Measurement FIAG.

FIAG-1 TABLE (MEASUREMENT FLAG)

A Accumulated Amount. This value is a total that may include data from a previous month or months (TPCP).

B Adjusted Total. Monthly value totals based on proportional available data across the entire month. (CLDD, HTDD, TEVP, TWND)

E An estimated monthly or annual total.

I Monthly means or totals based on incomplete time series. 1 to 9 days are missing. (DSNW, MMNT, MMXP, MMXT, MNTM, TCPC, TSNW)

M For variable length records 'M' is used only to indicate Non-occurrence of a specified threshold in the (FRZD) freeze data element. For fixed length records 'M' stands for any data element missing.

S Precipitation for the amount is continuing to be accumulated. Total will be included in a subsequent value. (TPCP)

Example: Days 1-20 had 1.35 inches of precip, then a period of accumulation began. The element TPCP would then be 00135S and the total accumulated amount value appears in a subsequent monthly value.

If TPCP = '99999' there was no precip measured during the month. FLAG 1 is set to 'S'and the total accumulated amount appears in a subsequent monthly value.

T Trace of precipitation, snowfall, or snowdepth. The precipitation data value will - '00000'. (EMXP, MXSD, TPCP, TSNW)

\+ The phenomena in question occurred on several days. The date in the Day of Observation - Tape Field 010 is the last day of occurrence.

(blank) When data value = '99999' it means no report.

TAPE FIELD	TAPE RECORD POSITION	ELEMENT NAME	CODE DEFINITIONS AND REMARKS
014	42	FLAG2	The Data Quality FLAG. FLAG2 is only used if FLAG-1 contains 'T'.

FLAG-2 TABLE

A Accumulated amount.
E Estimated value.
+ Value occurred on more than 1 day - last date of occurrence is used.

Sample (Digital Dump of Variable Length Record)

NOTE: Λ = Blank Space

```
(column             1         2         3         4         5         6
scale)     123456789012345678901234567890123456789012345678901234567890

(data)     0058MLY17001102EMNTΛF19819999990020118Λ00012ΛΛ0318Λ00005ΛΛ
```

DUMP POSITION	RECORD POSITION	CONTENTS	MEANING	
1-4		0058	Record control word used by the operating system. (Contains the total number of characters in the record - not available to user programs)	
5-7	1-3	MLY	RECORD-TYPE.	
8-15	4-11	17001102	STATION-ID for state 17, station 0011, Division 02.	
16-19	12-15	EMNT	ELEMENT-TYPE.	
20-21	16-17	ΛF	ELEMENT-UNITS.	
22-25	18-21	1981	YEAR.	
26-27	22-23	99	NOT USED.	
28-31	24-27	9999	NOT USED.	
32-34	28-30	002	NUM-VALUES: Two data entries follow.	
35-38	31-34	0118	TIME-OF-VALUE (Month 01, Day 18)	FIRST DATA ENTRY
39	35	(BLANK)	SIGN OF METEOROLOGICAL VALUE	FIRST DATA ENTRY
40-44	36-40	00012	DATA-VALUE	FIRST DATA ENTRY
45	41	(BLANK)	FLAG-1	FIRST DATA ENTRY
46	42	(BLANK)	FLAG-2	FIRST DATA ENTRY
47-50	43-46	0318	TIME-OF-VALUE (Month 03, Day 18)	SECOND DATA ENTRY
51	47	(BLANK)	SIGN OF METEOROLOGICAL VALUE	SECOND DATA ENTRY
52-56	48-52	00005	DATA-VALUE	SECOND DATA ENTRY
57	53	(BLANK)	FLAG-1	SECOND DATA ENTRY
58	54	(BLANK)	FLAG-2	SECOND DATA ENTRY

(In this case, values for months 2 and 4 thru 12 are missing.)