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PRECIPITATION AUGMENTATION FOR CROPS EXPERIMENT (PACE) - Pre-Experiment Studies

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APPENDIX A

CHAPTER 1. CLIMATOLOGICAL, METEOROLOGICAL, AGRICULTURAL, SOCIAL, AND LEGAL FACTORS AFFECTING PRECIPITATION MODIFICATION IN THE MIDWEST

by

Stanley A. Changnon, Jr.

Introduction

A rational approach to the design and conduct of weather modification experiments involves consideration of a host of factors that affect and can limit the conditions under which modification can and should be conducted. Hence, the design of PACE has considered and will continue to consider the integration of such limiting factors derived from past data and results. It is recognized that there are several factors affecting desired increases in precipitation and particularly those relating to the potential benefits in a given area.

Research using crop and water resource models (Changnon and Huff, 1979) has clearly shown that the major beneficiary of a capability to increase rainfall in the Midwest would be cash grain agriculture. To a lesser extent, water supplies, largely for municipal and industrial users, would be benefited.

Research has conclusively shown that midwestern corn and soybean yields are quite dependent upon July and August rainfall. Figure 1 shows this relationship for corn yields and rainfall from the 45 crop districts in the 5-state midwestern Corn Belt, as based on values from 1931-1975. One sees that when July rain was below normal, corn yields in 60% of all districts were more than 10% below normal, and only 5% of the district occurrences (with a below normal July rain) had yields more than 10% above normal. Prior research has shown that to be most beneficial, rain changes are needed in July and August

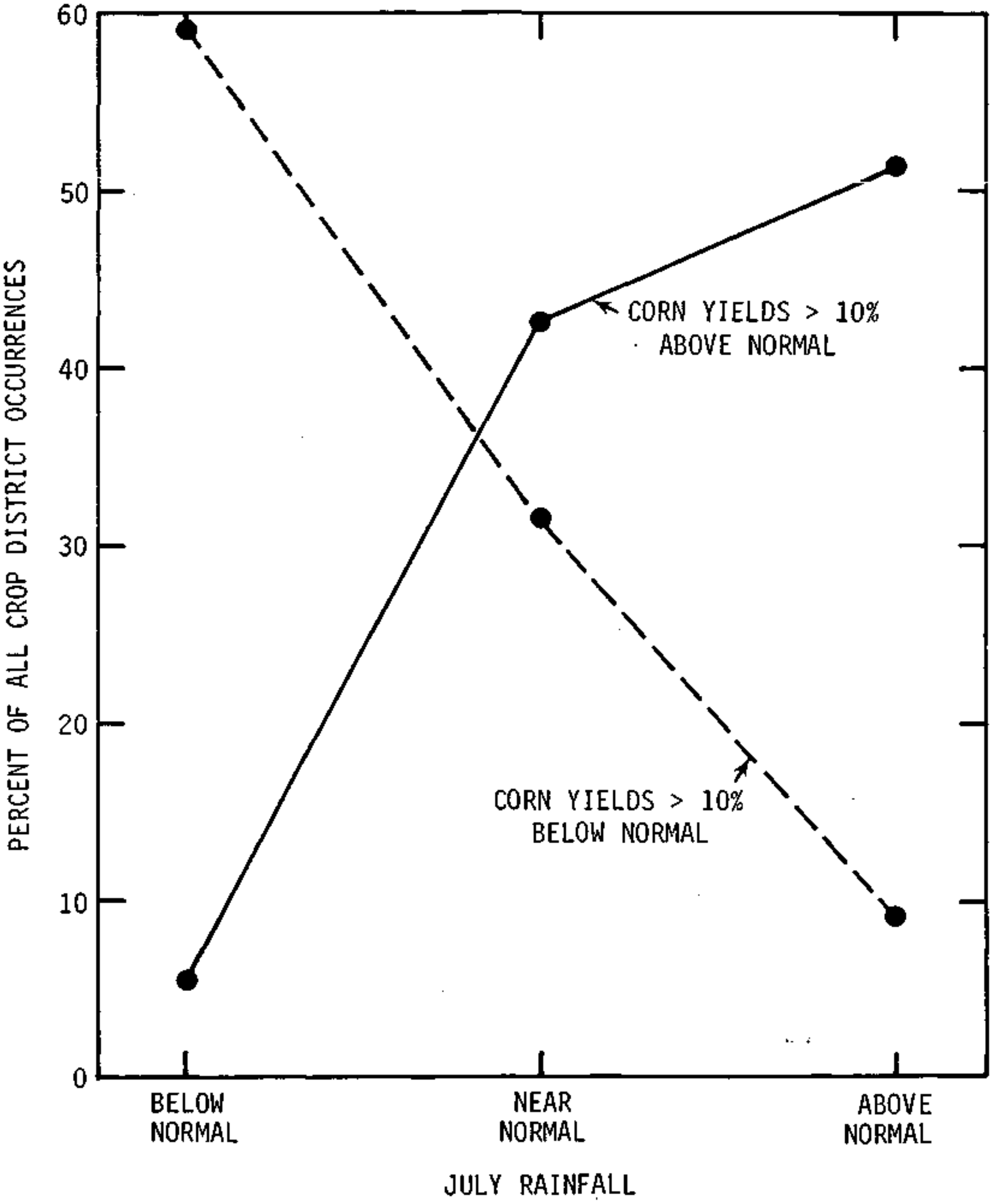

Figure 1. Frequency of midwestern crop districts (45) with major corn yield deviations as associated with different ranges of July rainfall, 1931-1975

and that agriculture is the main beneficiary of added rainfall. These facts become constraints: agriculture is the prime user, and to serve midwestern agriculture, the rain change is needed in July and August.

It must also be established, as a part of this assessment of constraints whether additional July-August rainfall in the Midwest, set within the realm of reasonable potential increases, could lead to marked benefits for the Midwest, the nation, and the world. Hence, the first section of text addresses the value of agriculture to the nation and then addresses the value of altered summer precipitation in the Midwest. Irrigation, as an alternative to rainfall modification, is also considered.

The final major section of this text relates to an attempt to dimensionalize and integrate the limitations of known climatological, meteorological, agricultural, social and legal factors on rainfall modification in the Midwest. Important factors include the types of rain increases that have been shown by 1) planned weather modification experiments with summer rainfall elsewhere, and 2) the inadvertent changes of summer precipitation by major cities. These give guidance as to the "degree" of precipitation enhancement that could be achieved in the Midwest.

Prior research relating to relationships between rainfall and crop yields indicate the magnitude of changes in daily rainfall needed to be "detectable" in yields. This sets a lower bound for considering useful increases in rainfall in cases of light rain. For example, a 25% increase in a July rain of 0.04 inch is an insignificant amount for aiding corn or soybean yields.

Furthermore, the advent of severe storms indicates periods of precipitation production in which modification would be unwise, from social and legal standpoints, as well as physical reasons. Illinois law forbids weather modification during such conditions and public controversy often grows from attempts to increase rain in severe storm situations. Heavy rains also cause erosion and added rain is undesirable in such situations. Thus, there is an upper bound on the daily rainfalls to be increased, as well as a lower bound.

Another constraint on agriculturally useful rainfall relates to that amount that actually enters the root zone for use by the crop. A large percent of heavy rainfall is lost to surface runoff and to evaporation. Integration of these factors bounds the issue and leads to a realistic assessment of the conditions that must be addressed in considering the potential for planned modification of summer rainfall to benefit midwestern agriculture. The question is, "How feasible is it with the known constraints and what needs to be considered in future, meteorological, societal, and agricultural research because of these constraints?"

The National and International Ramifications of Agricultural Production

The importance of food to the nation and the world, as reflected in the Midwest, needs to be considered. A recent National Academy of Sciences report (1977) reveals that fluctuations in weather and climate cause the greatest variations found in food production. World food reserves are insufficient to compensate for harvest losses due to serious fluctuations that could occur in a single bad year. The report notes, "efforts to alleviate problems arising from droughts, unseasonably high or low temperature, and severe storms are crucial." This nearness to the margin was reflected in the 1973-1974 food crises when the total grain stocks evaluated were only 10% of the total world consumption. There are major debates on how to address world food problems and whether agricultural production can keep up (Crosson and Frederick, 1978).

Some have claimed that the 1973-74 food problems were due to short-run factors, especially adverse weather. Others claimed that the food problems were symptomatic of our inability to increase production to keep pace with ever growing demands.

Table 1. Average Annual Rates of Change in U.S. Crop Yields.

	1950-60	1961-70	1971-76
Corn	+ 4.4%	+ 3.6%	+ 0.3%
Soybeans	+1.4%	+1.2%	- 0.1%
Wheat	+ 3.9%	+ 2.7%	- 1.4%

In the early 70's, crop yields in the United States did not increase, in contrast to the prior decades. Table 1 reveals the changes of crop yields in the United States. The annual change in corn yields during the 70's was nearly zero (+0.3%) and represented a marked reduction over the increases during the two prior decades. This decrease in the 70's is explained as a result of 1) expansion of farming into marginal lands, 2) poorer weather in the 70's and 3) no new agricultural technologies (Crosson and Frederick, 1978). Change, both to increase yields and to bring new lands into production, is considered the key to a successful increase in production. Here, planned weather modification to increase precipitation and ameliorate severe storms appears to be a potentially useful technology. Furthermore, added water is now becoming recognized as the only way to secure major new increases in yields and agricultural production. A key to agriculturally useful weather modification would be its effectiveness under dry periods (Nielson, 1978). The National Academy of Sciences, in considering climate and food issues, made a major recommendation for greater research in the utility of weather modification (NAS, 1977).

As the National Weather Modification Advisory Board (1978) commented, "In a world moving ever nearer to the margins in water, food, and energy needs, such gains (5 to 10% increases in grain crop yields from more rain) would prove very valuable to the Nation and the World. The potential benefits — are sufficient to justify the R and D spending we believe will be necessary."

Value of Midwestern Agriculture

The importance of agriculture in various parts of the United States can be evaluated in a variety of ways. Some of these include 1) the acreage in crops,' 2) amount and types of crops, 3) the monetary value of the crops, 4) food value of the crops, 5) total production, 6) average yields, and 7) the value of exported crops. Proper assessment of the agriculture in any state or region depends on the evaluation of several values. Thus, various expressions of agricultural worth have been used to weigh agriculture in the Midwest against elsewhere in the nation.

The leading U.S. crops, based on their 1974 values, in order were 1) corn ($14.4 billion), 2) soybeans ($8.1 billion), 3) wheat ($7.3 billion), and 4) hay ($5.8 billion). Table 2 reveals where the three leading U.S. crops are grown by analyzing total production. The importance of the Midwest is clear. Between 60 and 69% of the nation's two major crops are produced in the corn belt.

Another regional expression of agricultural values is the total monetary value of crops (Table 2). Here, the Midwest ranks first again. The nation's leading states in order are 1) California, 2) Illinois, 3) Iowa, 4) Texas, 5) Minnesota, 6) Nebraska, 7) Indiana, 8) Kansas, 9) Ohio, and 10) North Dakota. Thus, five (underlined) of the top ten states are in the Midwest.

Table 2. Various Regional Comparisons of Agriculture in the U.S.

1974 Production of the three Major U.S. Crops

Production expressed as a percent of national total

	Midwest(1)	**Great Plains**(2)	**Southeast**(3)	**All Other**
Corn	69	15	8	8
Soybeans	60	6	16	18
Wheat	18	59	1	22

Midwest = Illinois, Indiana, Iowa, Ohio, Michigan, Minnesota, Missouri, and Wisconsin.

(2) Great Plains = Montana, North Dakota, South Dakota, Colorado, Nebraska, Kansas, Oklahoma and Texas.

Southeast = Florida, Virginia, N. Carolina, S. Carolina, Georgia, Alabama, Mississippi, and Louisiana.

Total Value of Crops, 1975

Midwest	$20.1 billion
Great Plains	$13.1 billion
West Coast (includes California, Oregon, and Washington)	$ 7.4 billion
Southeast	$ 6.8 billion

Average Crop Value, Dollars per Acre, 1975

West Coast	$532
Southeast	$262
Midwest	$173
Great Plains	$109

Value of U.S. Crop Exports in 1975

	Billion of Dollars
Wheat	$5.0
Corn	$4.1
Soybeans	$3.6
Other grains	$1.9
Cotton	$1.0
Rye	$1.0
Tobacco	$0.9
Fruits	$0.6
Vegetables	$0.5

Another regional expression of agricultural values in their monetary value per acre (Table 2). This shows the highest values in the west coast and southeast, largely due to the high value speciality crops grown in two states, California and Florida. In the list of the nation's 100 leading counties (based on the value of crops sold), California leads with 26 counties, followed by Illinois with 12, and Florida with 8 counties. However, such values must also be viewed according to their relative food value.

In 1974, Illinois ranked first (16.8%) in nation's production of soybeans with 207.5 million bushels. Illinois ranked second (17%) in the nation's corn production (831 million bushels), and 12th (3%) in wheat (54 million bushels). Total farm income (1974) was $5 billion with 33% from corn and 29% soybeans (Hayes, 1977). Illinois ranks 18th nationally in beef cows, with Iowa third and Missouri first.

The sustenance of human life depends on the agricultural production of a few crops, the most important of which are wheat, rice, corn, soybeans, millet and grain sorghums (NAS, 1975). The primary source of calories and 75% of the protein consumed by man consists of the cereal grains (wheat, corn, and rice) and a few legumes (like soybeans). High value specialty crops (fruits, tobacco, and vegetables) are not essential to man's survival. The U.S. average of daily calories consumed per person derived from cereals is 744 calories as compared to 101 from fruits and 73 from vegetables (Willett, 1976). Furthermore, 598 calories per day (per person) came from meat, much of which is fattened on cereal crops. Clearly, the midwestern grain and legume crops are critical to sustaining the basic nourishment for U.S. citizens.

The importance of agriculture in any U.S. region can also be assessed by the value of the exports. The U.S. is the world's leading exporter of food stuffs. The leading exported crops are shown in the lower part of Table 2.

Most (> 80%) of the soybeans and corn exported from the U.S. is produced in the midwestern corn belt. Illinois alone produced 18% of all the crops exported from the U.S. and leads the nation. World demands for soybeans are increasing rapidly, and the $3.6 billion exported in 1975 (Table 2) surpassed the U.S. export sales of jet aircraft and computers.

In summary, the Midwest, often called the Corn Belt, produces between 60 to 70% of the nation's two leading crops, corn and soybeans. The Midwest is the leading food producing region of the United States. As a region, it ranks first nationally in:

1) total monetary value of its crops,
2) production of corn and soybeans (nation's leading crops),
3) production of foods essential to human and animal diets, and
4) monetary value of the food it exports.

An important perspective relevant to a new agricultural technology like weather modification is that a small percentage increase in a large number (say midwestern crop production or value), produces a large volume increase.

Irrigation and Weather Modification Issues

The recent expansion of irrigation into the Midwest reflects a recognition, on the part of farmers and the agricultural economy, that yield increases brought about by added water are economically feasible. The economic and environmental aspects of irrigation and of weather modification must be put into a comparable context. One of these relates to the production costs of midwestern crops. Table 3 presents the average crop costs in 1978 in the Corn Belt. One notes that total costs per acre of corn (based on 120 bushels per acre yield) is $266.00. This breaks down to a cost of $2.22 per bushel, as compared to an October 1978 price of $2.40. The slight $0.18 difference reveals the narrowness of the economic margin in corn.

Table 3. 1978 Crop Costs in Corn Belt.

	Corn (rotated, 120 bu/acre)	Soybeans (40 bu/acre)
Variable costs (seed, fertilizers, etc.)	$110	$ 70
Other costs (land, labor, interest)	$156	$145
Total cost per acre	$266	$215
Cost per bushel	$ 2.22	$ 5.38
October 1978 price	$ 2.40	$ 6.50
Difference	+ $ 0.18	+ $ 1.12

One notes that with a soybean yield of 40 bu/acre and a price of $6.50 per bushel, a sizable profit ($1.12) was made with soybeans in 1978. These corn and soybean differences reflect the sensitivity of farm profit both to price and to production (higher yield) levels.

The need to increase yields through the major remaining option, added water, is reflected in irrigation statistics for Illinois, considered a humid climate state with generally adequate rain in most years. The number of irrigated acres in Illinois during recent years was:

1966 = 28,000 acres
1972 = 50,000 acres
1977 = 100,000 acres
1978 = 115,000 acres

The 1978 acreage is small, equal to 180 square miles, or only 1% of the arable land of the state, but what is important is the rapid recent growth in the face of high costs. Although irrigation use began in Illinois for specialty crops (fruits, flowers, and vegetables), 70% of irrigated acreage is now for corn and soybeans. The cost is high. Some 65% of the irrigation systems in Illinois are the center pivot type which in 1979 cost $65,000 installed. These typically handle irrigation of 1/4 of a square mile (160 acres).

Table 4 presents irrigation operational costs based on a recent analysis done at Purdue University. This is based on two different types of irrigation systems and reveals the sizable operational costs for either system, above $100 a year per acre. Their break-even analysis for different prices of corn are also shown in Table 4, showing the additional corn production that must be developed to meet annual costs, ranging from 40 added bushels per acre at $3.00 per bushel, up to 59 more bushels to meet a $2.00 per bushel price. The portion of the costs related to the energy to deliver water are also shown in Table 4. The irrigation operational costs shown in Table 4 are sizable in relation to the existing total cost per acre for farming shown in Table 3., Irrigation operational costs represent about a 40% increase in annual costs for corn acreage, going from $266 per acre up to $379 (traveling gun) per acre or to $384 per acre if center pivots were used.

Planned rainfall modification, if it works, has decided cost advantages over irrigation. Rainfall modification, done at the,state-of-the-science level of operation in Illinois in 1979, would cost approximately $0.50 per planted acre. This is less than 0.5% of the irrigated acreage costs (Table 4), and suggests a considerable economic advantage of rainfall modification over irrigation. However, weather modification is not a certain technology by any means. Moreover, even if potential increases of 10 to 30% of rainfall could be achieved during all rains in July and August, the increases still would not satisfy, in certain very dry years, the needs for water that irrigation could provide. However, irrigation has other limitations in addition to its high costs. As yet, the best available estimates reveal that only 25% of Illinois agricultural lands could be irrigated, based on slopes, soil types, and available water supplies. This is not surprising since only 14% of the world's farmland is currently irrigated. The southern half of Illinois has higher average summer temperatures and shallower soils (less moisture holding capacity) than found in northern Illinois (which has the potential groundwater needed for irrigation). Hence, southern Illinois frequently needs more water in July and August and yet does not have the groundwater sources needed (> 500 gpm), except in the alluvial areas in its major river valleys.

Hence, irrigation, at best, is not the technology of widespread utility that weather modification could be in the Midwest.

Table 4. Irrigation Costs.

	Center pivot	Traveling gun
Annual Costs (fixed and variable)[1] per acre	$118.45	$112.90
Per acre yield increase needed to break even, when		
Corn = $2/bu	59 bu/acre	56 bu/acre
Corn = $2.5/bu	47	45
Corn = $3/bu	40	38

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[1] Water costs related to pumpage and other delivery costs. 1 inch of water over 80 acres costs $72 in electrical energy to pump.

The point of this discussion has been to provide certain qualitative and quantitative issues relating to major alternatives for providing additional water for crop production in the Midwest. Clearly, more definitive study needs to be performed on both alternatives. The spatial limitations of irrigation and its high costs suggest there would be utility for a rain enhancement technology, particularly in the southern half of Illinois.

Integration of Various Constraining Factors

The above assessments of agriculture and the importance (and sources) of added water have shown the importance of midwestern agriculture, the potential value of added water to increase and stabilize agricultural production, and the potential merits of rain enhancement, in contrast to irrigation, as a means to obtain additional water. Let us now consider in greater detail some of the known limitations relating to obtaining agricultural benefits from added rain.

Agricultural Issues. It should be noted that most of what is known about added benefits in the Midwest has been determined using crop-weather models (Changnon and Huff, 1979). Although moderately sophisticated, these models produce generalized estimates of relations between rainfall, temperature and crop yields over large areas. Hence, they ignore many technological and physiological interactions which, if known, would more specifically address desirable or undesirable rain changes. Figure 2 illustrates the difference in approaches to define impacts. Agricultural scientists interested in PACE wish to pursue the hydrologic modeling approach which has sub-elements dealing with those areas affected by summer rain changes. Inasmuch as this in-depth research is not yet accomplished, effects of rain changes on agriculture must be based on results generated in crop-weather models.

Earlier research relating corn and soybean yields to weather variables was able to show that increases, even sizable ones of up to 100%, in the daily

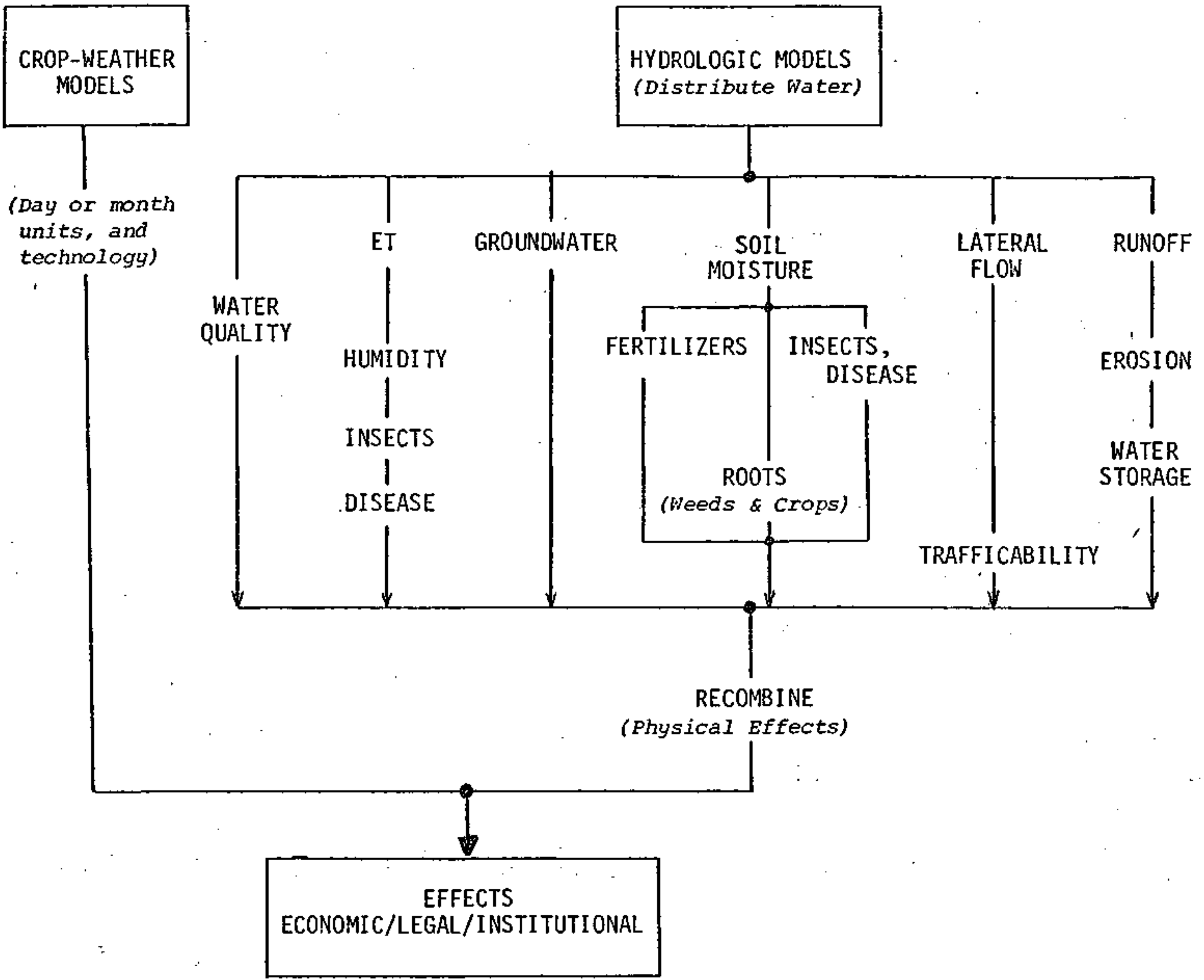

Figure 2. Two approaches to investigate agricultural impacts of changed rainfall.

rain events of ≤ 0.1 inch were of little consequence to yields. (Swanson, *et al*., 1972). An area of 500 square miles in Illinois typically has 10 days during July and August with amounts between 0.01 and 0.1 inch (Table 5), and the median rainfall of these days is 0.04 inch (per day). A 50% increase in 0.4 inch of rainfall (10 days x 0.04), an unlikely capability, would produce only an additional 0.2 inch in July-August, an amount that does not produce any measurable increases in yield (Changnon and Neill, 1968). This is not unexpected when one appreciates that a sizable fraction of all summer rainfall is lost to runoff and evaporation.

Studies of rainfall have also shown that when daily amounts exceed about 1 inch, at least two undesirable aspects occur. First, in general, most such rain falls at high rates in less than 3 hours (Changnon, 1964) and most of the rain in excess of 1 inch is lost to evaporation and runoff and does not reach the root zone. Second, the highest short-duration rainfall intensities are typically associated with these rains (Huff, 1967), producing much of the soil erosion experienced in the row crops. Hence, increases in naturally occurring rains in excess of 1.0 inch per day are agriculturally undesirable.

In fact, above average rainfall at any time during the midwestern growing season has advantages and disadvantages. A qualitative analysis of the effects of above average rainfall appears in Figure 3. Agricultural practices are helped and production increased in the area of the graph above 0, and things hurt (by above average rain) appear below the 0 line. Examination shows that at any given time, benefits and disbenefits occur with added rain. We know from crop-weather models and from irrigation that more water in July and August help corn and soybean yields, but the disbenefits shown at that time (soil erosion, foliar diseases, rootworm, aphids, etc.) call for

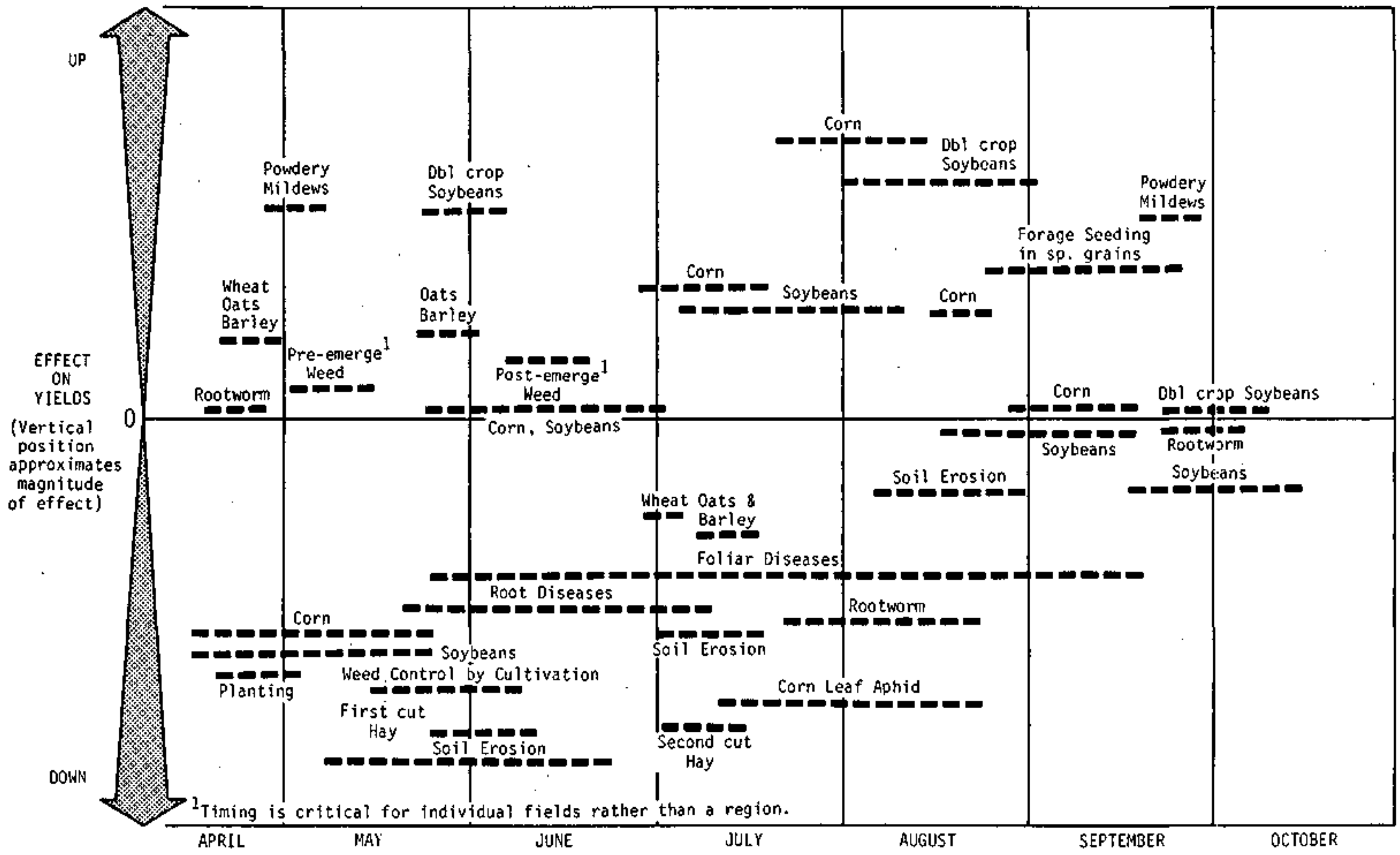

Figure 3. Effect of above average rainfall during various parts of growing season in midwest on agriculture production and practices

consideration in "tuning" rain changes. As noted earlier, the effects of rains above 1 inch are so disbeneficial to suggest their exclusion from modification.

Climatological and Meteorological Issues. Operations of dense raingage networks in central and southern Illinois have provided 10 years of data on the rain climatology of two areas of about 500 square miles (Changnon, 1964; Changnon and Huff, 1980). These median daily rain values in different classes have been combined with average daily frequencies in Table 5 showing how the July-August total of 7.90 inches is derived.

Also shown on Table 5 are the area average "severe storm" occurrences, as defined by actual area instances of severe weather: the frequency of NWS weather warning areas and/or having very tall (> 50,000 ft) storms. The Illinois Weather Modification Act exludes weather modification activities on rain events (days) when 1) severe weather warnings are issued, and/or 2) radar echo tops exceed 50,000 feet. These rules have been promulgated for two reasons. Attempted weather modification in various other regions of the U.S. at times when very severe weather occurred has been a source of occasional public controversy and lawsuits. Secondly, our lack of knowledge of the effect of attempted rain modification on such severe storm systems suggests extreme scientific caution. The results from the METROMEX study of inadvertent modification revealed an area increase in summer rainfall of 10 to 30%, but it was produced largely by rain periods producing area means of 0.25 inch or more, and with 40% increases in thunderstorms (and more lightning damages), 80% increases in hail events, and 100% increases in damaging surface winds (Changnon *et al*., 1977). All these results point to the undesirability of attempting to increase rainfall at times when nature is already capable of severe weather events and heavy rainfall production.

As shown in Table 5, the two heaviest rain days (> 1 inch, a 1.1-inch median) are both in the severe storm categories with fewer numbers in the lighter rain classes. This further supports the rationale for excluding conditions capable of 1 inch or more rain from experimentation in PACE. The average of 7 days represents 24% of the area rain days. Also calculated was the average amount of rain in the area produced on days with the limiting severe conditions. The total is 3.51 inches (Table 5) which is 44% of the July-August total.

Weather Modification Potential. Another limiting factor to be considered is the potential for rainfall enhancement. Models with reasonable potential increases were needed to incorporate in the assessment of limitations of rain enhancement. We excluded any potential to make rain on non-rain days, believing only that rain could be enhanced when it was already naturally occurring in a region.

In general, the more optimistic supporters of summer convective rain enhancement talk of seasonal average increases of between 15 and 25% above surrounding values. Very little research in the Midwest has been done. The only true modification experiment, Project Whitetop done in 1960-1964, concluded its seeding produced 1) an overall decrease in rain of around 20%, but 2) an increase in rain on days with moderate sized echoes (tops > 20,000 and < 40,000 feet).

The extensive studies of inadvertent rain modification due to St. Louis reveals that the rainfall has increased up to 30% in the summer, but this occurred with the heavier rain days, typically those producing ≥ 0.25 inch over the area. These events typically represented 30% of the total July-August rain days (Changnon et al., 1977). Experimental results from the Dakotas indicate summer rainfall increases of 10 to 20%, at least under certain weather conditions.

These types of results have been incorporated in five "potential" rainfall change models, as shown in Table 6. These include a capability for an average increase of 10% in the rainfall in all conditions. A greater capability to increase rainfall of 20% in all conditions but limited to exclude the heavy rains of > 1 inch (to miss the agriculturally and socially undesirable events) is labeled as the "20% bounded model." A third model was also based on a 20% increase capability, but it is "limited" to exclude days when severe storms occurred. The fourth and fifth models shown were based on the METROMEX findings and related to a potential to achieve a 30% increase but only on days when the area mean rainfall ≥ 0.25 inch. One of these 30% models was limited to exclude the severe storm days.

These percentages were applied to the appropriate totals (Table 5) for the rain day classes and amounts adjusted for the various bounds of light rains, heavy rains, and severe storm occurrences.

Table 5. Daily Rainfall Values for July-August in 500 Square Mile Areas in Illinois.

Daily Rain Values in July-August(1)			Average Daily Severe Storm Occurrences(2)			
Daily amount inches	Average number of days of rain	Average total rain, in.	Number of days	Percent of total days	Total rain, inches	Daily rain amount without severe weather
0.04	10	0.04	2	20	0.08	0.32
0.18	10	1.80	1	10	0.18	1.62
0.35	4	1.40	1	25	0.35	1.05
0.70	3	2.10	1	33	0.70	1.40
1.10	2	2.20	2	100	2.20	0
Totals	29	7.90	7	24	3.51	4.39

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(1) **Amount based on median value of area rain day categories: 0.01 to 0.1 inch class = 0.04; 0.11 to 0.25 = 0.18; 0.26 to 0.5 = 0.35; 0.51 to 1.0 = 0.7; and > 1.0 = 1.1.**

(2) Defined as being in severe storm watch area or with echo tops > 50,000 ft high.

The values resulting appear under the models in Table 6. Several interesting facts emerge. The 30% increase capability (under only heavier rain situations) produces an added value of 1.71 inches, which is 22% (not 30%) of the July-August total. However, when severe storm limits are added, the total decreases to 0.74 inch (9% of the total). The various limitations of agriculture, plus those societal and environmental concerns, also markedly reduce the percentage increases for the 10% and 20% models. Comparison of the two 20% models in Table 6 shows that the limited model in which modification does not occur in the light rains or in severe storm events, does not lose much, 10% vs. 13% with respect to the upper bounded 20% model.

Table 6. Examples of Area Rain Increases for Potential Rain Changes Models.

Total rain, in.	30%(1) Model	30% Model(2) Limited	20% Model(3) Limited	20% Model(4) Bounded	10% Model(5)
0.40	0	0	0.00	0.08	0.04
1.80	0	0	0.32	0.36	0.18
1.40	0.42	0.32	0.21	0.28	0.14
2.10	0.63	0.42	0.28	0.42	0.21
2.20	0.66	0	0	0	0
Total	1.71	0.74	0.81	1.14	0.57
Percent of July-August total	22%	9%	10%	13%	7%

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1) Capability to obtain 30% increases in conditions when area mean ≥ 0.25 inch.

2) Capability to obtain 30% increases in conditions when area mean > 0.25 inch but not when severe storm conditions existed.

3) Capability to obtain 20% increases in all conditions except when severe storms occurred or in light rain.

4) Capability to obtain 20% increases in all cases ≤ 1.0 inch.

5) Capability to obtain 10% increases in all conditions; except ≥ 1.0 inch.

A further potential restriction related to existing weather modification techniques is an inability to seed clouds effectively at night. Airborne cloud seeding typically requires visual identification of cloud updraft areas of growing cloud turrets, both either very difficult or impossible at night. If nocturnal operations are not possible then further reductions in potentially modifiable rainfall values occur. In central Illinois, 46 percent of the summer rain occurs between 2000 and 0600 CST, and in southern Illinois 34% is nocturnal (Changnon and Huff, 1980). A "working estimate" of the resulting reduction is 40%. Hence, the "obtainable" increases shown for the five models in Table 6 should be reduced 40%. The likely 20% model capability, approximately limited by all factors and further reduced by nocturnal limits, would lead to a rainfall increase of only 0.49 inch, or 6% of the July-August total.

<u>Integration and Physical Processes</u>. An important finding reflected in the results of Table 6, is that reasonable constraints as to when weather modification would be effective and should be attempted make a fairly sizable reduction in the seasonal percentage of achievable rain increases. Thus, when one talks of <u>average</u> rainfall increases for July and August of 10 to 30% one has to realize that the net added rainfall achieved, due to various limitations of a meteorological, agricultural, and legal nature will be lower than the capability.

Crop yield increases, percentagewise, will be even less than the rain increase. That is, an increase in July rain of 20% will not produce a 20% increase in yields. Let us examine Figure 4 and look at the routes that "more rain" takes. The stipled arrows show that some goes to more surface runoff, some to added evaporation, some to soil moisture (to the root zone) and some to shallow groundwater. Hence, only 65% of all summer rainfall reaches the root zone (Jones, 1966).

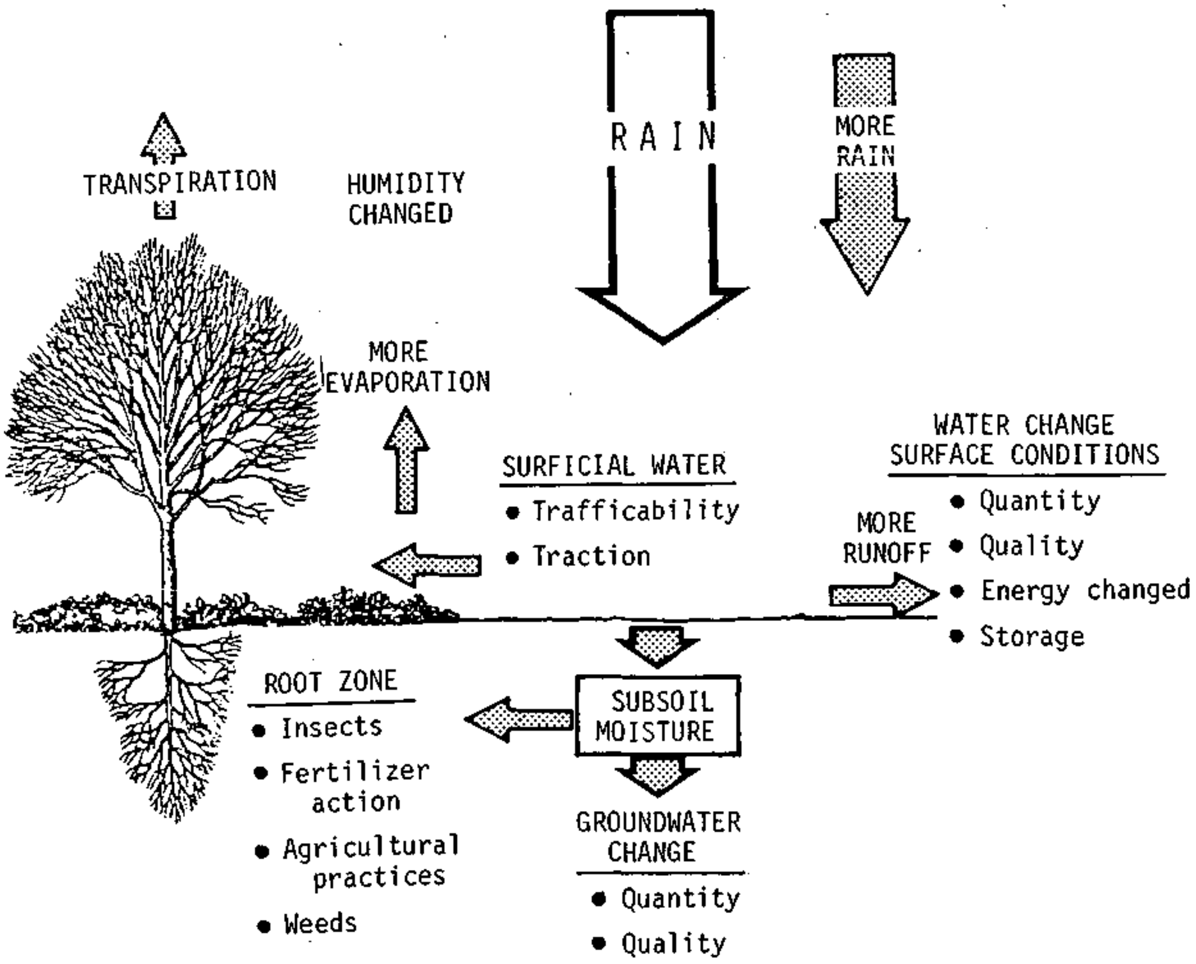

Figure 4. The pathways and impacts of added moisture derived from increased summer rainfall

These various effects, or limitations, affecting rain changes dramatically decrease the amount of yield increase achieved from a rain increase. At St. Louis, the area of inadvertent, urban-induced summer rain increases averaged 20% over a 2-county area, and this resulted in only a 4 to 8% increase in corn yields, depending on the dryness of the season (Changnon et al., 1977). Other research also suggests that the percentage yield increase will be about 25% of the rain increases (Huff and Changnon, 1972).

If we start with a 20% rain increase capability, which is reasonably limited as shown in Table 6, the net rain increase is 10%. The yield increase with a 10% rain increase is, in turn, only 2.5%. If the 10% were further reduced to 6% by an inability to work at night, the yield increase would be only 1.5%.

Conclusions

The above analysis treats a series of limitations that affect the utility of rainfall modification. We started by showing that available evidence indicates that more water in summer months would be of great benefit to agriculture in the Midwest, the nation's most important agricultural area. Rainfall enhancement, although unproven in the Midwest, has some apparent economic advantages over irrigation.

With these givens, a series of limitations as to when rain increases could and should be applied to natural rain conditions were presented. Seasonal limits (July-August) apply to crop benefits from added rain, leaving only 29 rain days to be modified, on the average. Agricultural factors further call for elimination of increases in rains of < 0.1 inch (inconsequential benefits) and those > 1.0 inch (too damaging). This reduces the candidate days to 17. Legal and social factors lead to elimination of increases on severe weather event days further decreasing the candidate days to 14. These 14 days on the average, produce 4.1 inches of rain. Timing of these days can also be important. For example, if several of these 14 occur in late August, their value to corn yields would be less than if they occurred (and were modified) in late July.

These relatively few days, 14, with area mean rains in the 0.11 to 1.00 inch range (and without severe storms) are a severe basic limitation.

They must be forecastable, from a sampling standpoint. Experimentation cannot fail to miss them.

Their scarcity also affects the PACE statistical design and experimental approach. Randomization at 50/50 level means only 7 days would be seeded per year, on the average. If cloud studies of these 14 rain classes of days further eliminates some due to a lack of suitable clouds, the sample size will become even smaller.

From a practical standpoint, and if we believe the 4.1-inch estimate is a working upper limit for useful modification, then the rain increase level to be sought must be high. For example, the 20% increase capability actually adjusts to 10%, and the expected yield increase is 1/4 of that, only 2.5%. If nocturnal cloud seeding cannot be achieved, the expected yield increase would be only 1.5%. This is sufficiently small to suggest that rain modification at that level may be economically questionable. With a 120 bu/acre average area yield, a 20% rain change, with all limitations, would be a 1.5 bu/acre increase representing about a $3 to $4 income increase at an acre cost of $1. This compares favorably with results from earlier studies which showed that a seeding model with an average seasonal rain increase of 25% would produce added incomes (per acre) of $1 to $2 in northern Illinois, and from $3 to $6 in southern Illinois (Swanson <u>et al</u>., 1972). However, these analyses do not account for the R and D costs to reach these capabilities, nor a series of other social and institutional costs related to a new technology. Further, the 14 seedable days in this analysis will likely be an overestimate, in that some seedable rain days will occur in late August, beyond their maximum effect on corn yields.

These results collectively seem to call for attempting to develop a capability to increase rainfall by much more than 20%. They also call for developing a capability to modify rain at night.

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CHAPTER 2. ECHO SYSTEMS: INITIAL ANALYSIS OF ECHO LINES

by

Greg Dzurisin and Arthur Jameson

Introduction

The role of radar in PACE investigations is two-fold. The first is to provide descriptions of the structure of summertime precipitating echo-systems which not only make it easier to interprete events unfolding on the radar screen during operations, but also provide a matrix for the comparison of a particular measurement with past findings. The second role is to provide information related to the precipitation formation processes throughout an entire storm volume. The present study deals with the first of these roles.

Radar data collected in Illinois by two different radars (HOT and CHILL) during three summers of operations (1975, 1977, 1979) are being analyzed to develop descriptions of summertime echo system structure. The primary information source for this part of the continuing study is 35 mm scope pictures of contoured reflectivity factor. Although the two radars operate at the same wavelength (10 cm), the beam sizes are different (1 for the CHILL and 1.5 for the HOT radar). In addition, the contour levels of the two radars may differ by as much as 10 dBZ on occasion. However, at the current level of analysis these differences are not expected to compromise the compatability of the two data sets. In order to increase the total sample size, therefore, the results from the two radars have been combined.

Data and Echo System Classifications

The CHILL and HOT radars were operated during June through August at the following locations:

	CHILL	HOT
1975	None	Pere Marquette State Park
1976	None	None
1977	None	Joliet
1978	None	None
1979	Champaign	Joliet (Partial data)

In 1975 the HOT radar was located in Pere Marquette State Park and its 80 nautical mile (nm) coverage included the metropolitan St. Louis area. In 1977 and 1979 the HOT radar coverage extended 120 nm and included the metropolitan Chicago area, Lake Michigan, northern Indiana and southwest Michigan. The radar was located immediately south of Joliet near the Des Plaines River.

In 1979 the CHILL radar was located at Willard Airport about 5 miles south of Champaign. Its coverage was an 80 nm semicircle with its eastern boundary being a north-south line through the airport.

Initially the inspection of the data was confined to a general inspection of echo system morphology at a low elevation angle relatively free of ground returns (usually at an angle of 1 - 2). From this inspection, three general types of echo systems could be defined. A group of 4 or more distinct echoes not falling into a single line was called an area of echoes. To be part of the area the distance between an echo and its nearest neighbor had to be less than the maximum linear dimension across the area. Multiple areas can therefore appear on the scope provided their borders are separated by at least the maximum of the linear dimensions across each of the areas. A group of echoes with a length at least twice its width and extending for at least 20 nm is called a line of echoes. Lines can appear either by themselves, with areas of echoes, or in conjunction with isolated echoes. An isolated echo system is any group of less than four distinct echoes separated from other echo structures. They usually appear as the first evidence of developing organized convection, the product of a decayed echo system, or simply the result of scattered, thermally driven convection. A single 35 mm picture is not adequate to classify an echo system. Rather it is necessary to follow the evolution of each echo system through time. Typically a classification of a particular echo system is founded on at least 4 consecutive samples separated by 15 minutes.

Following the process of defining echo systems, all of the radar data were scanned to define those periods when the different systems were observed. In this data set 254 lines, 119 areas, and 256 isolated echo systems were identified. Analysis was directed toward lines in part because of their high frequency of occurrence during precipitation events, defined here as the time from the first to the last echo development. This definition excludes the decaying stage of an echo system. The tabulation of parameters related to areas and isolated echoes is in progress, but that relating to lines is the most complete. Therefore, only results from the study of lines will be presented.

Several parameters were selected and sampled every 15 minutes throughout the duration of the line. Among those related to the line dimensions were the number of separate echoes (defined at the second contour level of intensity), and the length, width and area of the line. Several parameters were related to the line movement including the direction of motion of both the line and individual echoes, the directional orientation of the line, and the total line movement during its lifetime. Other parameters were sampled relating to echo morphology such as the interval between first detection to maximum intensity, total duration of the line and its association with isolated, area or separate echo lines, and whether it was transformed into another line, area, or isolated echoes. The data were stratified according to time of day (night: 2000 CDT - 0559 CDT; day: 0600 CDT - 1959 CDT) in an attempt to discern diurnal effects. Although by no means complete, the results from analysis of these parameters could provide direction for further, more detailed investigations.

Results

General Remarks. The occurrence of an isolated line is a relatively infrequent event in Illinois. This study showed that three times out of four the line occurred simultaneously with other echo systems. Half of these other systems were areas of echoes while the remainder was about evenly split between systems of isolated echoes or other lines.

This lack of isolation is not surprising when the origin of lines is investigated. Four times out of five, lines formed from pre-existing echo systems. Over 35% of all the lines appeared to organize out of an area of echoes while 20% developed as an organization of apparently isolated systems. The mechanism leading to this organization is as yet unknown. Future studies relating to these measurements to synoptic conditions may provide some insight into this phenomenon.

During the late stage of the duration of a line, rather than simply disappearing, four times out of five lines changed into other echo systems, perhaps reflecting the disappearance of the organizational forcing. Over 40% of all lines which lost their organization became areas of echoes while about 20% became isolated echo systems. These processes of formation and disintegration suggest that many lines may be formed by transient organizational forces acting on pre-existing regions of convection.

Characteristics of Lines. The distribution of the line orientation showed (Figure 1) that over 60% were aligned between NEE-SSW to ENE-WSW. The dominant (44%) direction of motion was toward the SE (Figure 2) while

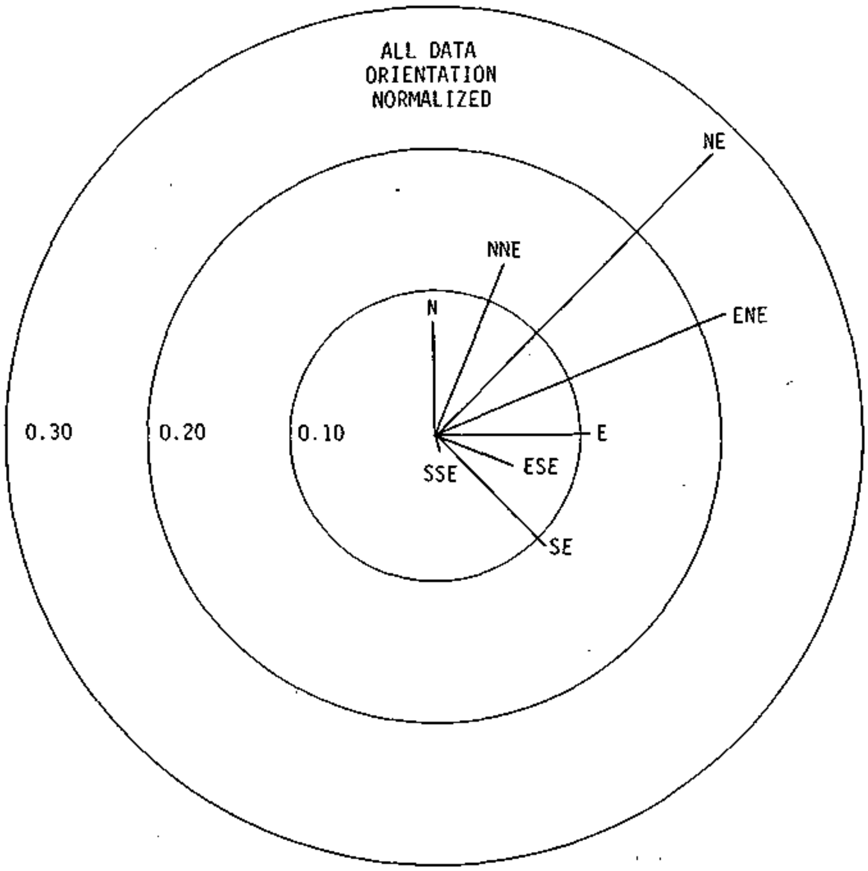

Figure 1. Normalized frequency distribution of line orientation (8 directions).

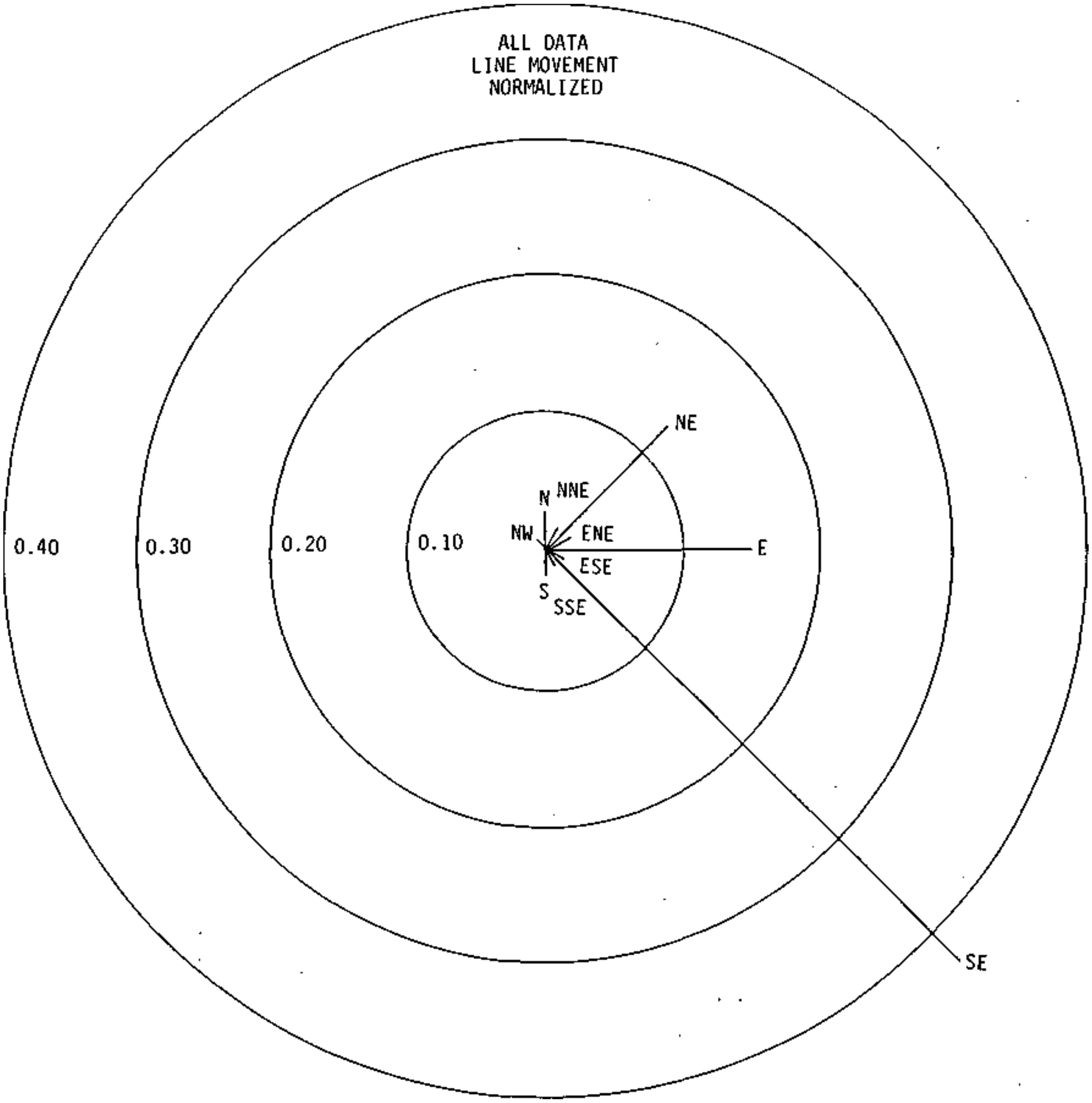

Figure 2. Normalized frequency distribution of line movement (toward - 16 directions).

individual echoes predominantely moved toward the NE (Figure 3) suggesting that with respect to the movement of the line, echoes formed at the leading edge of the line, traversed the line and decayed at the rear of the line. This point is still under investigation, however, since the speed of individual echoes is yet to be tabulated. It is interesting to note also that 25% of the time, the lines were stationary whereas this was true for only 1% of the individual echoes.

The average duration of a line was found to be about 60 minutes although the standard deviation was 47 minutes Figure 4a. Almost 20% of the lines lasted for more than 2 hours while about 60% persisted for 60 minutes or less. These results are based on those cases when the radar observed the line from its formative to its decaying stage. It would be interesting to investigate the possible relationship between synoptic conditions and line longevity.

On the average, the first occurrence of the maximum reflectivity contour level appeared about 16 minutes after formation although there was a great deal of variation with 65% of the maxima first occurring 30 minutes or more after line formation. Interestingly, although the distribution and average value of the maximum contour levels were almost identical for day and night storms, 80% of the first occurrence of maximum intensities were observed within 30 minutes during the night, but only 50% appeared by 30. minutes during the day. Whether this is a statistically meaningful difference is not certain since the daytime sample size was more than twice that of the night echoes. However, the reality of this difference is perhaps enhanced by the fact that the average duration and frequency distributions of daytime and nighttime lines are essentially identical implying that sampling errors may not necessarily be the origin of this observed difference. If real, the result is

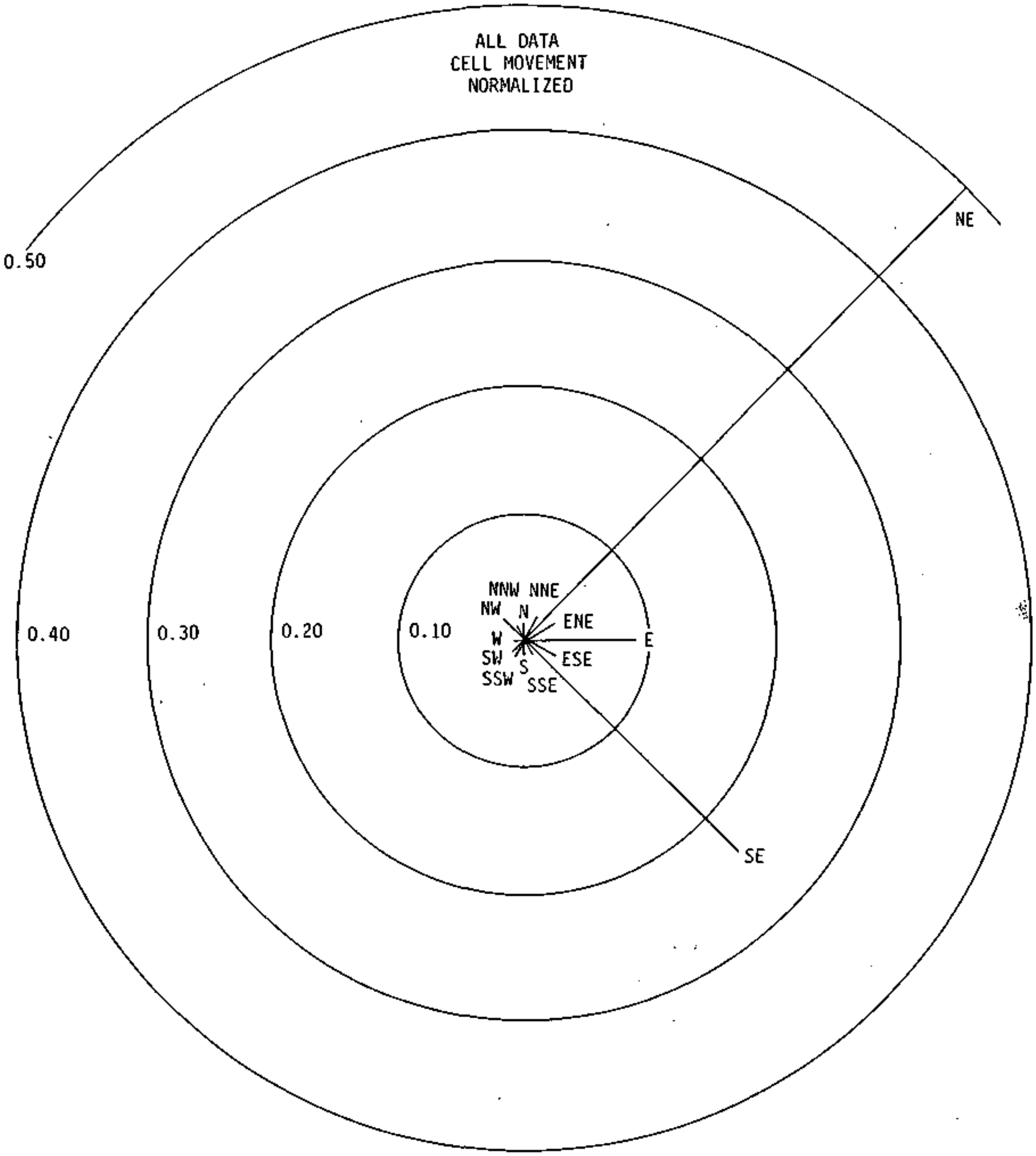

Figure 3. Normalized frequency distribution of cell movement in lines (toward - 16 directions).

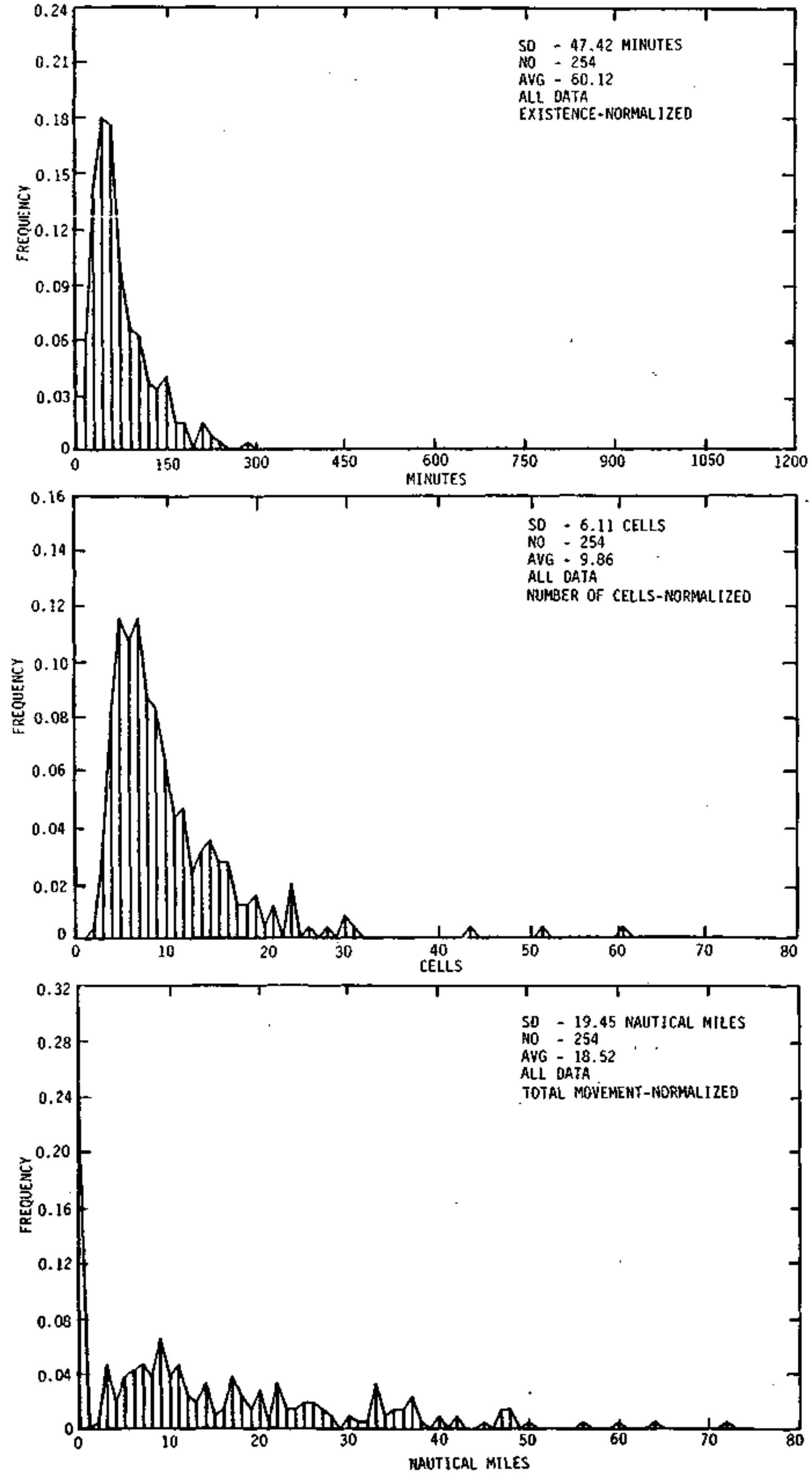

Figure 4. Normalized frequency distribution of: a) the existence time of a line, b) the number of cells in a line, and c) the total movement of a line.

somewhat puzzling since the characteristic time scale of convection during the warmer half of a day might be expected to be shorter than during the cooler night half. Factors other than heat-driven convective strength such as those related to microphysical processes and synoptic scale influences could, however, be more influential in determining the onset of maximum reflectivity factors.

The frequency distribution of the number of distinct echoes is shown in Figure 4b. On the average a line consisted of 9-10 distinct echoes. This did change with time, however, averaging between 10-11 during the first occurrence of the maximum contour level, but peaking on the average between 13-14 at the time of the greatest number of distinct echoes. The peak in the number of echoes occurred on the average about ten minutes after the first observation of the maximum contour level. There were no significant day-night differences.

The distribution of the total line movement (Figure 4c) shows no particular preferred value with the exception of stationary lines. It is possible that such lines are not really dynamically interconnected entities, but may represent a fortuitous alignment of echoes. The average distance covered was about 18-19 nm with almost 90% of the lines moving less than 36 nm. This suggests that squall lines associated with cold fronts which often travel hundreds of miles probably make little contribution to the total number of lines occurring between June and August. The connection between the majority of summertime lines and synoptic scale features, if such a connection exists is through more subtle mechanisms.

The frequency distributions of length, width and area of the lines are presented in Figure 5a, b, c. These values are the averages over the entire duration of the line. Although the average length of the lines was about 82 nm, over 50% averaged less than 44 nm in length. The average line width

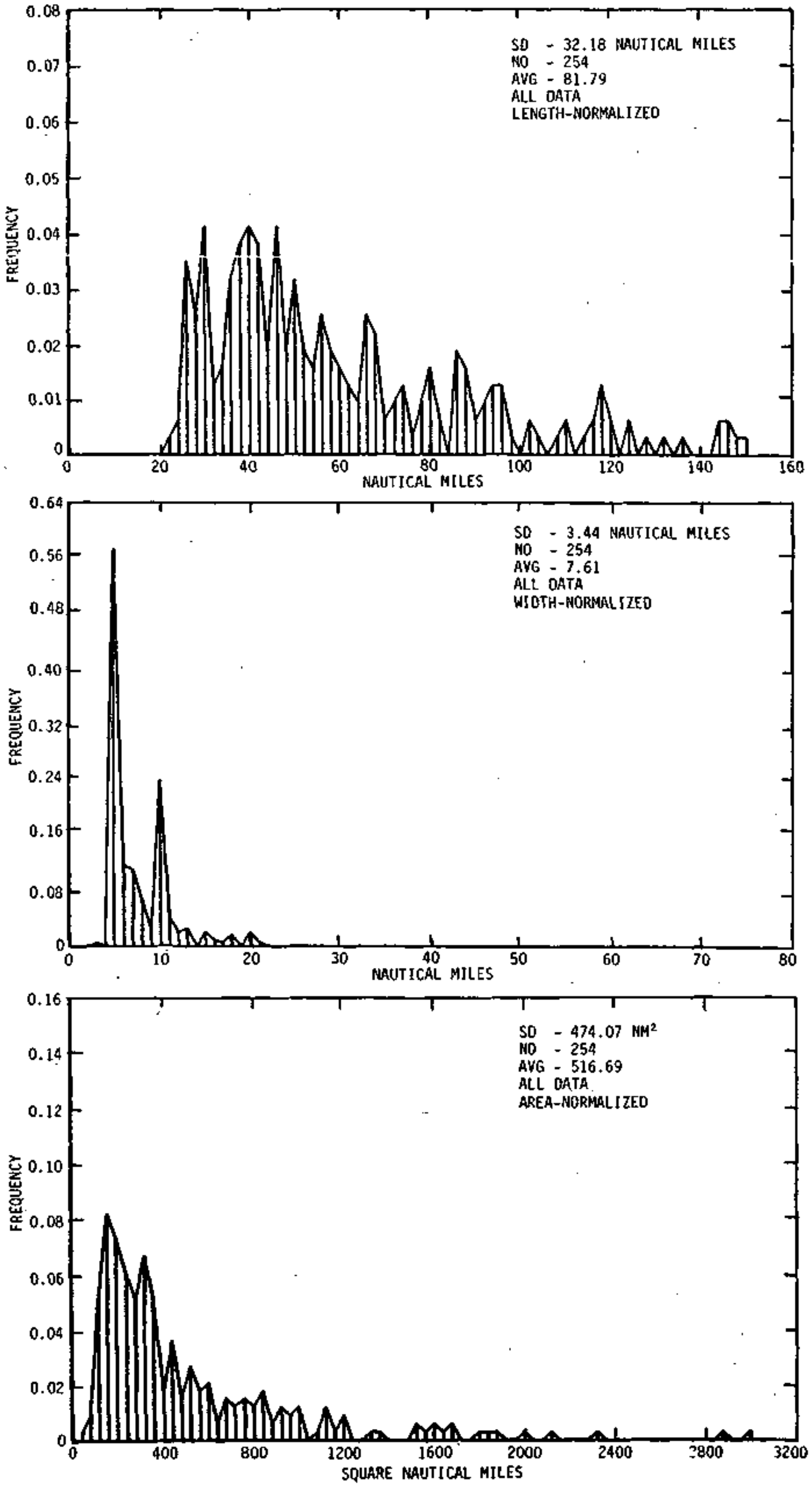

Figure 5. Normalized frequency distribution of: a) the length of lines, b) the width of lines, and c) the area of lines.

was about 7-8 nm with almost two-thirds of the line average widths between 4-10 nm. The average area of the line was 517 nm^2, but almost 60% were less than or equal to 400 nm^2.

Summary

Data presented here are only a portion of that produced in this investigation of lines. Obviously it is desirable to continue to expand the data base not only to provide better estimates of the average properties, but also to allow further stratification. Additional parameters can also be measured. Even at this level of analysis, however, there are observations suggesting a direction for future investigations.

The lack of day-night differences in conjunction with other observations previously mentioned strongly suggest that many of the properties of lines are not controlled only by heating. In fact, the surprising result that 80% of the nocturnal lines reached the maximum intensity level within 30 minutes as opposed to 50% for daytime lines warrants further study and explanation. There may be a link between the occurrence of lines (and their properties) and larger scale (perhaps synoptic) events. Investigations directed toward understanding this connection may permit the prediction of the occurrence and some general characteristics of lines based upon synoptic conditions and atmospheric soundings. In any event, the present study has provided basic information on the size and some properties of a frequently occurring rain-producing summertime phenomenon in Illinois.

CHAPTER 3. PACE MICROPHYSICAL STUDIES

by

David B. Johnson

Key Background Studies

Detailed studies of the meso and microscale properties of convective clouds in the U. S. Midwest started with the Thunderstorm Project. A. landmark in observational meteorology, this project obtained the first detailed picture of the multicellular nature of most Midwest storms. In the years following the Thunderstorm Project, the University of Chicago Cloud Physics Project continued to make valuable measurements of cloud properties with an instrumented B-17 and ground based radars. One of the major findings of this period was the discovery that "warm" processes not involving the ice phase were responsible for the initial formation of radar observable concentrations of precipitation in summer-time convective clouds. Until this discovery, meteorologists generally thought that these warm processes were only important in the tropics and that all continental precipitation formed through mechanisms involving ice.

In the early 1960's, the Cloud Physics Laboratory at the University of Chicago ran a large scale cloud seeding project in Missouri (Project Whitetop) that included a major effort in documenting the physical properties of seeded and unseeded clouds. During these studies the presence of large liquid drops grown by ice-free processes was confirmed. Once carried into the supercooled regions of the cloud, however, the large drops were found to freeze readily and seemed responsible for unexpectedly large concentrations of ice at temperatures of -10 C or warmer. The number of observed ice particles was so much larger than the measured concentration of ice-forming nuclei that some sort of "multiplication" process seemed to be involved.

During Illinois State Water Survey flights in conjunction with PACE forerunner, Illinois EPA, Ackerman (1974) showed that the large liquid drops often make up a major portion (> 50%) of the total liquid in Midwest convective clouds. Since the standard airborne liquid water measuring device (the Johnson-Williams hot wire instrument) does not adequately measure these large drops, commonly reported liquid water contents may be seriously underestimated.

The probable origin of these large liquid drops was explained by Johnson (1978) in his study of giant and ultragiant aerosol particles. The unexpectedly high concentrations of these particles found in rural areas in Illinois and Missouri suggested that they might be the growth centers from which the large drops form. Subsequent calculations have generally confirmed this explanation, and it now appears that natural concentrations of these particles are adequate to explain the rapid formation of large liquid drops wherever the cloud base temperature is high enough to assure adequate supplies of condensed water and sufficient cloud depth before encountering competing "cold" processes.

Recent laboratory studies by Hallett and Mossop (1974) have confirmed the reality of the type of ice multiplication mechanism hypothesized during Whitetop. The Hallett-Mossop multiplication process seems to explain many aspects of cloud particle evolution in Midwest clouds, and elsewhere, and when coupled with prior theoretical and observational studies provides a firm foundation for interpreting observational studies such as the 1978 PACE aircraft measurements.

1978 Aircraft Data

In a two week period in 1978, an instrumented NOAA P-3 aircraft collected data on the microphysical and dynamical characteristics of midwestern clouds at about the $-10^{\circ}C$ region, the most likely seeding level for any future seeding experiment. Data acquisition concentrated on the evolution of ice, water and updraft structure with flights designed to produce a mix of case histories in which clouds were repeatedly penetrated and ensemble sampling which addressed population characteristics.

During the 1978 field season we made over 280 cloud penetrations through almost 100 different clouds on seven major flights (see Table 1). In the analysis, second-by-second data for each pass were used to obtain the properties of each individual updraft or downdraft unit. On June 17 a number of lower level penetrations at the melting level were performed in addition to the standard passes at the -10 C level. On June 22 the speed and mobility of the P-3 was used to investigate two separate types of clouds in two different areas.

Table 2 shows the distribution of the number of passes made through each cloud. For example, on June 18 a total of 15 different clouds were sampled. Of these 15 clouds, 3 were penetrated once, 6 were penetrated twice, etc., etc. All in all, about one-third of the clouds investigated received a single penetration. Another third were penetrated twice, and the remaining clouds were penetrated three or more times.

Tables 3 and 4 show the distribution of maximum updraft velocities and maximum liquid water contents which went into the average values shown in Table 1. About 84% of the clouds penetrated had updrafts greater than 5 m/sec on at least one pass and over 50% of the clouds had updrafts exceeding 10 m/sec. Virtually all active cells contained significant quantities of liquid

Table 1. Summary of 1978 PACE Aircraft Data.

Date (June 1978)	Brief Description	No. of Clouds Sampled	Total No. of Penetrations	Total No. of Updraft and Downdraft Units	Average Maximum Updraft (m/sec)	Average Maximum Liquid Water Content (g/m^3)
17	Cold front & pre-frontal lines	15	52	226	16.2	1.6
17(B)	Low level penetrations @ 0°C isotherm	8	12	48	7.3	1.8
18	Thunderstorm line along a cold front	15	41	164	14.7	2.4
22(A)	Warm front thunderstorm line	8	25	107	6.7	1.3
22(B)	Cold front thunderstorm line	7	21	99	9.0	2.4
24	Feeder cells to an isolated hail storm	15	41	231	15.9	2.1
26	Showers in thick altocumulus	7	18	99	8.6	1.0
29	Warm sector thunderstorms	8	30	121	11.7	2.1
30	Frontal thunderstorms	16	41	317	10.7	NA
	Totals	99	281	1412		

Table 2. Number of Clouds Studied and the Number of Cloud Penetrations.

Date (June 1978)	Total No. of Clouds Penetrated	No. of Penetrations per Cloud							
		1	2	3	4	5	6	7	8
17	15	6	4	3	1	0	0	1	0
17(B)	8	4	4	0	0	0	0	0	0
18	15	3	6	1	4	1	0	0	0
22(A)	8	1	4	1	2	0	0	0	0
22(B)	7	2	3	0	0	0	2	0	0
24	15	4	5	4	0	1	1	0	0
26	7	2	2	1	1	1	0	0	0
29	8	2	2	1	2	0	0	0	1
30	16	6	2	4	2	1	1	0	0
Totals	99	30	32	15	12	4	4	1	1

Table 3. Maximum Updraft Velocity (V_m)*.

Date (June 1978)	$V_m \le 5$	$5 < V_m \le 10$	$10 < V_m \le 15$	$15 < V_m \le 20$	$V_m > 20$
17	1	0	6	3	5
17(B)	0	7	1	0	0
18	0	6	0	5	4
22(A)	3	3	2	0	0
22(B)	2	2	1	2	0
24	3	1	3	1	7
26	1	4	2	0	0
29	3	2	0	1	2
30	3	5	4	4	0
Totals	16	30	19	16	18

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* V_m specified in m/sec

Table 4. Maximum Liquid Water Content (L_m)*.

Date (June 1978)	$L_m \leq 0.5$	$0.5 < L_m \leq 1.0$	$1.0 < L_m \leq 1.5$	$1.5 < L_m \leq 2.0$	$L_m > 2.0$
17	1	4	2	3	5
17(B)	0	1	2	3	2
18	1	0	0	3	11
22(A)	0	3	4	0	1
22(B)	0	0	1	0	6
24	0	4	0	2	9
26	2	2	1	2	0
29	0	0	0	4	4
Totals	4	14	10	17	38

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*L_m specified in g/m^3

water as measured by the Johnson-Williams instrument. Only 22% of all clouds (25% of all passes) had maximum water contents less than 1 g/m . If a seeding criterion of 1 g/m^3 (as used in FACE) had been used with these Midwest clouds, at least 75% of the clouds penetrated in 1978 would have qualified as candidates for modification.

Table 5 shows the distribution of the cloud dimensions for each cloud penetrated as reflected in the pass length. On June 18, for example, 3 cloud passes were one kilometer in length, or less, while 12 passes were between 1 and 2 km in length. For the total data set, two-thirds of the clouds penetrated exceeded 2 km in length, while more than a quarter of the clouds exceeded 4 km.

The size of the "target" clouds and, in particular, the size of the updraft and downdraft units within the cloud are particularly important. If the entire cloud is to be influenced by a seeding operation, the seedable cells must obviously make up a major portion of the cloud. Furthermore, if the seeding effects are to be monitored by instrumented aircraft or radar, then the seeded volumes must be large enough to be easily found on post-seeding penetrations and large enough to be easily identified by radar. This generally means that the seeded cells should be at least one half kilometer in diameter or larger. Table 6 shows the distribution of sizes of each individual updraft or downdraft unit for each of the seven major flights. The sizes are presented in 2 sec groupings, where a 2 sec pass would correspond to a cell size of 300 m.

Table 7 shows the total number of separate updraft and downdraft units per cloud penetration. For the most part, the smallest features are not particularly important to the overall cloud structure. Stratification 1 duplicates the presentation of numbers of updrafts and downdrafts, but in this

Table 5. Pass Length (km).

Date (June 1978)	1	2	3	4	5	6	7	8	9	10	>10
17	8	18	14	6	3	2		1			
17(B)		4	7	1							
18	3	12	8	7	6	2	2	1			
22(A)	6	6	6	4	1	2					
22(3)	2	5	5	3	3	1	1	1			
24		10	9	6	11	2			1		2
26	1	5	3	4	2	1	2				
29	5	5	8	7	4		1				
30		3	7	10	9	8	1	1	1		1
Totals	25	58	67	48	39	18	7	4	2	0	3

Table 6. Number of Updraft and Downdraft Units with the Indicated Dimensions (sec)*.

Date (June 1978)	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18	19-20	>20
Updrafts											
17	47	23	13	4	3	3	4	3	2	1	
17(3)	9	4	5	2	1						
18	23	14	7	6	4	2	2	5	4	1	3
22(A)	20	16	7	5	3		1	1			
22(B)	18	11	9	3	1	2	3		1		
24	47	14	19	10	5	'6	3	2	1		3
26	17	13	6	2	2		3				2
"29	31	11	4	1	5		1		1	1	
30	76	40	16	9	4	1	2	3			1
Totals	289	146	86	42	28	14	19	14	9	3	8
Downdrafts											
17	67	43	7	4	1				1		
17(B)	13	8	4		1	1					
18	44	24	14	4	5	1	1				
22(A)	27	16	5	2	2	1	1				
22(B)	25	10	5	6	3	1	1				
24	62	25	12	10	4	4	3				
26	28	15	8		1	2					
29	24	15	13	5	4		1	2	1		1
30	71	45	24	10	9	1	2	1	1		1
Totals	360	201	92	41	30	11	9	3	3	0	2

Table 7. Number of Updrafts and Downdrafts per Penetration.

Date (June 1978)	0	1	2	3	4	5	6	7	8	9	≥10
17	0	5	10	9	9	9	0	4	1	2	3
17(B)	0	0	1	3	3	5	0	0	0	0	0
18	0	3	4	10	8	11	1	2	2	0	0
22(A)	0	5	3	4	2	4	1	2	2	1	1
22(B)	0	2	3	3	3	4	2	0	2	0	2
24	0	2	7	5	5	6	2	5	0	5	4
26	0	1	1	5	1	2	2	0	4	1	1
29	0	4	2	6	5	8	2	2	0	1	0
30	0	1	3	2	5	5	5	4	1	3	12
Totals	0	23	34	47	41	54	15	19	12	13	23

Stratification 1: Eliminate all features smaller than 0.5 km

17	7	27	11	4	2	1	0	0	0	0
17(B)	1	3	5	3	0	0	0	0	0	0
18	4	17	10	5	3	2	0	0	0	0
22(A)	5	8	8	3	1	0	0	0	0	0
22(B)	2	7	4	6	1	0	1	0	0	0
24	0	13	16	6	3	1	1	0	0	1
26	1	5	5	3	4	0	0	0	0	0
29	3	10	11	4	2	0	0	0	0	0
30	0	7	10	11	7	4	1	0	1	0
Totals	23	97	80	45	23	8	3	0	1	1

Stratification 2: Eliminate all features smaller than 1.0 km

17	31	18	1	2	0	0	0
17(B)	8	3	1	0	0	0	0
18	13	21	4	3	0	0	0
22(A)	12	10	3	0	0	0	0
22(B)	6	11	3	0	0	0	0
24	11	17	9	2	1	0	1
26	9	9	2	0	0	0	0
29	11	16	2	1	0	0	0
30	7	27	5	1	0	1	0
Totals	107	131	29	11	1	1	1

case only considers features larger than 0.5 km. Stratification 2 repeats this procedure for features larger than 1.0 km. Less than 10% of all cloud penetrations had no features larger than 0.5 km and more than 60% of all cloud penetrations had either updraft or a downdraft larger than one kilometer. Table 8 shows a similar presentation for updrafts alone. In this case more than 70% of the clouds penetrated had updrafts larger than half a kilometer and 43% had one or more updrafts larger than a kilometer.

Tables 9-12 show the distribution of both the mean values and peak values of liquid water content and updraft velocity for each of the more than 1400 separate updraft and downdraft units analyzed in this study. In each case the data are presented in three versions: (1) all updrafts and downdrafts; (2) updrafts or downdrafts larger than half a kilometer; (3) updrafts or downdrafts larger than a kilometer. While close examination of these tables reveals many interesting features, the single most important result may be the confirmation of the common sense that the largest updraft units are the most important ones and are disproportionally represented with the highest liquid water contents and updraft velocities.

While approximately 75% of the clouds sampled had liquid water contents equal to or greater than 1 g/m at some point within the cloud, it is obviously very important to know what fraction of a normal updraft might reasonably be expected to have this high of a water content. This type of information is shown in Table 13. For example, on June 18, 26 updraft units had liquid water contents ≥ 1 g/m^3 over less than 10% of their length, while 21 updrafts exceeded 1 g/m^3 more than 90% of the time. When all flights are considered, 30% of the sampled updrafts had liquid water in excess of 1 g/m over more than half their length. If only updrafts larger than 0.5 km are

Table 8. Number of Updrafts per Penetration.

Date (June 1978)	0	1	2	3	4
Stratification 1: Eliminate all features smaller than O.S km					
17	13	33	5	1	0
17(B)	4	6	2	0	0
18	13	19	8	1	0
22(A)	10	10	4	1	0
22(B)	6	10	3	1	1
24	6	23	8	3	1
26	3	9	5	1	0
29	16	9	5	0	0
30	6	21	10	2	2
Totals	77	140	50	10	4
Stratification 2: Eliminate all features smaller than 1.0 km					
17	32	20	0	0	
17(B)	9	3	0	0	
18	18	19	4	0	
22(A)	16	8	1	0	
22(B)	14	5	1	1	
24	17	19	5	0	
26	10	7	1	0	
29	21	9	0	0	
30	23	16	2	0	
Totals	160	106	14	1	

Table 9. Number of Updraft or Downdraft Units with Peak Velocities (V) in the Indicated Range.

Date (June 1978)	V≤-10	-10<V≤-5	-5<V≤0	0<V≤5	5<V≤10	V>10
17	9	31	83	53	24	26
17(B)	2	9	16	11	9	1
18	5	30	58	34	18	19
22(A)	0	3	51	41	10	2
22(B)	0	18	33	30	9	9
24	14	35	72	61	20	29
26	0	9	45	28	10	7
29	4	24	38	38	9	8
30	7	60	98	110	23	19
Totals	41	219	494	406	132	120
Stratification 1: Eliminate all features less than 0.5 km						
17	4	12	12	7	17	22
17(B)	1	7	4	2	7	1
18	4	19	13	9	10	19
22(A)	0	2	14	13	7	1
22(B)	0	12	8	10	5	9
24	11	22	10	8	16	28
26	0	5	13	7	8	7
29	3	20	10	5	6	8
30	6	38	24	19	16	19
Totals	29	137	108.	80	92	114
Stratification 2: Eliminate all features less than 1.0 km						
17	1	5	0	2	3	15
17(B)	1	0	1	0	3	0
18	2	8	1	2	8	17
22(A)	0	0	6	4	5	1
22(B)	0	9	2	0	3	7
24	6	14	2	3	4	23
26	0	1	2	0	3	6
29	3	8	3	0	2	7
30	4	15	6	2	6	12
Totals	17	60	23	13	37	88

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*V specified in m $\sec^{-1}$

Table 10. Number of Updraft_or Downdraft Units with Mean Velocities (V) in the Indicated Range*.

Date (June 1978)	$\overline{V}\leq 10$	$-10\overline{V}\leq -5$	$-5<\overline{V}\leq 0$	$0<\overline{V}\leq 5$	$5<\overline{V}\leq 10$	$\overline{V}>10$
17	1	22	100	72	24	7
17(B)	0	3	24	20	1	0
18	0	15	78	51	13	7
22(A)	0	0	54	50	3	0
22(B)	0	1	50	39	9	0
24	1	21	99	80	19	11
25	0	2	52	38	7	0
29	1	6	59	44	8	3
30	0	19	146	133	18	1
Totals	3	89	662	527	102	29
Stratification 1: Eliminate all features less than O.S km						
17	0	6	22	24	15	7
17(B)	0	0	12	9	1	0
18	0	9	27	18	13	7
22(A)	0	0	16	20	1	0
22(B)	0	0	20	17	7	0
24	0	12	31	24	18	10
26	0	0	18	16	6	0
29	0	6	27	9	7	3
30	0	11	57	37	16	1
Totals	0	44	230	174	84	28
Stratification 2: Eliminate all features less than 1.0 km						
17	0	1	5	7	8	5
17(B)	0	0	2	3	0	0
18	0	3	8	9	11	7
22(A)	0	0	6	9	1	0
22(B)	0	0	11	5	5	0
24	0	7	15	8	13	9
26	0	0	3	4	5	0
29	0	2	12	2	4	3
30	0	5	20	10	10	0
Totals	0	18	82	57	57	24

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*$\overline{V}$ specified in m sec^{-1}

Table 11. Number of Updraft or Downdraft Units with Peak Liquid Water Contents (L) in the Indicated Range*.

Date (June 1978)	Downdrafts			Updrafts		
	L≤1	1<L≤2	L>2	L≤1	1<L≤2	L>2
17	110	13	0	79	18	6
17(B)	22	5	0	10	9	2
18	59	23	11	27	23	21
22(A)	53	1	0	42	10	1
22(B)	35	8	8	29	5	14
24	94	23	4	62	35	13
26	50	4	0	37	8	0
29	36	26	4	27	22	6
Totals	459	103	27	313	130	63
Stratification 1: Eliminate all features less than 0.5 km						
17	25	3	0	27	13	6
17(B)	9	3	0	2	6	2
18	20	11	5	7	13	18
22(A)	15	1	0	11	9	1
22(B)	12	3	5	13	3	8
24	35	5	3	18	24	10
26	17	1	0	14	8	0
29	13	18	2	2	12	5
Totals	146	45	15	94	88	50
Stratification 2: Eliminate all features less than 1.0 km						
17	5	1	0	6	11	3
17(B)	1	1	0	0	1	2
18	4	4	3	3	9	15
22(A)	6	0	0	4	5	1
22(B)	7	0	4	6	1	3
24	18	3	1	7	15	8
26	3	0	0	4	5	0
29	6	8	0	0	5	4
Totals	50	17	8	30	52	36

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* L specified in g m^{-3}

Table 12. Number of Updraft or Downdraft Units with Mean Liquid Water Contents (L) in the Indicated Range*.

Date (June 1978)	$\bar{L}\le 1$	$1<\bar{L}\le 2$	$\bar{L}>2$	$\bar{L}\le 1$	$1<\bar{L}\le 2$	$\bar{L}>2$
17	117	6	0	87	15	1
17(B)	24	3	0	13	8	0
18	71	17	5	34	29	8
22(A)	54	0	0	49	4	0
22(B)	40	7	4	31	9	8
24	103	17	1	75	29	6
26 »	53	1	0	42	3	0
29	55	9	2	31	23	1
Totals	517	60	12	362	120	24

Stratification 1: Eliminate all features less than 0.5 km

Date (June 1978)	$\bar{L}\le 1$	$1<\bar{L}\le 2$	$\bar{L}>2$	$\bar{L}\le 1$	$1<\bar{L}\le 2$	$\bar{L}>2$
17	27	1	0	33	12	1
17(8)	11	1	0	5	5	0
13	27	9	0	17	4	0
22(A)	16	0	0	17	4	0
22(B)	16	3	1	14	6	4
24	39	4	0	28	21	3
26	18	0	0	19	3	0
29	29	4	0	6	13	0
Totals	183	22	1	.134	85	13

Stratification 2: Eliminate all features less than 1.0 km

Date (June 1978)	$\bar{L}\le 1$	$1<\bar{L}\le 2$	$\bar{L}>2$	$\bar{L}\le 1$	$1<\bar{L}\le 2$	$\bar{L}>2$
17	6	0	0	12	7	1
17(B)	2	0	0	0	3	0
18	8	3	0	5	19	3
22(A)	6	0	0	8	2	0
22(B)	8	0	0	8	2	0
24	22	0	0	15	13	2
26	3	0	0	7	2	0
29	14	0	0	2	7	0
Totals	69	5	1	56	54	8

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*$\bar{L}$ specified in g m^{-3}

Table 13. Number of Updrafts having Liquid Water Contents ≥ 1 g m^{-3} over the Indicated Fraction of the Updraft (F).

Date (June 1978)	F≤0.1	0.1<F≤0.3	0.3<F≤0.5	0.5<F≤0.7	0.7<F≤0.9	F>0.9
17	76	5	5	5	7	5
17(D)	9	1	3	3	1	4
18	26	2	6	3	13	21
22(A)	39	2	6	2	1	3
22(B)	27	1	4	2	1	13
24	60	3	8	8	8	23
26	37	0	2	4	2	0
29	26	0	2	3	4	20
Totals	300	14	36	30	37	89

Stratification 1: Eliminate all features less than 0.5 km

Date (June 1978)	F≤0.1	0.1<F≤0.3	0.3<F≤0.5	0.5<F≤0.7	0.7<F≤0.9	F>0.9
17	25	5	2	5	7	2
17(B)	2	1	2	3	1	1
18	7	2	3	2	13	11
22(A)	10	2	4	2	1	2
22(B)	12	1	1	2	1	7
24	18	3	6	6	8	11
26	14	0	2	4	2	0
29	3	0	1	3	4	8
Totals	91	14	21	27	37	42

Stratification 2: Eliminate all features less than 1.0 km

Date (June 1978)	F≤0.1	0.1<F≤0.3	0.3<F≤0.5	0.5<F≤0.7	0.7<F≤0.9	F>0.9
17	5	4	2	4	3	2
17(B)	0	0	1	1	1	0
18	3	1	1	2	13	7
22(A)	3	2	2	1	1	1
22(B)	6	1	0	0	0	3
24	7	2	3	5	5	8
26	4	0	1	3	1	0
29	0	0	0	2	3	4
Totals	28	10	10	18	27	25

considered, this rises to 45% of the updrafts, and if only updrafts larger than 1.0 km are considered then almost 60% of the updrafts have water contents above 1 g/m over half their length or more.

In addition to data on the sizes and basic properties of the sampled clouds, the 1978 aircraft data included a great quantity of detailed data on the number, size, and type of hydrometeors present. The most important data of this kind was obtained with a pair of Knollenburg 2-D probes which can store 2-dimensional pictures of the cloud and precipitation particles observed in flight. Since this instrument merely records the time dependent shape of the particle shadows it can not distinguish between a supercooled liquid drop or a frozen drop crossing its field of view. In actual operation, however, the presence of large drops of supercooled water can be inferred from the distinctive patterns associated with shedding of the liquid water which builds up on the probe tips (see Fig. 1). These elongated patterns are termed "streamers" and are easily distinguished from frozen graupel or crystalline ice (see Figs. 2 and 3).

In our 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 are only slightly lowered. While this process is presumably going on in all active clouds growing past the -10 C level, we see this pattern most often in the later passes through a cloud as the updraft begins to weaken. On occasion, as the updraft dies we see a shower of millimeter sized ice pellets in concentrations of over 1000 per cubic meter with little or no evidence of supercooled liquid water present.

On days when the entire sky fills with stratiform layers with embedded convective elements we see an additional form of ice evolution. In the layers between active cells ice crystals grow by diffusion producing large numbers of

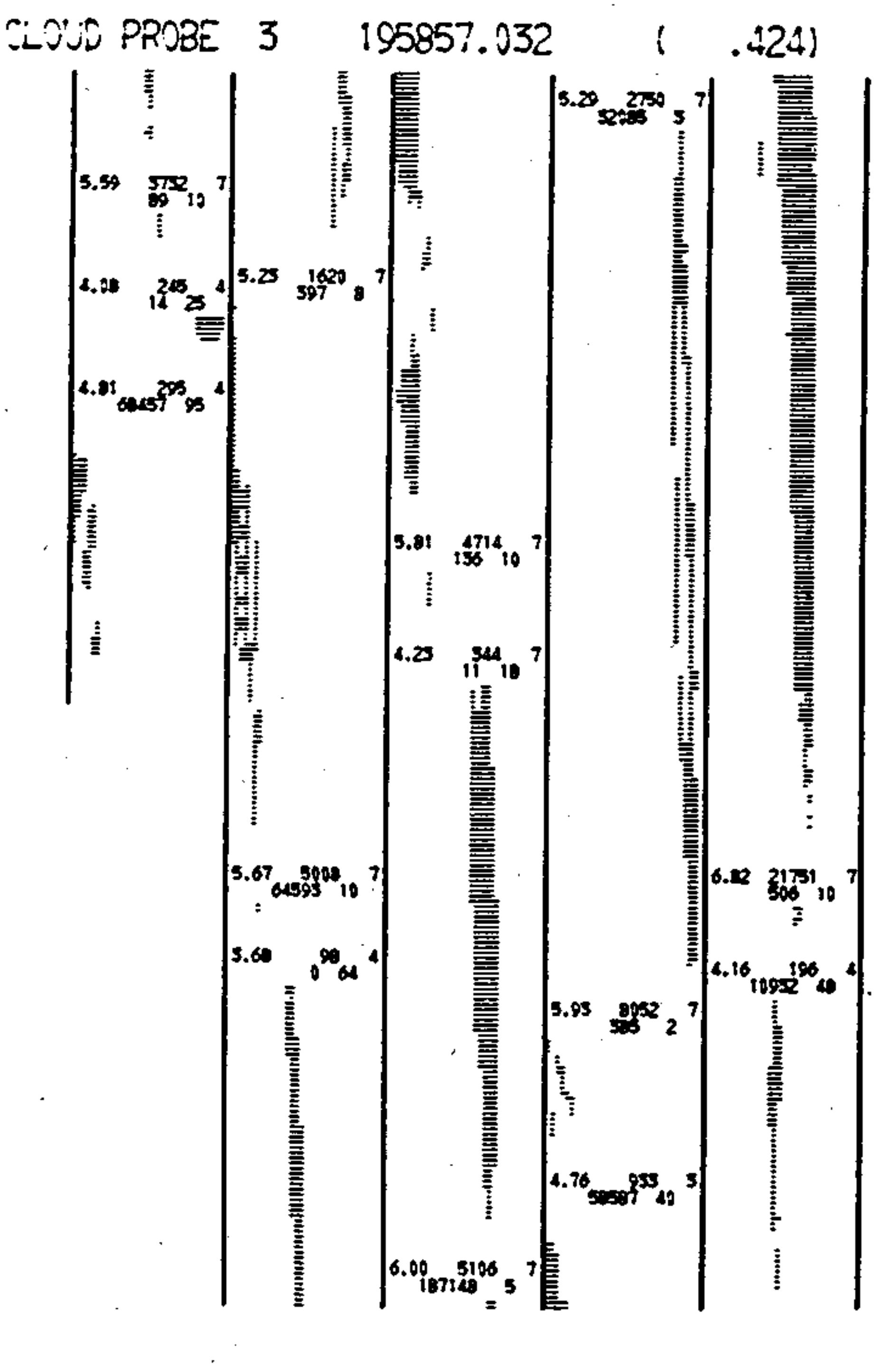

Figure 1. Example of "streamers," large water drops blowing off probe tips and moving slowly through sampling area. The shaded area in each column shows the particle moving through the 1.6 mm wide array of photodiodes. Particles moving slower than the free airstream will be elongated in the direction of their motion. Streamers are an indirect indicator of the presence of large supercooled water drops.

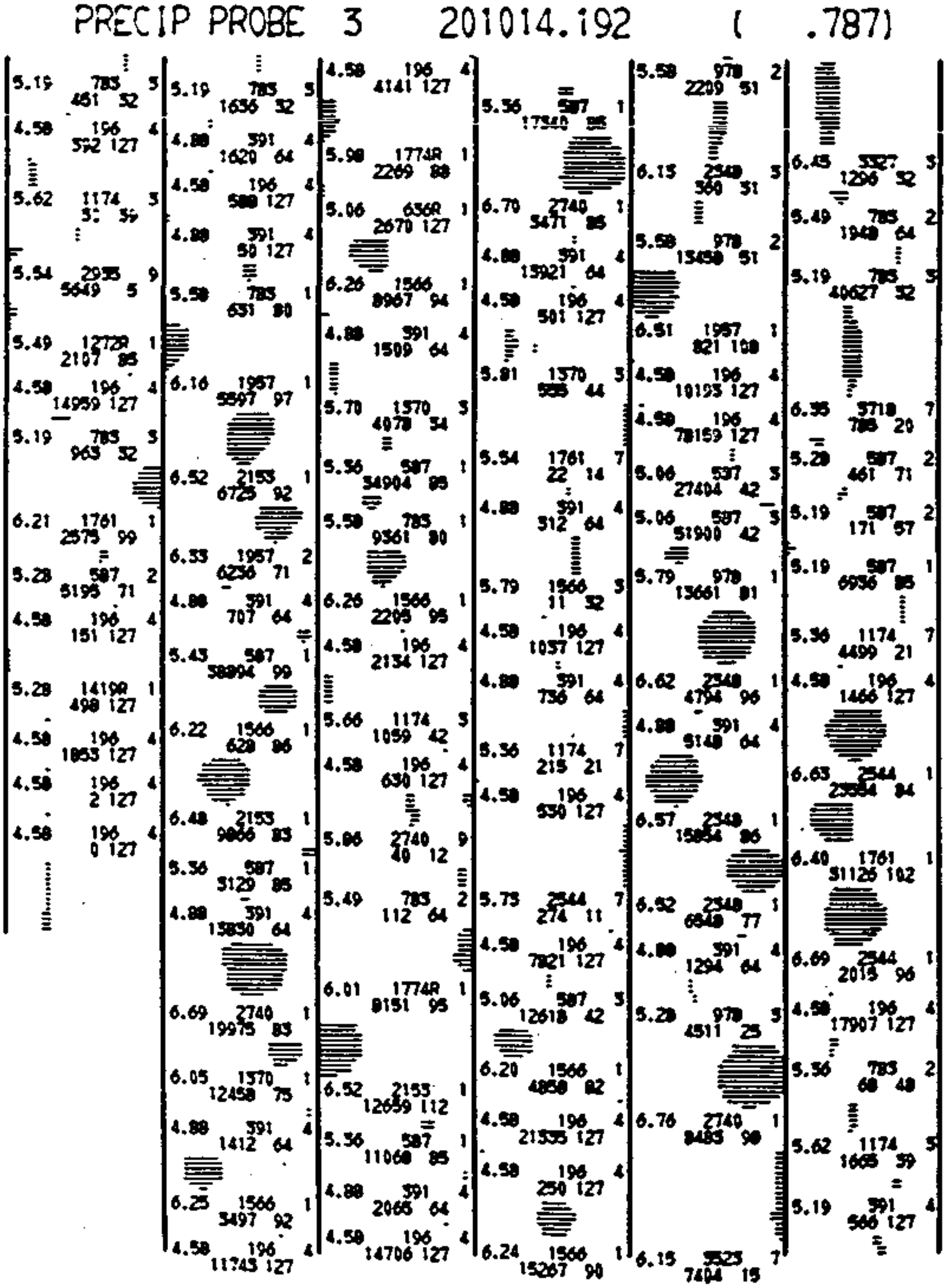

Figure 2. Examples of large particles that are likely to be frozen drops or graupel. This picture, generated with the larger sampling volume precipitation probe (each column represents a 6.4 mm wide array of photodiodes), shows many particles larger than 2 mm in diameter without evidence of streamers.

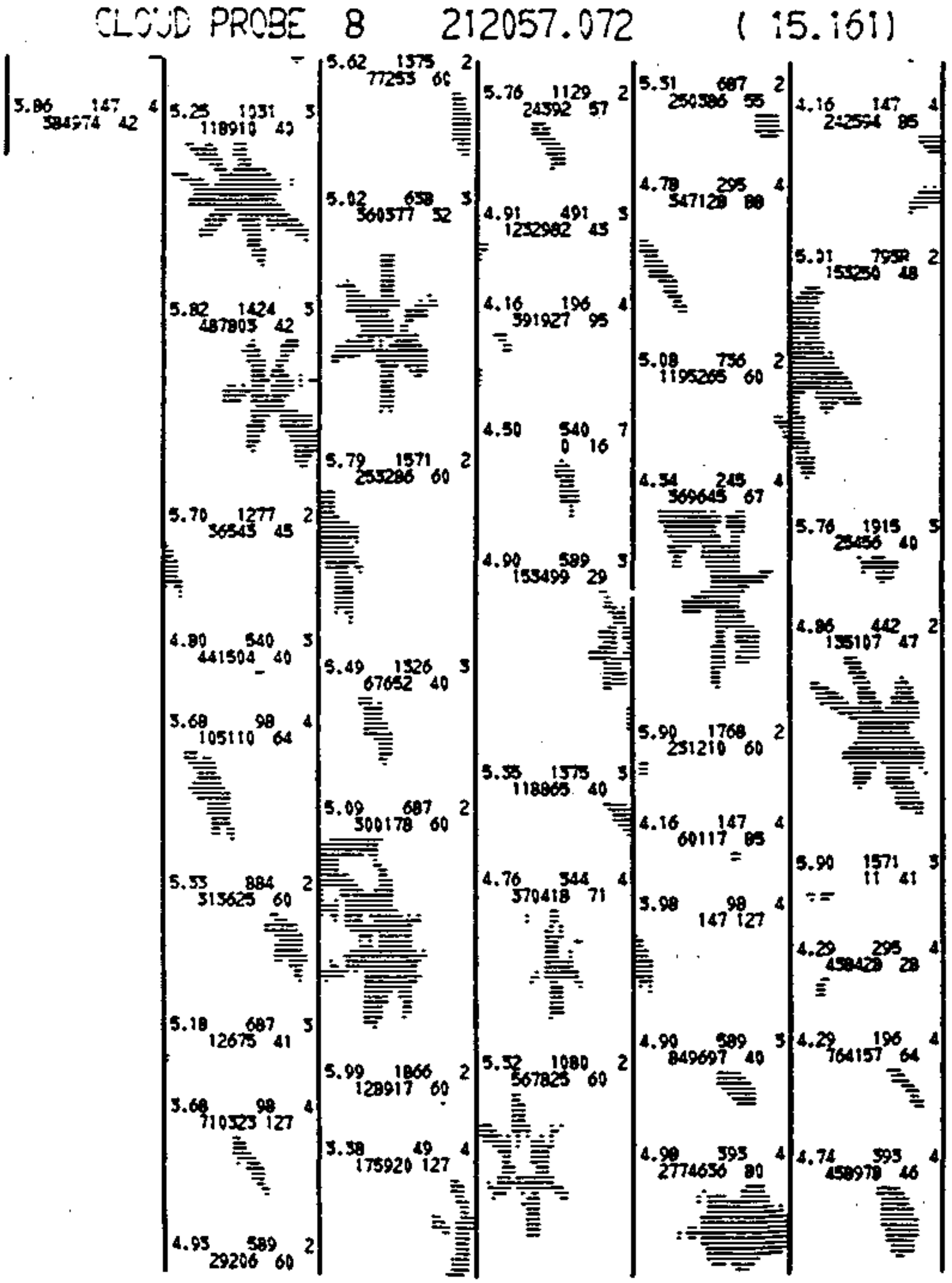

Figure 3. Examples of crystalline ice particles seen by the cloud probe.

millimeter sized crystals or aggregates. These crystals appear to mix into the convective cores pushing up through the stratiform layers where they show immediate evidence of riming, eventually producing large pellets. The ingestion of crystals into these growing cells does not seem to seriously deplete the small drop liquid water content, and the hot wire instrument confirms significant liquid water contents in these cells.

While the "streamers" resulting from the build up of liquid on the Knollenburg probes seem to provide a way of monitoring the glaciation of the large drops, they prevent a more quantitative assessment of the actual sizes and numbers of drops involved. To the extent that the available data gives a general pattern, however, agrees well with prior studies and recent theoretical advances.

This limited sampling program suggests that Midwest clouds have relatively high liquid water contents coupled with active ice processes. The earliest views of seeding clouds to assist relatively inefficient ice production seem totally inappropriate for this type of cloud. Dynamic seeding, in which glaciation is used to release heat to invigorate the cloud, remains an attractive possibility of seeding could initiate the natural multiplication processes sooner than might naturally occur. In this case, however, it is not the existence of adequate quantities of supercooled water that would define an appropriate seeding window, but rather an adequate quantity of <u>large</u> supercooled drops. This is a much more difficult quantity to measure from an instrumented aircraft, but may be amenable to modern remote probing techniques such as dual wavelength or polarization diversity radars.

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CHAPTER 4. THE STATISTICAL-PHYSICAL DESIGN OP PACE

by

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Introduction

The research conducted in this task area was concerned with the statistical and physical design for the experimental phases of PACE. Before describing these efforts, an overview of PACE and its problems are presented to put the statistical work in perspective.

The overall effort of PACE, to be undertaken by the ISWS and others involves a sequential approach to 1) discern if precipitation from individual midwestern summer clouds can be enhanced, and then 2) to learn if the precipitation can be increased over an area, as a consequence of the augmentation of precipitation from individual clouds and cloud groups, to lead to utility for midwestern agriculture. PACE consists of four phases.

The pre-experimental exploratory studies (Phase 1) define the problem within the scope of available knowledge and technology. These studies develop the body of observations and knowledge needed for deciding on the initial experimentation. Modification hypotheses are to be identified and tested, and systems field tested. Simultaneously, the available knowledge of the socio-economic and environmental conditions pertinent to the Midwest will be assembled. Development of concepts and models will be initiated.

The exploratory experimentation (Phase 2) is likely to be concerned with single clouds and semi-isolated convective cloud groups. It will focus on a randomized experimentation to help establish the physical basis for precipitation enhancement for cumuliform clouds. A major result expected from the cloud group modification phase will be the scientific understanding on which to base the formulation of a hypothesis for the confirmatory experiment (Phase 3).

The confirmatory experimentation (Phase 3) will be carried out according to hypotheses developed from the Phase 2 results. It will consider precipitation from convective cloud systems as well as individual convective clouds, and focus on area rainfall.

Phase 4 will be the interpretation and transfer activities at the end of PACE.

The Problem

A primary target of PACE is the reduction of meteorological and technological uncertainties in rain modification. That many unknowns exist is obvious from the mixed results of past modification experiments with convective clouds, in both target and extra area rainfall.

There are major uncertainties with respect to the particular types of convective cloud conditions which provide opportunities for modifying the precipitation, and the stage(s) in the cloud evolution during which alteration in the microphysics should be effected.

There are other critical uncertainties concerning the cloud response to the altered microphysics, and the relationship between the cloud response and the amount and character of the precipitation produced at the ground. The interaction between the microphysics and dynamics of the cloud is a central factor in determining the rain productivity.

Another group of uncertainties concerns the extension of the effects of the local modification, if any, beyond the limits of the seeded clouds and the net effect on the total surface precipitation over both nearby areas and more distant downwind areas.

A major problem area among the physical and technological uncertainties and perhaps the most crucial of all, is in the realm of proof — how to distinguish between modified and naturally-occurring phenomena. One major problem lies in the difficulty of predicting the natural cloud behavior and rain productivity. A parallel problem occurs in predicting how the altered cloud behavior and productivity differs from the natural case.

Lacking this capability to predict natural behavior, is it adequate "proof" to demonstrate, through measurements, differences between seeded and unseeded populations? Problems arising here lie in:

- Sampling so as to produce unbiased, uncorrelated seeded and unseeded samples;
- Accuracy and representativeness of the measurements;
- Establishing the level of significance which is acceptable;
- Identification of key parameters to measure which would be accepted as demonstrated seeding effect if significant differences were found;

Identifying appropriate and sensitive statistical tests.

As a result, an integral part of the total program design of PACE is the statistical design and evaluation effort.

Goal and Objectives

The goal of this part of the Pre-experimental Phase has been to conduct research leading to the development of the statistical and physical designs of the Phase 2 (and to some extent Phase 3) seeding experiments and the related evaluation techniques.

An important part of the research has been the integration of past Illinois results, those from the on-going pre-experimental field programs, and those from other theoretical and empirical studies within a statistical framework. The current in-cloud and rain system research using radar data will develop the baseline information on the characteristics of the summer rainfall, the synoptic and meso-synoptic conditions which produce rain-bearing clouds, and the individual cloud and cloud systems for Illinois. This baseline information is very important for defining conditions suitable for modification, for forecasting such conditions, for selecting the proper seeding technology, and for evaluation.

The research underway has three objectives within the development of the statistical and physical design for the single cloud experimental phase. These are 1) estimation of experimental units, sampling requirements, and durations required for each experimental phase; 2) the specification of covariates and essential atmospheric measurements needed for the evaluation, and 3) definition of the statistical activities and aspects of PACE.

The results of the research to date on several aspects of the statistical design and evaluation of Phase 2 of PACE are extensive, the results of that research led to certain research recommendations, including the need to define better the Illinois raincell climatology, and these results are included herein. Findings relating to the three objectives noted above are presented in the ensuing text.

Perspective on Statistical Research and Advisory Activities of PACE

As a guideline to the use of staff and external statistical skills throughout PACE, it was deemed important to delineate the "statistical phase" of PACE during its initial, pre-experimental phase. Such a statement of goals and definitions should provide clarity throughout PACE, both for the atmospheric scientists and for the statisticians involved. It is important to describe the meteorological phases of PACE in statistical classifications.

The Pre-experimental Phase of PACE, just beginning, has the statistical classification of "exploratory and design development."

The second experimental phase of PACE, identified as the single cloud and cloud group experiment (Phase 2), has a statistical classification of "exploratory and partial confirmatory."

Phase 3 of PACE, identifed as the area experiment, will have a statistical classification of "generally confirmatory."

The summary phase, Phase 4 of PACE, will be classified statistically as the "analysis, interpretation, and final evaluation."

There are four statistical aspects of PACE. The first is the design of the experiment; the second is the conduct of the experiment; the third is the exploration phase; and the fourth is the confirmatory activity. The activities under these four statistical phases are now described.

Under the design aspects, the atmospheric scientists involved in PACE state the program goals, identify the main variables, and express the hypothesis to be tested. The statisticians involved at this stage offer the best methods of "mathematical statistics." The ultimate design then is based on the planning for the exploratory and confirmatory phases.

The "conduct of experiment" phase, the second statistical phase, involves two principal activities. First, the experiment is based on the planning for exploratory and confirmatory phases. Secondly, statisticians are to provide "quality control," and to determine acceptable variations in the operations from the plan.

In the third "exploratory phase," all conceivable analyses of the results are examined. Statistically, several approaches are to be utilized. First, we should use a descriptive (simple) classification or stratification type of analysis. Exploratory data analysis should also be employed, but methods of hypothesis testing should not be used. Any striking findings should be judged by their likelihood of pure chance (using standard errors). The major problem with the use of confirmatory type calculations with the exploratory type findings is that of multiplicity. Very robust statistical techniques (nonparametric, especially permutation task, and jackknifing) are to be used.

The fourth set of activities to be addressed are of a confirmatory (or evaluation) nature. There are two sets of activities, the initial and the ending activities. The initial activities all fit within a 2-decision significance test theory. The hypothesis is formulated, variables are chosen, distributions are postulated, parameters are defined, and the statistics derived to maximize test power. The ending activities and products, include getting a statement of significance, and an estimate of relevant parameters with error intervals.

Another area of delineation in the statistical overview concerns the roles and involvement of statisticians. Two major thrusts are desired. First, staff statisticians will be needed for in-depth involvement in the design phase and the exploratory phase, with external statisticians to furnish guidance and quality control during the experimental activities. Second, external statisticians are needed to give advice and quality control, particularly during the conduct of the cloud experimentation, and during the performance of the confirmatory phase.

Potential Duration of the Confirmatory, Area Experiment

Considerable earlier research by the Illinois State Water Survey dealt with statistical analysis of area mean rainfall variations. Some of these results are applicable to considering the duration of the confirmatory experiment of PACE, envisioned to utilize, as a central assessment feature, rainfall over one or more areas.

This earlier research dealt with a variety of statistical experimental designs including 1) one area of randomization, 2) one area of randomization coupled with historical data, and 3) randomized crossover involving three areas. For each, rain characteristics were examined for simulated rain increases of 10, 20, and 40 percent. The single area simulations addressed rain in areas of 1500 up to 2000 square miles. The crossover, 3-area research dealt with simulations utilizing three areas of 600-square miles each. Precipitation factors evaluated included 1) area mean rainfall, area maximum precipitation, and the area-depth relationship values, as based on log-normal distributions of the rainfall (Huff, 1971).

Certain results, considered informative to the PACE planning at this stage, include comparisons of the experimental sampling periods required to detect rainfall changes. These are based on an alpha of .05 and a beta of 0.5.

Single Cloud Experiment Design and Evaluation (Phase 2)

The second phase of PACE involves the Single Cloud Experiment, which is concerned with precipitation from single, semi-isolated convective entities. It will likely consist of two efforts: 1) an initial effort in which hypotheses are tested and systems are field tested, and 2) a second effort in which a proof of concept experiment (POCE) is designed to establish the physical basis for precipitation enhancement for cumuliform clouds. A major result from the single cloud modification phase should be the scientific understanding upon which to base the formulation of a hypothesis for rain enhancement over an area (which is Phase 3 of the overall design effort). The fourth phase is one of final assessment and information transfer.

Attention has been given herein to several but not all aspects of the statistical design and evaluation of the Single Cloud Experiment. This effort deals with 1) the randomization scheme, 2) the experimental unit, 3) the sampling units, and 4) the statistical techniques of evaluation. We also attempted to identify critical unknowns and areas of further study and data collection in Phase 1.

An essential feature of the design of the PACE experimental program is an appropriate method for randomizing the treatment. The most commonly used scheme in recent years has been the random-experimental design, which involves the randomization of the experimental unit (usually day or subset of days) over a single target area into seeded and non-seeded units. The evaluation is usually based on the daily rainfall or hailfall averaged over the target area. In view of the objective of the Single Cloud Experiment, the reduction of the scientific uncertainty, the use of areal rainfall is not appropriate for evaluation in Phase 2.

The terms "single cloud" and "storm" are used according to the following definitions.

> <u>SEMI-ISOLATED SINGLE CLOUD</u> - a complex of convective elements, visually distinct and separable from other complexes by distances ranging from one to several diameters.

The definition covers a broad spectrum of clouds which, in the Middle West, typically have diameters of 2 to 15 km, separations of 5 to 20 km, and depths ranging from 3-4 to 10 km. A complex may consist of one large cloud containing one or more active cells, plus a number of small adjacent clouds or several active convective centers of equal but moderate size. Frequently, low-level stratocumulus or small cumuli form a nearly continuous layer around the base level of the large units. (Cumulus towers embedded in multiple layers, primarily altocumulus and altostratus, are usually associated with synoptic systems in which large scale lifting plays an important role. These are not subjects for the Single Cloud Seeding Experiment. They will, however, be included in the area experiment and consequently should be the subjects of exploratory (non-seeded) study during the Single Cloud Experiment).

> STORM - a clearly identifiable cloud region encompassing one or more semi-isolated single clouds which, throughout its history, is clearly separable from all other such areas in space by a cloud-free area of at least 50 km and in time by at least 1 to 2 hours.

The clouds comprising the storm may be clustered, arrayed in lines, or scattered randomly within the region. The areal extent and shape of the storm will vary with time as its member clouds develop, mature and die. The storm lifetime may be as short as a couple of hours—or as long as 15 or more hours—but it is identifiable throughout, and its motion (both from translation and propagation) is determinable. There are conceivably three randomization schemes between 1) days, 2) storms and 3) single clouds that could be employed for the single cloud experiment. Since the experimental unit is defined to be the unit to which the treatment (seeding) is applied (Steel and Torrie, 1960), the choice of randomization specifies the experimental unit. However, the effect of the treatment may be measured on the sampling unit, which can be the entire experimental unit or some fraction thereof (Steel and Torrie, 1960). Thus, in 'between-day' randomization, the experimental unit is the day and the sampling unit may be the single cloud. In 'between-storm' randomization, the experimental unit is the storm and the sampling unit is the single cloud. In 'between-cloud' randomization, the experimental unit and the sampling unit are the same—the single cloud.

Choosing the Sampling Unit. Adequate measurement systems (radar and raingages) for detecting the effect of seeding on single cloud complexes exist. Hence, it is recommended 1) that the treatment be randomized by storm or day, but 2) that the effect of the treatment be measured on a subset of the storm or day, the single cloud. Thus, it is recommended that the experimental unit for the single cloud experiment be the storm or day, and the sampling unit be the individual cloud.

In this scheme, if the "draw" is for seeding, all clouds in the storm would be seeded, to the extent that facilities permit. If the draw is for no seeding, clouds that might have been candidates for seeding would be as closely monitored as if they had actually been seeded.

The single cloud is rejected as the experimental unit in PACE because of 1) the likelihood of interaction between clouds in the frequent midwestern multi-cloud convective systems; 2) the difficulties in cloud recognition prior to treatment and hence the danger of a sacrificing a priori definition of unit for a posteriori definition of unit; and 3) the risk that the randomization may be invalidated because of possible contamination or because of a change in the character of a single cloud (e.g., cloud merger). The choice of the cloud to be the sampling unit instead of the experimental unit has three advantages. It permits the cloud or cells to be defined in a variety of ways without severely affecting the statistical inference. It also provides greater flexibility in regard to testing physical hypotheses, and it permits testing of hypotheses associated with interaction between adjacent clouds.

Choosing the Experimental Unit. Although the single cloud should not be used as the experimental unit, the choice between the storm or the day for the epxerimental unit is not so obvious. If the storm is chosen, as opposed to the rain day, a more exact identification of the synoptic weather type producing it can be obtained for each experimental unit. Such a determination is not always possible if the day is used as the experimental unit, because summer synoptic conditions can change radically within the course of a day. The dominating force in determining the character of the rainfall within a storm is the atmospheric forcing, and it is quite likely that seeding effectiveness will vary substantially with respect to existing synoptic conditions. Therefore, the ability to make this distinction removes an extraneous source of variation which increases the precision of the experiment. Also, if the storms are suitably separated in time and space, it is possible to have more than one experimental unit on a given day. This increases the sample size.

It is recognized that the risk of contamination exists between storms, but there are options available to minimize the risk. One option could be to establish a buffer period or a buffer area between storms wherein no treatment of clouds takes place. Another option during the analysis stage could be the skillful stratification of data based on the probability of contamination.

The choice of the storm as the experimental unit also provides an opportunity to assess downwind effects if proper measurements such as those suggested by Elliott et al. (1974) are available to permit the tracking of the seeded and non-seeded storms into the downwind area.

However, as useful as the storm can be as the experimental unit for the above reasons, there is one overriding disadvantage; it is extremely difficult to delineate the storm in real-time. Unless a satisfactory method of storm delineation can be made during Phase 1 (pre-experimental) research, the experimental unit should be based on the day. During the testing of seeding equipment, randomization schemes, and the general "dress rehearsal" of the POCE (late Phase 1 and early Phase 2), the day should be the experimental unit.

Randomization Procedure. If the final determination of the experimental unit were the storm, the randomization would be conducted in the following manner: (1) The storm would be delineated as it approaches the study area or as it initiates in the study area. The storm would be identified in real-time by airborne scientists in radio communication with the radar. The entity must be clearly recognizable to both the airborne scientist (visually) and the radar scientist as an isolated echo or close group of echoes. (2) If the storm is designated to be a seeded storm, all clouds selected by the cloud seeding aircraft as suitable are to be seeded. Cloud physics aircraft monitor the physical characteristics of the seeded clouds until they dissipate or until they become so intense that they represent a hazard to the aircraft. (3) If the storm is designated to be a non-seeded storm, clouds suitable for seeding are selected in the same manner and the cloud physics aircraft monitors the storm system as before to provide a valid control sample. If additional seeding aircraft are available, they could be used to handle other incoming storms. This would provide another sample unit for evaluation based on the radar, dense raingage and cloud physics information.

When the day is employed as the experimental unit, the day is randomized and an attempt is made to seed as many storms as possible. On the non-seeded days, storms and clouds are selected in the same manner as on the seeded days to provide an adequate control sample. If either the day or the storm is used as the experimental unit, non-seeded storms can be used in subsequent analyses to provide additional information for the experiment.

Whether the experimental unit be the storm or the day, there is a need to prevent the person declaring its suitability from knowing the randomization decision. Since seeding effectiveness will likely vary with synoptic conditions, recognition of the synoptic type of the experimental unit provides crucial information. For reasons stated above, we believe that the declaration of suitability is somewhat easier when the storm rather than the day is the experimental unit.

A final point concerning randomization is related to its purpose in the experiment. Because of the rudimentary state of knowledge of the detailed processes involved in midwestern cloud and precipitation development, and the difficulty of predicting outcomes, it is necessary to rely on comparisons between treated and untreated cases. Randomization is required to ensure a more precise estimate of experimental errors and/or treatment means and the differences between them. That is, randomization tends to reduce the correlation among errors.

To avoid bias in the comparison of the treatment (seeded and non-seeded samples), it is considered necessary to have a means of ensuring that the seeded cases will not be consistently handicapped by some extraneous sources of variation, known or unknown (Steel and Torrie, 1960). In order to achieve this goal, concepts of grouping, blocking, and balancing should be considered. Grouping is the placement of the experimental units into different groups so that they can be subject to seeding; this is accomplished by the randomization procedure itself. In blocking, the experimental units are allocated so that the units within a block are relatively homogeneous. In order to properly account for persistence, it may be wise to group experimental units into equal seeded and non-seeded samples (balancing). Adequate balancing and blocking ("spread" of treatment over the various meteorological regimes) should be sought after the experimental unit is selected. This combination of balancing and blocking will be tested in future Phase 1 research and in the initial parts of Phase 2.

Test Comparisons. The advantages of the proposed statistical design can best be illustrated by the various options available for a posterior comparisons of seeded and non-seeded samples. These include, among other possibilities, comparisons between seeded and non-seeded 1) clouds, 2) collections of clouds, 3) storms, and 4) days.

In addition, the individual convective complexes (clouds) can be subdivided into cells either by raincells at ground level or by radar cells at cloud level. The raincells can be defined by isohyetal entities within the background isohyet of the rain-producing system, by the total rain isohyet of each, or by the rainfall defined by the "track" of the radar cell. Schickedanz and Busch (1975) offered one definition of the raincell. The radar cells are defined by relative maxima in reflectivity above the cols separating other relative maxima. Changnon (1970) offered a third definition based on total cell rainfall defined in a dense raingage network. Standard definitions of raincells and radar cells must be finalized before the start of the POCE, and the two existing surface raincell definitions need a comparative study. Then, a fifth type of comparison is available; comparisons between seeded and non-seeded cells.

With regard to the first group of comparisons (clouds), it is recognized that the clouds (sampling units) are correlated with each other within the experimental unit. This correlation may be allowed for in various ways. First, the clouds can be stratified according to the degree of correlation. The amount of correlation can be considered as a reflection of the physical nature of the storm system (i.e., isolated clouds versus imbedded clouds; air mass situation versus squall line, etc.). Thus, the stratification according to correlation can provide physical insight for the evaluation. Secondly, the second and third groups of comparisons (collections of clouds and storms) do not involve correlations between clouds; consequently, valid comparisons are available, while pertinent and useful cloud information is retained. Similar statements can be made concerning the fourth and fifth group of comparisons involving days and raincells. Third, there must be comparison of clouds of different storms. An approximate error estimate is so derived for testing the means of the treated sample. The experimental error is the mean square among the sampling units from different experimental units.

The number of clouds is unlikely to be the same on each day or storm. Parameteric analyses would therefore turn out to be exceedingly difficult, but evaluation can be handled by re-randomization. The methodology could use any statistic that compares observations on seeded units with observations on unseeded units. The observed value of this statistic would then be compared with the values it would assume for (a sample of) re-randomizations of the units. The important point here is that the original randomization was one of units, so that the observations (clouds) on that unit were designated either as all seeded or all unseeded. The re-randomization must mimic that and may therefore not apply re-randomization to individual clouds.

For the second group of comparisons, there can be any number of cloud collections. For example, Simpson and Woodley (1974) used the "floating target", a collection of all seeded clouds and those that merge with them. Another possible collection of clouds would be the seeded clouds and all clouds that are within a specified distance of the seeded clouds. Comparisons between seeded and non-seeded collections stratified according to distance would provide an excellent method of testing for extra-area effect on the cloud scale. Furthermore, any of these collections can be compared to clouds not seeded during the storm for within-experimental-unit controls. However, caution should be exercised due to the possibility of inter-cloud contamination.

In the third group of comparisons, the characteristics of the storm are compared. The storm's total rainfall depth, total number of clouds, areal size, and duration are examples of the parameters that might be compared. These need to defined. In this way, the effect over the area as well as on individual single clouds can be assessed, and the experiment can be considered as a form of an "area" experiment that will be performed in Phase 3; the "true" area experiment will treat complex systems of cumuliform clouds in addition to the simple, semi-isolated entities. However, the Area experiment (Phase 3) must not begin until an acceptable level of statistical and physical certainty is obtained in the Single Cloud experiment.

Other comparisons can be envisioned. Clouds that have a complete set of data measurements (i.e., cloud physics, radar, and ground rainfall) could form a special class of comparisons. Another class would consist of those which have only radar and rainfall measurements, or those which have only rainfall measurements (raincells). The proposed statistical design provides not only an opportunity to make valid statistical comparisons but also the opportunity to use physical information and deduction in conjunction with the statistical design.

Statistical Methods. Since the emphasis in the Single Cloud experiment is on the removal of scientific uncertainty, the evaluation of the seeding effect will include tests of hypotheses regarding changes in cloud and cell parameters, as well as changes in the rain at the ground. In addition, the samples will be stratififed based upon "predictor" variables, those parameters based on pre-treatment environmental, cloud and/or precipitation conditions which appear to have some influence on cloud development and precipitation. Under these conditions, the application of a univariate statistical test to a single cloud or rain parameter has its limitations in that it fails to utilize the information contained in the other cloud parameters and, in some cases, it overestimates or underestimates the importance of a particular parameter. A multivariate test, whereby the information supplied by all of the cloud parameters can be utilized, would be far superior. The use of discriminate analysis can provide the appropriate multivariate test statistic in this case. This method was successfully applied by Schickedanz (1974) to discriminate between characteristics of raincells exposed to differing urban and industrial influences. This technique is especially appropriate for the Single Cloud Experiment since the storms are separated into randomized groups, while the cloud and cell parameters represent the basic components on which the physical effects are measured.

The discriminant analysis also provides an indication of which cloud characteristic is the most sensitive insofar as distinguishing potential differences between seeded and non-seeded clouds is concerned. The most important advantage is that the discriminant function can include characteristics of 1) the radar echo (e.g., base height, top height, area of the echo base, etc.); 2) micro-physical or dynamical parameters (e.g., ice/water ratio); and 3) the surface rainfall from the individual clouds (raincells). The discriminant analysis permits an association between the physical events within the clouds and the rainfall that reaches the surface from these clouds. In a sense, the discriminant function provides a set of predictor variables for single clouds which can be used to remove extraneous sources variation, thereby increasing the precision of the experiment. All that is required is that a complete set of measurements of the variables be available for each sampling unit. One goal of the test seeding in early phases of Phase 2 should be to discern those cloud characteristics most sensitive to distinguishing seed vs. no seed clouds.

Obviously, not all variables will be available for each experimental unit; therefore, different discriminant functions and stratifications will be required depending on the quantity and quality of data. For example, clouds which have a complete set of data measurements (cloud physics, radar, and ground rainfall) could form a special discriminant function. Another discriminant function could consist of data which have only radar and rainfall measurements, and another could have only rainfall measurements.

The discriminant function can also be applied to the characteristics obtained from the collections of clouds and cells. Hence, parameters such as maximum rain, duration, etc., as well as radar characteristics of corresponding collection of echoes can be used. The discriminant function can also be applied to the storm parameters and the corresponding radar information. The use of collections of clouds within the storm along with the total storm and/or day parameters in conjunction with the discriminant function eliminates the correlation problem completely and incorporates useful and necessary information with regard to individual clouds.

Raincell Climatology

The efforts to develop and state the design and evaluation of the single cloud and cloud group experimentation of PACE (Phase 2), led to a recommendation to utilize raincell characteristics, as defined by raingages and radar, in the evaluation. Many aspects of the statistical design and evaluation of PACE, as well as the operations, and the design of the surface networks, require detailed climatological information on raincells. To serve this need, raincell data collected in three of the Water Survey networks operated in central and southern Illinois were analyzed.

The data utilized in this study came from raincells in the central Illinois network during May-September 1968. These raincells were not defined in the METROMEX manner, but based on a "rain-no rain" outer isohyetal extremity. The METROMEX raincells were defined based on cores of raincells. Kence, this research also focused on raincells that had been delineated with considerable care, based on the total rain yield of cellular type entities defined using high speed and high resolution raingage charts.

The 1968 data came from the Central Illinois network which was 40 miles by 40 miles (1600 mi^2") with raingages every 3 miles. There were 73 raincells, most with hail, and 27 of these were totally defined within the network. The other partially measured 44 raincells defined totally traversed the network, entered and dissipated, or developed and departed from the network.

Another set of raincell data available for study came from the Shawnee Raingage Network located in extreme southern Illinois. The raincells during the June-August 1965 were analyzed from this network that was 60 by 22 miles. In this 3-month period, there were 638 raincells defined with 287 completely contained within the network.

The third set of raincell data, analyzed for comparison with the rain-no rain definition used for the cells on the Shawnee and Central Illinois networks previously described, was based on 58 cells from the summers of 1972-1973 of the METROMEX network, a circle of 50-mile diameter in southwestern Illinois. Raingage density was identical in all three networks.

Results. The principal analyses of these raincells were done on the following characteristics: orientation, lengths, and widths. Various other characteristics were defined for the Shawnee Network.

Table 1 presents the distributions of raincell orientations by 10-degree intervals. A raincell with an orientation of 180 -189 was nearly a north-south oriented cell. Inspection shows relatively similar distributions

Table 1. Illinois Raincell Orientations.

	Number of Cells		
Orientation	**Raincells with Hail(1)**	**All Raincells (2) in Southern Illinois**	**METROMEX Raincells(3)**
180 -189 (S)	1	1	1
190 -199	0	0	0
200 -209	0	1	2
210 -219	1	2	2
220 -229 (SW)	8	22	3
230 -239	5	28	5
240 -249	22	20	4
250 -259 (WSW)	18	29	11
260 -269	11	77	10
270 -279 (W)	5	69	4
280 -289	1	10	3
290 -299	0	5	8
300 -309	0	5	1
310 -319 (NW)	1	5	1
320 -329	1	3	1
330 -339	0	1	1
340 -349	0	2	1
350 -359	0	7	0
Total	73	287	58
Average —	252	262	261

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(1) Raincells, some with hail in CIN in May-Sept. 1965 some complete inside the network and some only partially in the network.

(2) Raincells in June-August 1965 completely defined in Shawnee Network, 22 x 60 miles.

(3) Raincells in June-August 1972-73 in METROMEX Network, circular diameter of 50 miles.

from the three networks. All have very similar average orientations, around 250 to 260 degrees (west southwest-east northeast). Although most cells are shown to have southwest, west southwest, or west orientations, practically every orientation was found for a few raincells. The sample seems adequate to express the climatology of Illinois summer raincell orientations.

Table 2 presents information on Illinois raincell lengths. Because the sample from Central Illinois network was small, values for those with known lengths, as well as those with underestimated lengths (not totally in the network), are presented to give some estimate of their distributions. It is notable that in comparing the two columns of central Illinois raincells, that the underestimated ones reveal considerable lengths ranging up to 60 miles across this 40-by-40 mile network. The differences between the known and unknown lengths for central Illinois, reveal that the network dimensions there and also in southern Illinois (which had a network length of 60 miles) and METROMEX (with one of 50 miles) partially influenced the "known length" category. The southern Illinois raincells and METROMEX raincells show a preference for lengths generally 20 miles or less. Both have average and median lengths of 10 to 12 miles. However, the 27 known raincell lengths in central Illinois had a higher median, 16 miles. This may result because of the small sample plus the fact the sample was drawn from some cells that produced hail, potentially more vigorous convective cells than a sample that includes all summer raincells. The results do provide useful estimates of the length characteristics of Illinois raincells. It is also of interest to note that the METROMEX raincells defined by the objective approach provided averages, medians, and distributions that were comparable to the southern Illinois raincells defined in a different manner (rain-no rain).

Table 2. Illinois Raincell Lengths.

	Central Illinois Raincells(1)			
Length, miles	Known Length	Underestimates of lengths	Southern Illinois Raincells(2)	METROMEX Raincells(3)
6-10	3	4	168	26
11-15	9	5	75	17
16-20	6	5	39	7
21-25	4	6	3	7
26-30	1	6	1	0
31-35	3	8	1	0
36-40	1	3	0	0
41-45	0	3	0	1
46-50	0	5	0	0
51-55	0	0	0	0
56-60	0	1	0	0
Totals	27	46	287	58
Average	17	--	1	12
Median	16	--	10	12

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(1) Raincells, some with hail, in 40 x 40 network, some incomplete, May-September 1968.

(2) All completely within Shawnee Network (22 x 60 mi) in June-August 1965.

(3) All completely within METROMEX Network (50 mi radius), June-August 1972-73.

An analysis of the widths of raincells appears in Table 3. These widths are expressed as those occurring at cell "maturity," or when their width was greatest. Again, the widths of the METROMEX and southern Illinois cells provided comparable averaqes and distributions, although the METROMEX sample showed a slightly narrower width, a not unexpected result considering a more restrictive core-only definition employed for METROMEX. Most of these types of cells, at their widest, are 6 miles or less in width. The raincells from central Illinois show greater widths. Their averages and medians are nearly twice those of the other cells, indicating a double maximum: one at 4 to 6 miles (like cells in the other networks), and a second at 10-12 miles (large hail producers). Notably, some raincells in the Central Illinois network (with hail) achieved widths of up to 30 miles.

Another comparison of raincells involved examinations of the relationships between their lengths and widths. Table 4 presents the frequency distribution of lengths and widths, by class intervals, for the 73 raincells with hail in central Illinois in 1968. This distribution shows that the longer cells, in general, were the wider cells. The line drawn inside Table 4 envelops, above and to its left, the 27 complete raincells to reveal those with both dimensions that are accurate. These distributions further support the length and width direct relationship, the wider cells are longer cells.

Another study of raincell lengths was done in relation to their orientations. The distribution of raincell lengths from the METROMEX network is shown in Table 5. There is a suggestion that the shorter raincells, those of 6 to 10 miles, are more frequently with southwest to west-southwest orientations. The longer raincells tend to have orientation distributions that show a greater frequency of west and west-northwest orientations.

Table 3. Illinois Raincells Widths (at maturity)

Widths, Miles	Raincells with hail Number	Raincells in Southern Illinois Number	Raincells in METROMEX Number
1-3	5	120	30
4- 6	34	135	21
7-9	9	28	6
10-12	12	3	1
13-15	5	1	0
16-18	3	0	0
19-21	2	0	0
22-24	1	0	0
25-27	1	0	0
28-30	1	0	0
Totals	73	287	58
Average—	7	4	4
Median—	6	4	3

Table 4. Raincell Length vs. Widths for Cells in May-September 1968, Central Illinois Network.

Lengths,			(1)			Width, miles					
in miles	1-3	4-6	7-9	10-12	13-15	16-18	19-21	22-24	25-27	28-30	Totals
6-10	2	5									7
11-15	3	10	1								14
16-20		8	2				1				11
21-25		7	0	2	1						10
26-30		1	4	2							7
31-35		3	1	4	2	1					11
36-40			1	1	1	1					4
41-45				1			1	1			3
46-50				2	1	1				1	5
51-55											0
56-60									1		1
Totals	5	34	9	12	5	3	2	1	1	1	73

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(1) This line envelops (above and to the left) all but one of the 27 complete cells (9 miles or less wide and 40 miles or less long).

Table 5. Distribution of METROMEX Summer Raincells by Length and Orientation.

Orientation of Cell	**Length, Miles**							
	6-10		**11-15**	**16-20**	**21-25**	**>26**		**Totals**
180 -189	1							1
190 -199								
200 -209	2							2
210 -219		1	1					2
220 -229		1	1		1			3
230 -239		1	3	1				5
240 -249		1	1		2			4
250 -259	6		3	2				11
260 -269	4		2	3	1			10
270 -279	3		1					4
280 -289	2		1					3
290 -299	2		2	1	2		1	8
300 -309			1					1
310 -319	1					1		2
320 -329	1							1
330 -339					1			1
340 -349	1							1
350 -359								
Totals	26		17	7	7	1		58

Another analysis, based on the central Illinois 27 raincells with known lengths and widths, is provided in Table 6. Here, the ratio of the length divided by the width is compared with the length of the cells. In general, this shows that as the length of the cells become ever greater, the widths increase, but not relatively as much.

Table 7 presents a series of other types of raincell characteristics for the raincells from the Shawnee Network from the summer of 1965. The median values of the their durations and rainfall production are shown. The raincell area values were determined by planimetering the edge of the rain area, and as shown, the median was 29 square miles. They typically last 15 minutes, produce a point maximum rain 0.1 inch, and an area mean rainfall of 0.06 inch. As shown in Table 7, the summer rain periods each associated with a given synoptic condition in the network, produced anywhere from 2 up to 47 raincells during the summer. There were 41 rain events during the summer. The median number of raincells per rain period was 14.

Summary and Discussion

A basic requirement placed on the design of PACE is that of randomization. The most commonly used design in recent years has been the random-experimental design, which involves the randomization of the experimental unit (usually days or sub-sets of days) over a single target area into seeded and non-seeded units. The evaluation is usually based on the daily rainfall or hailfall averaged over the target area. Cloud physicists have often criticized this design, claiming that the statisticians are not properly accounting for the physical considerations in their evaluation process. The design recommended for Phase 2 of PACE focuses on the cloud element.

Table 6. Comparison of Length-Width Ratio of Central Illinois Raincells with Length for Cells.

Ratios, L W	Lengths, Miles 6-10	11-15	16-20	21-15	26-30	31-35
1.0-2.0	1	1				
2.1-3.0	1	3				
3.1-4.0		2	3	1	1	
4.1-5.0		2	1 3			1
5.1-6.0			1			
6.1-7.0		1				2

Table 7. Shawnee Network Raincells Characteristics (1965).

Median Values of Raincells

1. mean rainfall = 0.6 inch
2. maximum rainfall = .10 inch
3. duration = 50 minutes
4. area = 29 mi^2 (90% values between 7 and 94 mi^2)
5. length = 11 miles
6. maximum width = 4 miles

Number of Cells per Rain Period

1. range 2 to 47 raincells
2. median = 14 cells

However, the single cloud design focus places severe constraints on the measurement system since the tracking of single clouds in time and space to a sufficient degree of accuracy requires 1) a dense network of surface raingages, 2) a very accurate and sophisticated 10-cm radar system, and 3) a combination of a less dense raingage network to calibrate the radar system. The measurement system must be developed to be adequate for individual clouds.

The treatment and randomization in Phase 2 are to be applied to the storm, typically a group of clouds in the Midwest. Since the experimental unit is defined to be the unit to which the treatment is applied, the choice of randomization also determines the experimental unit. However, the effect of the treatment should be measured on the sampling unit, which can be some fraction of the experimental unit and, in this case, is to be the single cloud. Thus, it is recommended that the experimental unit for the single cloud experiment should be the storm and the sampling unit should be the individual cloud (cell). However, further study of the day versus the storm as the experimental unit is needed.

The single cloud should not be the experimental unit because of 1) interaction and, hence, contamination between clouds in multicellular convective systems; 2) difficulties in cell recognition prior to treatment and hence the danger of sacrificing a priori statistical inference for a posteriori inference; and 3) danger that the definition of the experimental unit may be jeopardized by the merger of individual clouds or cells. It would appear that the choice of the cloud to be the sampling unit, instead of the experimental unit, permits a variety of defintions without severely affecting the statistical inferences. It also provides greater flexibility in testing physical hypotheses.

Although the single cloud (cell) should not be used as the experimental unit, the choice between the storm or the day as the experimental unit has not been resolved. It would appear, however, that the opportunity to meaningfully determine the synoptic type for each experimental unit would be a decided advantage for the storm since such a determination is not always possible if the day is used as the experimental unit.

Since the dominating force in determining the character of the rainfall within a midwestern storm is the synoptic weather situation, the ability to make this distinction removes an extraneous source of variation which, in turn, increases the precision of the experiment. It is recognized that there may be a contamination problem from storm to storm, but the contamination problem could be handled by either allowing a buffer period or buffer area to occur in which no seeding takes place or by skillfully stratifying the storm during the analysis stage into categories of potentially contaminated storms and into storms where there is little chance that contamination occurred. Research is needed to define these buffers and the probability of contamination. The choice of the storm as the experimental unit also provides an opportunity to assess downwind effects if propoer measurements (i.e., synoptic surface and upper air, radar, satellite, aircraft and silver detection) are available to permit the tracking of the seeded and non-seeded storms into the downwind area. It is noted, however, that the use of the storm as the experimental unit requires a method of real time storm recognition and delineation, based on radar or aircraft. This must be researched because recognition is absolutely essential. If such a method is not available, the experimental unit will have to be based on the day instead of the storm.

In this scheme, the randomization would be conducted in the following manner: the storm (experimental unit) is delineated as it approaches the network or as it initiates on the network. The storm would be identified in real time by airborne scientists in communication with the radar. The entity must be clearly recognizable to both as an isolated echo or close group of echoes. If the storm is designated to be a seeded storm, all cells selected by the cloud aircraft and/or radar controller during the storm are to be seeded. Cloud physics aircraft monitor the cells by collecting the physical measurements of interest. If the storm is designated to be a non-seeded storm, cells are selected in the same manner as if they were to be seeded, and cloud physics aircraft monitor the storm system as before. A final point concerning randomization is that the concepts of grouping, blocking, and balancing should be employed and research on these is yet to be done.

In regard to evaluation, we will employ multivariate statistical tests instead of univariate tests. The use of discriminant analysis provides 1) a method of including characteristics not only from the radar (echo base height, echo tops, area of cloud base, etc.) but also from the cloud physics measurements and the rainfall characteristics from individual cells at the ' surface; 2) a measure of which cell characteristic is the most important parameter with regard to distinguishing potential differences between seeded and non-seeded cell characteristics; and 3) a reduction of the detection times -since more information concerning the radar, cloud physics covariates, and surface rainfall can be included.

Recommendations for Future Research

The initial planning analysis for the statistical design and evaluation of the Single Cloud Experiment (Phase 2) of PACE has pointed to several areas that need data, more information, and future research before finalizing the design for this phase.

1. The choice of the storm or the day as the experimental unit is not obvious. Certain research must be accomplished to descern which of these units must be used. Available results indicate the storm is the better unit, if some uncertainties can be resolved (see #2 and #3 below).
2. The potential for contamination of seeding material between storms affects the use of storms as the experimental unit. It is recommended to establish the probability of contamination between storms, presumably through use of tracers and through experimental seeding as part of the late stages of the pre-experimental phase and/or the early trials of Phase 2, the Single Cloud Experiment.
3. The use of storms as experimental units also hinges on being able to define storms in real time; otherwise, we must use days as experimental units. This real-time delineation relates to future capabilities: a) to forecast approaching storms into the study area, and b) to forecast the initiation of storm units in the study area.
4. Future research must address, through study of historical data, proper approaches for grouping, blocking, and balancing. This should be done once the experimental unit is chosen as storm or day.
5. Further studies of surface raincells defined in different ways are needed so as to decide on a suitable definition for Phase 2.
6. Re-randomization tests should be accomplished on available samples of raincells, clouds, and radar echoes derived in the pre-experimental research to examine for the best statistics.

7. Comparisons must be made of groups of seeded clouds and groups of non-seeded clouds occurring during the same unit to measure the potential for contamination, and to discern whether statistically valid comparisions can be made, and the limits to be set (time and distance). Tracer and test seeding studies are recommended in late Phase 1 and early Phase 2.
8. If storms are chosen as the experimental units (see No. 1 above), storm characteristics which can and should be measured for "storm" comparisons must be defined.
9. The raincell statistics, future echo cell statistics, cloud physics characteristics, and the predictor variables (from ongoing research) need to be integrated to discern future sampling requirements of the Phase 2 Single Cloud Experiment.

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CHAPTER 5. COVARIATE STUDIES

by

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Introduction

The PACE meteorological studies have been directed toward developing rawinsonde data sets and analysis techniques necessary to find environmental variables to stratify the natural variability of convective rainfall in Illinois. Conceptually, these variables can be used for operational decision making, including general forecasting, dispatching aircraft, and monitoring for severe weather. Most importantly, these variables can be used as an aid to the evaluation of the seeding experiment. Potentially, they can make the difference between whether or not the experiments are statistically significant.

Covariates (environmental variables related to rainfall) have been proposed or used for cloud seeding experiments for at least 20 years (Spar, 1957). Their effectiveness in explaining the rainfall variance has been demonstrated by Neyman and Scott (1967), Estoque and Partagas (1974), Biondini (1976), Biondini *et al*. (1977), and many others.

Approach to Finding Illinois Covariates

The strength of the statistical relationships between rainfall and environmental variables for Illinois agricultural areas are subject to the follwing physical constraints. First, there are no unique physiographical/ mechanical (forced upslope flow) or physiographical/dynamical (mountain induced circulations, sea and lake breezes) influences that initiate convective precipitation locally, except in proximity to large urban centers. Second, precipitation is associated with diverse weather systems. Therefore, the covariates should be about equally related with rainfall and correlation coefficient magnitudes are likely to be small.

The strengths of the statistical relationships also depend upon the measurements of rainfall and environmental variables. Convective showers typically have large spatial rainfall variability. Lower correlations between rainfall and covariates will be expected if the rainfall measurements from a sparse raingage network are not representative of the actual rainfall (Huff, 1970) . Inappropriate timing and/or positioning of the environmental observations with respect to rain-producing weather systems can also decrease the correlations. (Achtemeier and Schickedanz, 1979).

Fortunately, a large data bank of dense raingage measurements is available for Illinois covariate studies. One of these data sets (METROMEX), including raingage measurements for June, July, and August, 1971-1975, has been used with 24 covariates derived from surface weather data. The purpose of this study was to determine the temporal and spatial density of observations necessary to resolve weather systems that produced the rainfall over the network (Changnon *et al*., 1979). The results indicate that environmental observations should be taken within 6 hrs from the time the rain begins and that the station density should not be greater than 150 km (the NWS surface station density for the Midwest).

Part of this study was rerun using raingage data from a 1000 km^2 subset of the METROMEX network stratified so that the mean rainfall was greater than 0.1 inch. This is the minimum rainfall criteria established for storms. considered applicable for PACE. The results for the 70 storms that met the criteria are summarized in the following tables. Table 1 gives a list of the surface covariates that were used in the study. The three-letter abbreviations are used in Tables 2 and 3. (See Changnon *et al*., (1979) for physical descriptions of the covariates.)

The covariates were presented in 63 point gridded fields, the boundaries of the grid extending from northwest Iowa to southern Lake Michigan, to western Tennessee, to eastern Oklahoma to northwestern Iowa. The correlation coefficients between the 70 storm average rainfalls and each covariate field are summarized in Table 2 for 8 time lags determined relative to the rainfall begin time. The maximum correlation and the percent variance explained for each covariate field are listed in the third and second columns from the right of the table. The number of points that satisify the 0.5 significance criteria for inclusion into the model are also shown.

The points listed on the rightmost column of Table 2 were combined into a second stepwise regression that is summarized in Table 3 for the first 11 variables retained. These 11 variables were able to explain 76% of the rainfall variance (correlation coefficient 0.87). However, because of the large number of points initially included in the regression, the fact that some of the variables were intercorrelated, and the possibility of chance correlations, the predictive power of this regression is inflated. When the regression is tested with independent rainfall data, the explained variance will more likely be in the neighborhood of 0.3-0.4, still a significant level for predicting convective rainfall amount.

Approach to Analysis of the Upper Air Data

The studies with surface data showed that a new analysis approach was needed to better treat the problems of observation timing and spatial

Table 1. List of Surface Covariates and their Abbreviations.

1. Mixing ratio (MIX)
2-5. Geostrophic wind line projections (DGA-DGD)
6-9. Observed wind line projections (OBA-OBD)
10. Divergence (DIV)
11. Vorticity (VOR)
12. Moisture advection by the geostrophic wind (GMA)
13. Moisture advection by the observed wind (OMA)
14. Moisture divergence (MDV)
15. Wet bulb potential temperature (WPT)
16. Cumulative lift (CML)
17. Pressure trough analysis (PTA)
18. Pressure tendency (t-t   ) (PTY)
19. Sky cover (SKY)
20. Cloud base height index (CHT)
21. Pressure (PRS)
22. Temperature (TMP)
23. Dew point temperature (DEW)
24. Spot index (SPT)

Table 2. First 8 Columns: Stepwise Correlation Coefficients for each Covariate Field by Time Lag Relative to Rainfall Begin Time (70 Storms, Average Rainfall > 0.10 in), Next 3 Columns: Maximum Correlation, Percent Rainfall Variance Explained, and Number of Points that Exceeded 0.5 Significance Criteria.

	Time Lag in Hours										
	Before Rain Begin				**After Rain Begin**				**Max**	**Pcnt**	**No**
Variable	**10-12**	**7-9**	**4-6**	**1-3**	**0-2**	**3-5**	**6-8**	**9-11**	**Corr**	**Var**	**Pts**
MIX	.55	.22	.66	.71	.69	.49	.35	.56	.71	50	6
DGA	.35	.52	.44	.55	.71	.71	.48	.55	.71	51	8
DGB	.62	.57	.44	.46	.42	.63	.47	.66	.66	43	7
DGC	.66	.60	.26	.46	.50	.47	.32	.48	.66	44	8
DGD	.32	.56	.58	.63	.75	.68	.32	.24	.75	57	12
OBA	.41	.56	.30	.17	.57	.41	.32	.33	.57	32	5
OBB	.40	.52	.24	.64	.32	.42	.22	.24	.64	41	8
OBC	.73	.47	.68	.48	.26	.63	.32	.58	.73	54	9
OBD	.42	.73	.54	.42	.58	.51	.17	.55	.73	54	9
DIV	.50	.62	.70	.65	.53	.75	.54	.44	.75	57	9
VOR	.20	.75	.70	.62	.84	.62	.40	.70	.84	71	16
GMA	.53	.71	.53	.81	.58	.78	.49	.62	.81	65	11
OMA	.26	.20	.60	.63	.59	.67	.73	.87	.87	75	14
MDV	.47	.66	.76	.75	.72	.85	.59	.53	.85	73	13
WPT	.67	.44	.73	.56	.67	.46	.44	.42	.73	53	6
CML	.61	.64	.55	.63	.48	.35	.24	.26	.64	41	7
PTA	.62	.68	.79	.68	.47	.49	.56	.68	.79	62	7
PTY	.32	.58	.46	.60	.47	.50	.55	.63	.63	40	7
SKY	.54	.57	.41	.32	.20	.40	.33	.33	.57	32	5
CHT	.80	.54	.20	.17	.45	.49	.33	.32	.80	64	9
PRS	.24	.00	.45	.52	.35	.55	.36	.39	.55	30	5
TMP	.65	.44	.50	.57	.57	.58	.56	.55	.65	42	4
DEW	.51	.22	.59	.81	.52	.45	.46	.50	.81	65	11
SPT	.37	.44	.74	.54	.74	.56	.39	.71	.74	55	9

Table 3. Cumulative Correlation Coefficient, Cumulative Rainfall Variance Explained, Mean Square Error, and Covariate Location for the First 10 Covariates Selected by Stepwise Regression.

Variable Number	Variable Name	Cumulative Correlation Coefficient	Cumulative Percent Variance	Mean Square Error	Distance From Site (km)	Direction From Site
1	PTA20*	.49	24	363	100	SE
2	PTA15	.59	35	316	230	WSW
3	PTA16	.70	49	253	175	WSW
4	DGA02	.74	55	225	240	SW
5	MIX17	.77	59	209	125	SW
6	DGB38	.79	62	198	120	NW
7	VOR38	.81	65	187	120	NW
8	DGD06	.82	68	175	175	SSE
9	PTA03	.84	70	164	225	SW
10	V0R16	.85	73	148	175	WSW
11	DGD62	.87	76	135	280	N

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*The 2-digit numbers identify the gridpoint at which the variable was selected by the stepwise regression.

resolution when historical rawinsonde data are used to develop covariate-rainfall relationships for PACE. With regard to observation timing, atmospheric measurements should be taken almost simultaneously with the initiation of rainfall if maximum correlative power is to be attained (Achtemeier and Schickedanz, 1979). The 12-hour interval between soundings leads to low correlations with rainfall when the covariates are derived from single soundings (Achtemeier et al., 1978). This problem can be partly overcome by spatial analysis, but the station spacing (300-400 km) is much larger than required to permit resolution of mesoscale systems found from the study with surface data (Achtemeier, 1980).

A new analysis technique designed to make maximum use of the information available in rawinsonde data will permit resolution of subsynoptic scale disturbances aloft. The method designated 0BAN3D, makes use of the detailed vertical temperature resolution of rawinsonde data and meshes temperature (height) data with wind data through variational fitting. Stephens (1971) has shown that dynamically constrained analysis including two variables better resolve smaller scale phenomena than does an analysis that uses the variables independently.

Preliminary tests with the temperature analysis part of this technique indicate that the desired scale reduction is obtainable for certain types of weather systems. The variational part is still under development. We have proceeded with the acquisition of upper air data and continued development of the multi-variable objective analysis. The next section describes progress thus far in the handling of the upper air data and the last section discusses the development of the temperature, height, and moisture phases of the OBAN3D analysis technique.

Quality of NCAR Rawinsonde Data

Four magnetic tapes containing rawinsonde data for 0000 and 1200 GMT June-August 1971-1975 were obtained from the NCAR data archives for use in the investigation of predictor variables derived from upper air observations. NCAR acquired the data from the NWS. Each rawinsonde data set was broken into a number of "reports" which summarized the data for specific uses. Three reports were needed for the ISWS-PACE analyses. These were:

1. The standard level reports that included heights, temperatures, temperature-dew point spread, wind direction and wind speed.
2. The significant level reports that included pressure, temperature, and temperature-dew point spread.
3. The winds aloft reports that included heights, wind directions, and wind speeds.

The analysis technique requires the fine vertical scale of the significant level temperatures. The variational phase requires winds aloft to 100 mb. The winds aloft reports usually gave winds up to approximately 10 km. It was necessary to merge the winds aloft reports with the standard level wind reports to get an estimate of the winds aloft to 100 mb.

It was soon found that the standard level heights for some stations were in error. The significant level pressure, temperature, and moisture data were used to recalculate the standard level heights hypsometrically (Hess, 1959). It was also found that some of the significant level temperatures were coded as missing. This, of course, can decrease the hydrostatic accuracy of the recalculated height data.

The editing program was modified to compress out the missing significant levels. Then the standard level heights were calculated and the standard level winds merged with the winds aloft report. However, as the temperature data was assessed through test objective analyses, a number of other errors were found. Some examples of these are given in Table 4.

The error in the observation 72340 (a) was found at 400 and 314 mb where the negative signs for the temperatures had been dropped. The error in 72354 (b) was found at 937 mb where a negative sign had been added to the temperature. Since the data sample was for the summer period, temperature variations were not as great as seasonal variations and pressure levels could be established for which the temperatures below a reference level (850 mb) could not be negative and a reference level (500 mb) above which temperatures could not be positive.

The temperature lapse rate was used to determine the accuracy of the data between 850 and 500 mb. If the lapse rate was superadiabatic, it was recalculated as adiabatic. If an inversion lapse rate was greater than 10 C km , it was recalculated as equal to 10 C km

Another kind of problem is presented by station 72349 (c) for which there are only 3 significant levels between 959 and 90 mb. The intermediate levels were either missing or garbled in the process of data transferral from NWS to NCAR. The observations within the layer of missing data were given in the standard level NWS analyses height and temperature analyses.

Station 72340 (d) presents another type of error. Significant level temperature data were coded as missing in the layer from 850-180 mb. The temperature and dew point depression given for 180 mb were probably for the first missing layer above 850 mb. The sign check in the editing program changed the temperature to -138 however this was still much too warm for temperatures at 180 mb.

Table 4. Examples of Errors in NCAR Archived Rawinsonde Data. Temperatures and Temperature-Dew Point Depressions are in Tenths of a Degree C.

			Pressure	**Temp.**	**$T-T_d$**	**Height**
a)	72340	3473	9223	81	73 6	2 1200
		27				
			445	-147	13	6697
			400	198	19	7563
			314	336	36	9751
			300	-365	40	10116
b)	72345	3452	9738	393	73 6	2 1200
		17				
			963	170	18	393
			937	-173	0	612
			868	160	16	1224
c)	72349	3688	9390	439	73 6	3 0000
		3				
			959	172	9	439
			193	-587	999	12284
			90	-695	999	16952
d)	72340	3473	9223	81	73 6	3 1200
		14				
			850	150	33	1516
			180	138	110	14679
			176	-547	999	14846
e)	72662	4405	10307	966	73 6	3 1200
		2				
			895	44	44	966
			263	-485	999	9968
f)	72340	3473	9223	81	73 6	5 1200
		21				
			300	-347	70	9556
			289	-575	999	9804
			185	-575	999	12620

Station 72662 (e) had an error similar to 72349 in that only 2 significant levels were not coded as missing. Further, the 895 mb temperature was in error; the 44 likely being a carry over from the temperature-dew point depression.

Finally, the temperature at 289 mb at station 72340 (f) was coded at -575, an error of approximately 20 C.

Numerous errors of the type described in this section have been found in the 1-15 June 1973 upper air data subset selected for testing the objective analysis method. A number of lengthy delays have arisen because of the need to find these errors and develop software to handle them. The types of problems found in c) and e) of Table 4 result in the loss of the entire sounding. But all of the errors are of a serious nature because they lead to gross hydrostatic errors that will spread into the objectively analyzed height fields and invalidate the windfield analyses. These problems may lead the ISWS to seek an alternative data set with better quality control.

Description of Objective Analysis for PACE (OBAN3D)

The objective analysis technique, designated 0BAN3D is a three-dimensional analysis of temperature, moisture, height and wind. The basic principle behind OBAN3D is that the horizontal resolution of meteorological fields can be improved by exploiting the vertical resolution of rawinsonde temperature and moisture observations. There is the underlying assumption that the observed thermal structures have spatial continuity and that the slopes of these features do not depart significantly from the slopes resolvable within the current synoptic rawinsonde network. It is the experience of synoptic meteorologists that the above assumptions are largely valid for certain types of weather systems. Precipitation-producing mesoscale systems form along the intersections of thermal structures or at intersections between the thermal structure and the surface.

On the other hand, there are mesoscale systems of small spatial scale that are not related to the synoptic scale temperature fields. These systems cannot be resolved by 0BAN3D.

By using local isentropic interpolation to fine mesh sigma surfaces, 0BAN3D better locates temperature zones spatially, and better defines temperature gradients than does isotropic interpolation to grid surfaces alone. Detailed height fields can be derived from the improved temperature fields through the hypsometric equation (Hess, 1959). Finally, analytical windfields can be derived from the height data given an appropriate wind-height relationship. These analytical windfields can be meshed with the observed winds to develop windfields with greater spatial resolution than the resolution obtained by interpolation of the observed winds alone.

The 0BAN3D fields of temperature, moisture, height, and wind serve as basic fields from which an almost limitless number of quantities can be derived for the various PACE meteorological tasks. These include covariates for the evaluation, predictor variables and diagnostic variables for forecasting and monitoring purposes.

The following sections describe the 0BAN3D analyses for temperature, moisture and height. Several analytical height-wind relationships (geostrophic and gradient wind approximations) were investigated and found to be unsatisfactory for the subsynoptic motion scales. A general variational method that meshes the winds and heights through the primitive equations is being developed **and will** be described at a later time.

A Nonlinear Vertical Coordinate. In order to maintain dynamical consistency for the variational meshing phase of OBAN3D, the vertical layers of grid surfaces are defined by a coordinate system that varies as a function of the earth's surface elevation (Phillips, 1957). A sigma coordinate system that is linear in pressure has been extensively used in variational objective analysis models (Achtemeier, 1975; 1978; 1979). It is this experience with the sigma coordinate that has led to the adoption of a vertical coordinate that is nonlinear in pressure. This new coordinate system relates σ to pressure by

$$p = \sigma \, (p_\ell - p_u) + p_u + \sigma^N \, (p_s - p_\ell). \qquad (1)$$

When N=1, (1) reduces to the linear form, viz,

$$p = \sigma \, (p_s - p_u) + p_u. \qquad (2)$$

In these equations, p. is a reference pressure set equal to 1000 mb, p is the pressure at the top of the atmospheric volume to be analyzed (for PACE, p = 100 mb), and p is the surface pressure (not sea level pressure).

The nonlinear term of (1) restricts the influence of the surface elevation on the coordinate surfaces to the lower one half of the analysis volume.

Figure 1 shows the height variations within a 7-level sigma coordinate system for N=1 (dashed lines) and N=6 (solid lines). The upper boundary is the 100 mb pressure surface and the lower boundary follows the surface physiography which includes a primary mountain extending to 800 mb (1930 m) and a secondary mountain extending to 900 mb (870 m). The U.S. standard atmosphere was used to determine the pressure-height relationship.

The percentages of surface physiography retained at each sigma-level are also shown. When sigma varies linearly with pressure (N=1), the physiographic influence at the interior levels ranges from 51% to 91%. By contrast, the

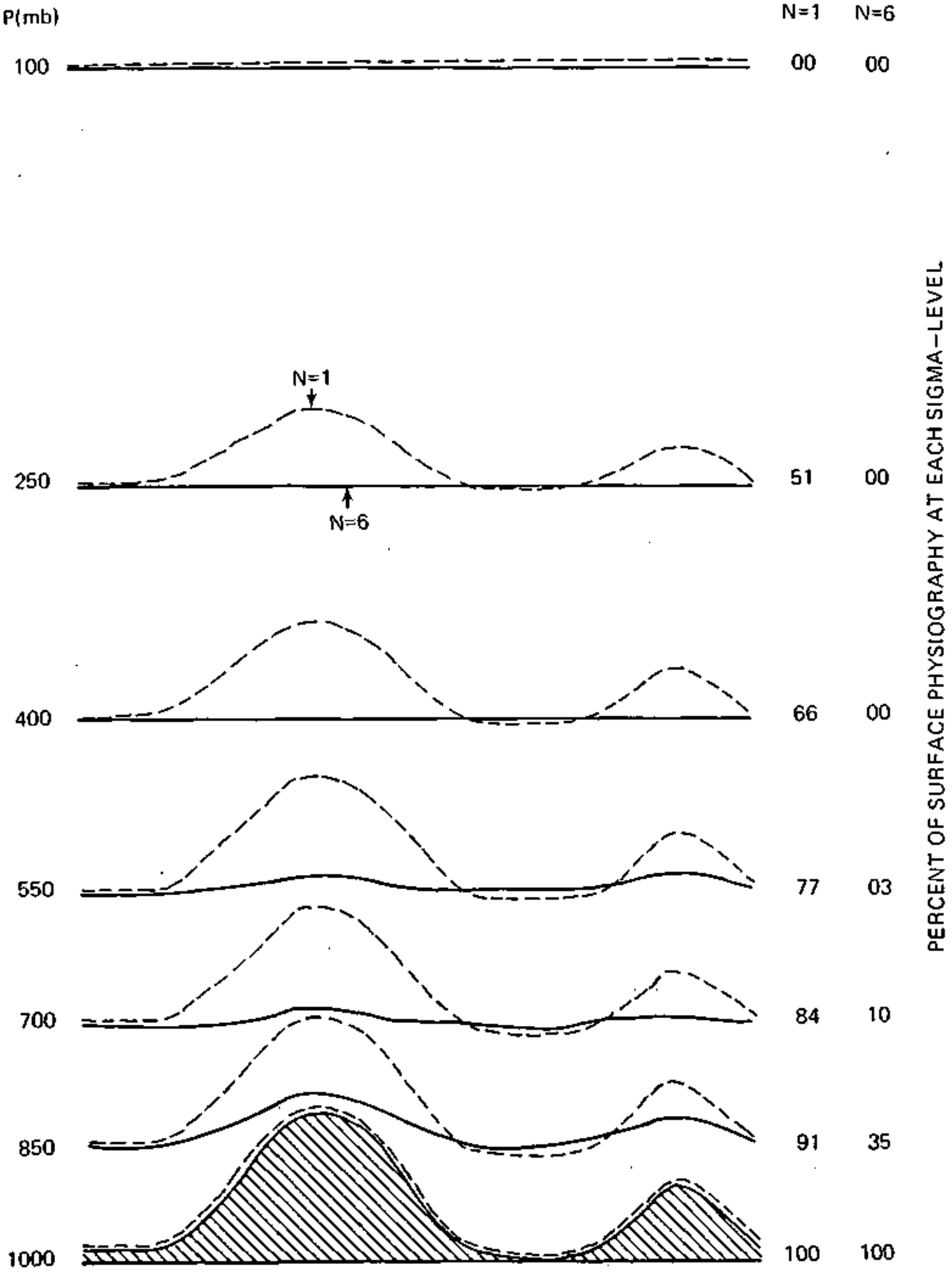

Figure 1. Schematic of a seven layer sigma model showing height variations for the linear (dashed lines) and nonlinear (solid lines) vertical coordinate.

surface influence does not extend above 500 mb for N=6. Only 3% of the surface physiography is retained at 550 mb and this increases to only 35% at the first sigma-level above ground.

There are several advantages to the nonlinear vertical coordinate system. First, as is shown in Figure 1, the nonlinear coordinate surfaces are aligned more realistically with the actual flow. Observed influences of surface physiography normally do not extend with large amplitude to such great heights. Second, if the vertical shear of the horizontal wind is large, local wind maxima can be introduced where the coordinate surfaces extend to high elevations. Objective interpolation partially smooths these out leaving convergence/divergence dipoles which cannot be compensated by the coordinate transformation terms of the continuity equation. Third, the removal of the terrain influence at upper levels eliminates the development of small differences between two large pressure gradient terms with opposing signs in the variational part of OBAN3D. Fourth, at levels above 500 mb, there is no need for additional interpolations to present results on constant pressure surfaces for viewing because the fields are already available on constant pressure surfaces.

Vertical Interpolation to Grid Columns. OBAN3D interpolates thermodynamic data along local isentropic surfaces to develop objective soundings at each grid column. This procedure requires the temperatures and pressures at significant levels as initial input. At each significant level, the pressures and temperatures are converted to pressures and potential temperatures through the Poisson equation

$$\theta = T\ (1000/p)^{r} \tag{3}$$

where r=1.4.

A scanning routine selects the nearest seven rawinsonde stations for each grid point and assigns them a distance-dependent exponential weight which also varies with the average distance between the stations and the grid point (Achtemeier <u>et al</u>., 1978). Once the seven stations are found, the maximum and minimum potential temperatures are determined for the set and each sounding extended above 100 mb or below ground according to its lapse rate until all seven stations have the same maximum and minimum potential temperature. If the boundary layer lapse rate is adiabatic or superadiabatic, the pressure level of the minimum potential temperature is arbitrarily set at 2000 mb.

Beginning with the coldest even potential temperature greater than or equal to the minimum potential temperature, the pressures that correspond to the potential temperature are interpolated to the location of the grid point. This is done at 2 K intervals up to the maximum potential temperature. The result of this isentropic interpolation is a detailed sounding in pressure and potential temperature at the grid point location. The interpolation was done once using the distance-dependent weights for the seven stations. There were no corrective passes.

A schematic illustration of this phase of the OBAN3D interpolation (Figure 2) shows the creation of a pressure-potential temperature sounding at the grid point i, j from the soundings at two stations A, B. Pressures p. and p. (i=l, 8) have been interpolated along the potential temperature surfaces (dashed lines) to yield the pressures $p_a - p_h$ at the grid point. A stable layer at the levels 4-7 is shown preserved at the grid point location.

The final temperature interpolation step couples the grid point sounding with the nonlinear vertical sigma coordinate surfaces defined by (1). Grid point potential temperatures on the sigma surfaces are obtained from linear interpolation in pressure. The PACE analysis uses 19 sigma levels each corresponding to 50 mb intervals from the surface to 100 mb if the surface pressure is 1000 mb.

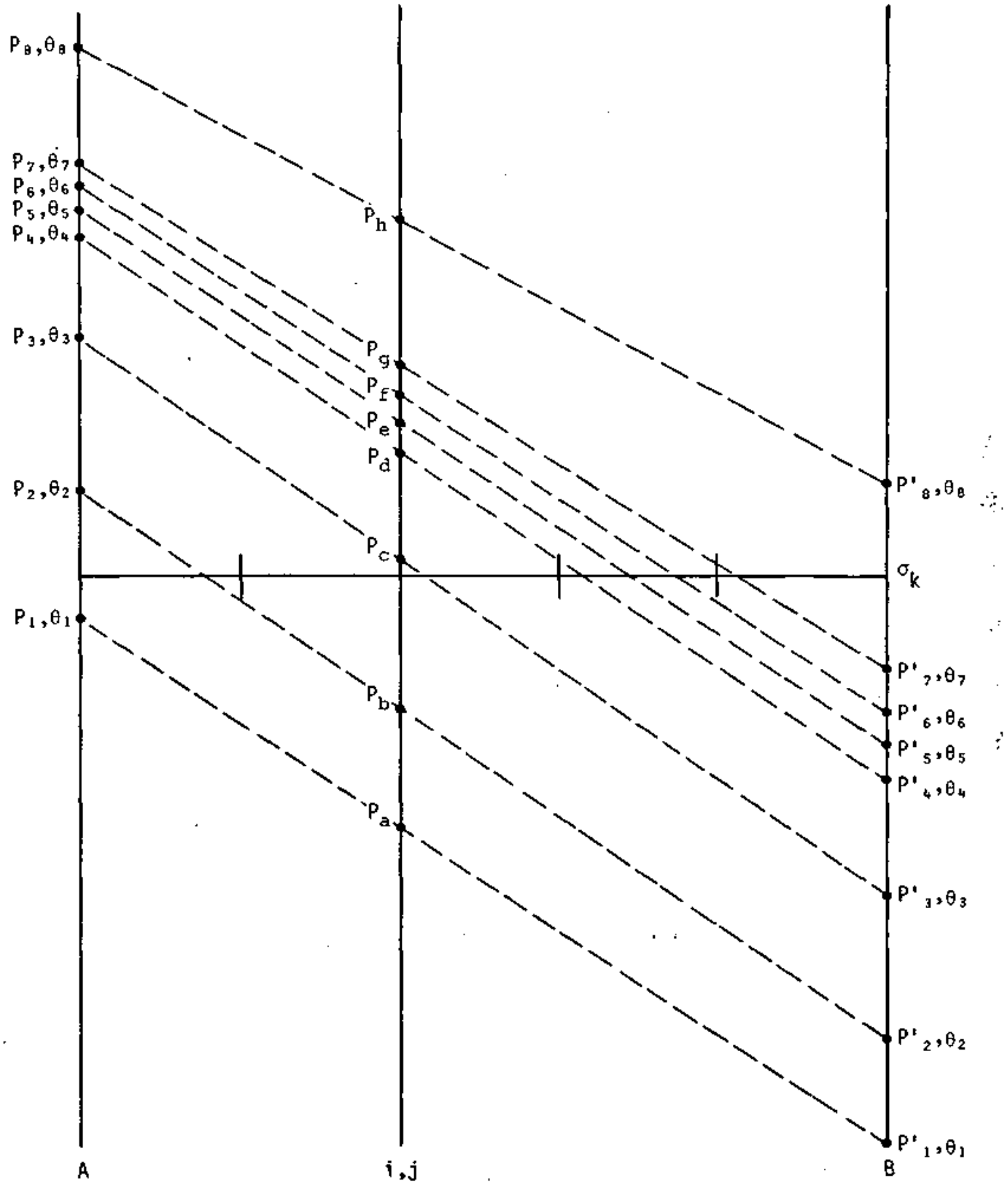

Figure 2. Illustration of isentropic interpolation between soundings A and B to develop a sounding in pressure and potential temperature at a grid point i, j.

OBAN3D Temperatures and Heights. The temperature fields are obtained by solving (3) for temperature. The isotherm spacing along the kth sigma surface (Figure 2) is proportional to the spacing of the intersections between the potential temperature surfaces and the sigma surface if the pressure along the sigma surface is constant from stations A to B. Thus, the stability zone bounded by the isentropic surfaces p'_4 θ_4 and p'_7 θ_7 has been projected onto the horizontal plane in the proper location and with the gradients preserved. Direct interpolation using only the temperatures at the intersections of soundings A and B with the kth sigma layer would have produced a linear temperature field.

The height field is constructed by vertical integration of the hypsometric equation (Hess, 1959) through the 19 sigma levels. The height field retains the spatial detail of the temperature field but ,is subject to slightly different heights than would be obtained hydrostatically using significant level temperatures. To correct for this, a successive corrections objective analysis was used (Achtemeier et al., 1978). This analysis uses the analytical heights as first guess fields, and one pass to correct toward the observed heights. The resulting height fields correspond closely with the observed heights and retain the spatial detail introduced through the isentropic temperature analyses.

The Moisture Analysis. The moisture analysis for PACE proceeds upon the assumption that air tends to flow along isentropic surfaces. Temperature-dew point departures, which express the moisture content of the air are interpolated along the 2°K potential temperature surfaces to give detailed moisture soundings at grid point locations. Temperature-dew point departures are found at sigma surfaces by linear vertical interpolation in pressure.

Examples of 0BAN3D Moisture and Temperature Analysis. Pre-production objective analyses of moisture and temperature have been using the PACE upper air data set. These runs have been useful for debugging OBAN3D and for finding the errors described previously. Some examples of the spatial detail found in these analyses are given in Figures 3 and 4. Figure 3 shows the analysis for the temperature-dew point departures at 1200 GMT, 1 June 1973, at level 4; approximately 850-800 mb with lower pressures along the left hand (west) edge of the grid which extends through the plains from Texas and South Dakota. The dots locate rawinsonde sites. The analysis identifies a zone of strong temperature-dew point departure gradient (arrows). The moisture gradient is the eastward boundary of a dry airmass that had apparently been drawn northeastward over moist surface-layer air.

In this area, the isentropic surfaces sloped downward to the west and the sigma surfaces, following surface elevations, sloped upward to the west. The sharp vertical moisture gradients at the two rawinsonde sites just east of the temperature-dew point departure gradient were projected into the horizontal field along the isentropic surfaces that intersected the sigma surface.

Figure 4 shows how the OBAN3D preserved a synopitc scale baroclinic zone (arrows) within an area of variable station density. The increased resolution of thermal fields will enable the representation of sub-synoptic scale wind systems such as jet streaks. Phase 2 of 0BAN3D, the variational analysis of the wind field, will develop dynamically consistent vertical velocity fields that accompany these middle tropospheric systems that act to release convective instability.

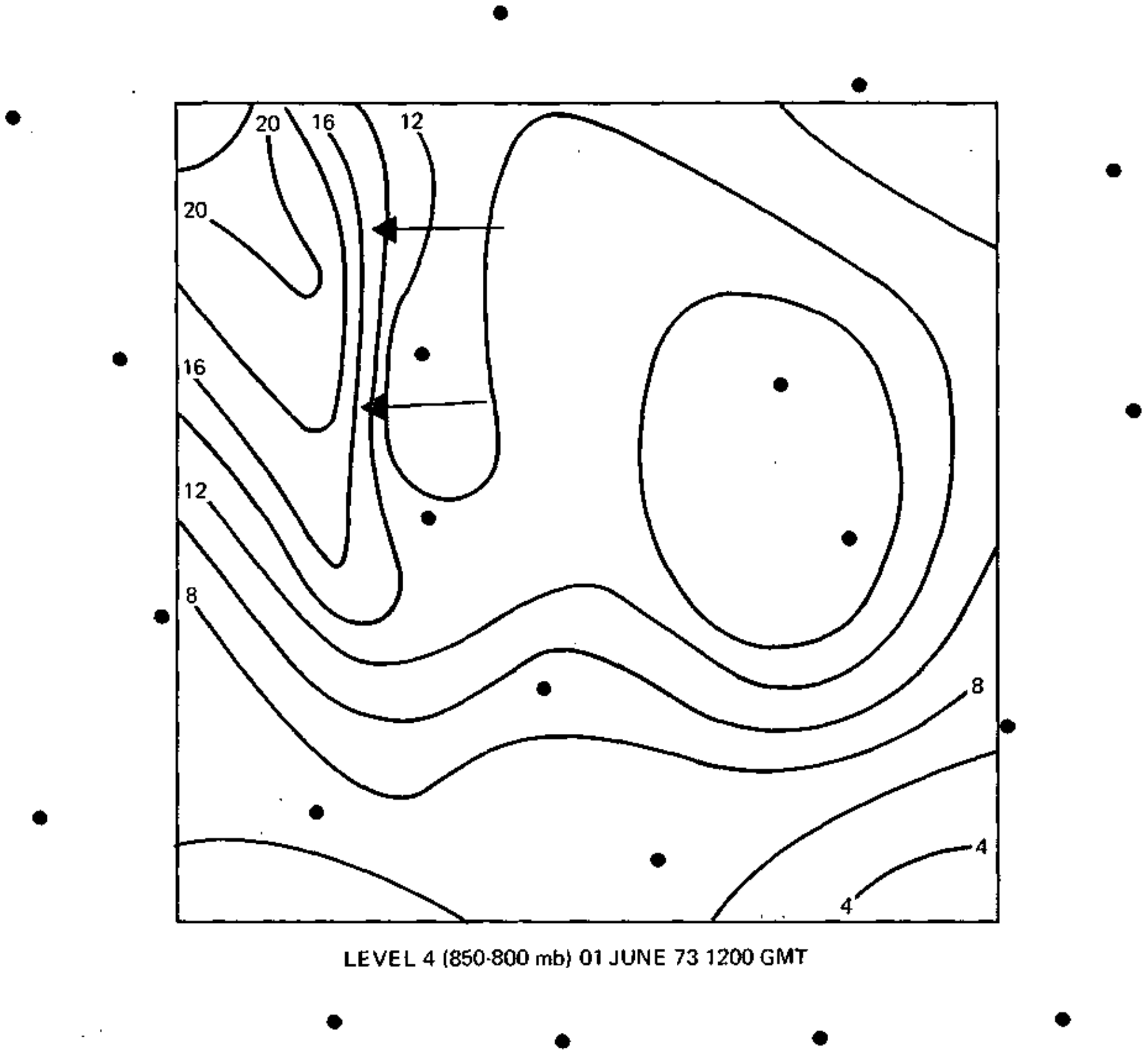

Figure 3. OBAN3D analysis for the temperature-dew point departure at level 4 for 01 June 1973 at 1200 GMT.

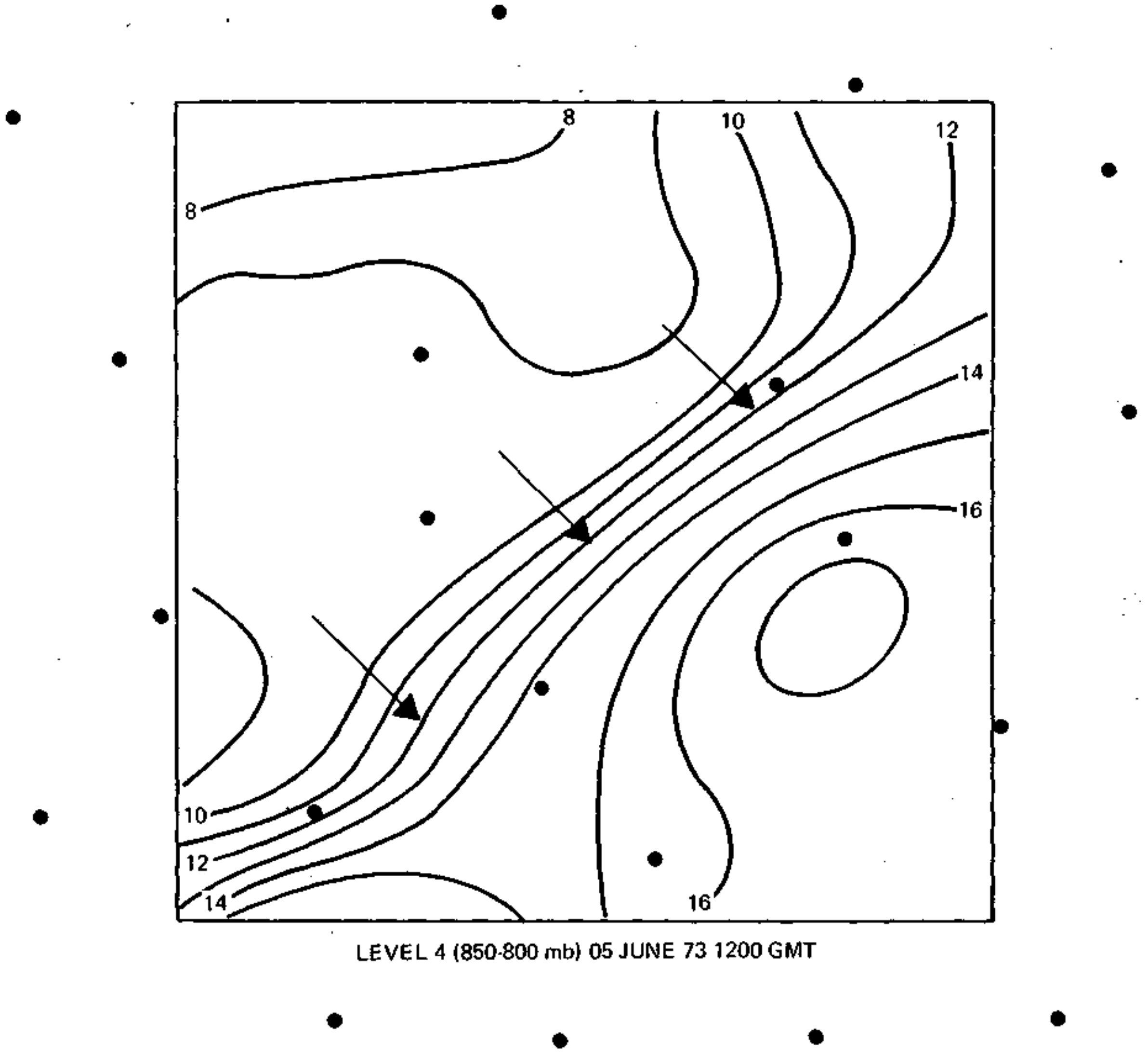

Figure 4. OBANB3D analysis for the temperature at level 4 for 05 June 1973 at

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APPENDIX A

REPORT, PAPERS AND TALKS RELATED TO PACE

Publications

Review of Illinois Summer Precipitation Conditions. Stanley Changnon and Floyd Huff, Bulletin 64 of State Water Survey, 160 pages, 1980.

Economics of Weather Modification. Steve Sonka, State Water Survey Report of Investigation 89, 57 pages, 1979.

Spatial and Temporal Correlations of Precipitation in Illinois. Floyd Huff, State Water Survey Circular 141, 14 pages, 1979.

"Measurment of Convective Mean Rainfall over Small Areas using High Density Raingages and Radar." Peter Hildebrand, Neil Towery, and M. Snell. Preprints 7th Conference on Inadvertent and Planned Weather Modification, pages 126-127, October 1979.

"Assessment of Weather Modification Potential for Alleviating Agricultural Droughts in the Midwest." Floyd Huff, Journal of Weather Modification, 11, 28-50, 1979.

"History of Planned Weather Modification Activities and Research at the' Illinois State Water Survey." Stan Changnon, Journal of Weather Modification 11, 156-165, 1979.

"A Midwest Weather Modification Experiment Designed for Agricultural." Preprints Conference on Agricultural and Forest Meteorology, 4 pages, April 1979.

"Hygroscopic Seeding of Convective Clouds." Preprints 7th Conference on Inadvertent and Planned Weather Modification, 6 pages, D. B. Johnson.

"Evaluation of Operational Objective Streamline Method", Monthly Weather Review, G. L. Achtemeier.

Talks

In addition to the above publications, several talks were presented by staff members concerning PACE. Stanley A. Changnon presented talks about PACE at the North America Interstate Weather Modification Council Meeting in Minnesota, at the Cooperative Economic and Marketing Research Conference in

Central Illinois, at the University of North Dakota, at the Annual Conference of Vegetable and Fruit Growers in Illinois, and at the University of Nebraska. Staff members gave testimony concerning PACE at three hearings in various parts of Illinois during February and March 1980. Richard Semonin gave a talk concerning PACE and weather modification at the Convective Cloud Workshop in Colorado in May 1979. Dave Johnson gave a talk concerning PACE at a seminar at the University of Illinois, and C. F. Hsu gave a talk relating to statistics in PACE at the Annual Meeting of the American Statistical Association at Washington in August 1979.