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Applied Climatology Research: Miscellaneous Papers

Illinois State Water Survey
2204 Griffith Drive
Champaign, Illinois 61820-7595

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APPLIED CLIMATOLOGY RESEARCH: MISCELLANEOUS PAPERS

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CONTENTS

APPLIED CLIMATOLOGY RESEARCH OF THE ILLINOIS STATE WATER SURVEY

This report consists of a series of papers presented at several American Meteorological Conferences held at Salt Lake City, Utah during September 9-13, 1991. In total, the Illinois State Water Survey (ISWS) staff presented 11 papers at the Seventh Conference on Applied Climatology, 2 papers at the Twentieth Conference on Agricultural and Forest Meteorology, and 1 paper at the Special Session on Hydrometeorology. Seven of these papers report on research supported by the Midwestern Climate Center. These papers illustrate the spectrum of research being pursued by ISWS scientists in the Applied Climatology Program.

The Applied Climatology Program of the ISWS can be categorized as follows:

- **Agricultural Meteorology** - evaluation of the sensitivities of Illinois and midwestem agriculture to weather and climate

- **Climate Impact Assessments** - impacts of midwestern climate fluctuations on socioeconomic activities

  Climate System Investigations - studies of the fundamental spatial and temporal characteristics of Illinois and midwestem climate

- **Climate Services** - provision of climate information to outside users and the development of new information products

A brief description of each paper as it relates to the above categories follows.

Agricultural Meteorology

"Operational Large Area Corn and Soybean Yield Estimation" by Kenneth E. Kunkel and Steven E. Hollinger discusses work attempting to use crop development models (CERES-Maize and SOYGRO) to make real-time assessments of potential yield outcomes. The models are able to simulate about half of the interannual variability in yields. The models have been used in an operational mode for the 1989, 1990, and 1991 growing seasons.

"Response of Com Yield Components to Simulated Precipitation Augmentation" by Steven E. Hollinger and Stanley A. Changnon presents the results of field experiments in which com plots under shelters were subjected to a wide range of precipitation conditions over several growing seasons. There are many interesting results showing how com yields react to varying amounts of precipitation.

Climate Impacts

"Impacts of a Climatologically-Unique Year (1990) in the Midwest" by Stanley A. Changnon and Kenneth E. Kunkel summarizes the socioeconomic impacts of climate fluctuations in 1990. It illustrates the types of climate impact information that can be gathered in a near real-time mode.

"Identifying Climate Variables That Are Important for Forest Growth and Health" by James R. Angel, Michael B. Richman, and Peter J. Lamb discusses the results of a workshop hosted by the ISWS to address the issue of what parameters and processes should be considered in climate studies that relate to U.S. forests.

"Relations Between Thunder Reports and Cloud-to-Ground Lightning Flashes from Lightning Networks" by Stanley A. Changnon presents the results of a study seeking to define the space and time relationships between thunderstorms and cloud-to-ground lightning flashes in the United States. This study has applications to the assessment of lightning threat to structures.

Climate Services

"Potential Wind and Solar Power Resources in Illinois" by Beth C. Reinke and Steven E. Hollinger discusses the development of a computer-based climate atlas illustrating wind and solar power resources in Illinois. This atlas, designed to run on an IBM-compatible PC, includes tabular, graphical, and map products.

"Operational Climate Information Dissemination: Products, Problems, and Progress" by Kennedi E. Kunkel, Stanley A. Changnon, Carl Lonnquist, and Mary Schoen Petersen discusses the Midwestern Climate Center's experience in operating a real-time on-line climate information system. It discusses some of the problems that have been encountered and solutions that have been arrived at in response to these problems.

"Implementation of a Semi-Physical Model for Examining Solar Radiation in the Midwest" by Mary Schoen Petersen, Kenneth E. Kunkel, and Peter J. Lamb discusses a special data set of daily solar radiation values that have been estimated from hourly surface observation data. These data area being used in certain operational applications by the Midwestern Climate Center. A trend analysis of these data indicates that significant changes in solar radiation values have occurred in some seasons in the Midwest. In particular, there has been a downward trend in solar radiation values during mid-fall over the last 40 years.

Climate System Investigations

"Estimations of a Changed Climate on Heavy Rainfall Frequencies" by Stanley A. Changnon and Floyd A. Huff discusses the possible effects of changed climate on the magnitude of extreme rainfall events. The magnitudes of extreme rainfall events during past warm periods were examined. Significant changes were found compared to present-day climatology.

"Extreme Precipitation Events: The Link to Temporal Variability in Seasonal Precipitation" by Kenneth E. Kunkel, Stanley A. Changnon, and Robin T. Shealy examines the relationship between the frequency of occurrence of extreme rainfall events and longer term climate anomalies. The frequency of extreme events did not appear to be tied strongly to longer term climate anomalies. The extreme precipitation events were also found to account for about half of the longer term variability in seasonal precipitation.

"Development of New Rainfall Frequency Relations for Nine Midwestern States" by James R. Angel and Floyd A. Huff is an update of the Weather Bureau's Technical Paper 40, which presents the expected frequencies and magnitudes of extreme precipitation events. These updated results can be used by engineers and hydrologists in designing water control structures.

"Soil Moisture/Evaporation/Precipitation Feedback: A Case Study of the 1988 Drought" by Kennedi E. Kunkel, Steven E. Hollinger, and Felix N. Kogan (National Oceanic and Atmospheric Administration) discusses the results of a study using a wide variety of data to estimate the potential changes in the atmospheric water vapor budget due to modifications of the surface energy budget during the 1988 drought. The analyzed data included field measurements, model estimates, and satellite measurements.

General

"Applied Climatology: Atmospheric Sciences' Biggest Success Story Faces Major New Challenges" by Stanley A. Changnon was the talk given at the conference banquet. This paper discusses some of the major advances and some of the future challenges in the field of applied climatology.

OPERATIONAL LARGE AREA CORN AND SOYBEAN YIELD ESTIMATION

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1. INTRODUCTION

In earlier work, Duchon (1986) suggested the use of CERES-Maize to make corn yield predictions using climate data as input to the model. He used the current year's daily weather to the current date and completed the growing season with data from selected historical years to make the yield prediction. This approach produced a probability distribution of possible yield outcomes. Hodges et al. (1987) used CERES-Maize to simulate midwestern U.S. corn production for the period 1982-1985 using climate data from 51 stations. Our work extends these research-oriented efforts in that we have implemented this model and a similar model for soybeans (SOYGRO) in an operational setting with the information being available to agribusiness and other subscribers (Kunkel et al., 1990). Because this information is being used in every day decision-making, we have been careful to ensure that implementation of these models provides a reasonably good fit to the USDA estimates of yields for the recent past

The area of study is the nine-state region of Illinois, Indiana, Iowa, Kentucky, Michigan, Minnesota, Missouri, Ohio, and Wisconsin. This area accounts for about 70% of the U.S. production of both corn and soybeans. The yield estimates are made on a crop reporting district (CRD) scale. Yield estimates were made only for CRD's with at least 40,000 hectares of production.

2. APPROACH

The CERES-Maize and SOYGRO models (Jones and Kiniry, 1986; Wilkerson et al., 1983) require a set of varietal coefficients, a set of soil characteristics, daily weather data, and certain other information such as planting date, depth, and density. Each crop reporting district was assigned a representative soil type (Kunkel, 1990).

Daily values of precipitation, maximum and minimum temperature, and solar radiation were obtained from the National Weather Service's (NWS) cooperative observer network. Solar radiation was estimated using the method of Meyers and Dale (1983), which utilizes hourly cloud cover, humidity, and air temperature observations. These estimates of solar radiation, along with the hourly observations of wind speed, humidity, and air temperature, were used to estimate daily potential evaporation (Kunkel, 1990).

The United States Department of Agriculture's (USDA) estimates of corn and soybeans yields by crop reporting district for the period 1979-1990 were used as data sets for model calibration and testing purposes. This period is a highly variable one with several severe Midwestern droughts (most notably 1980, 1983, and 1988) causing significant reductions in yields. There were also several years of record or near record yields (1982, 1985, 1986, 1987).

The calibration process consisted of a sensitivity analysis of the model to determine which agronomic and soil variables had the largest effects on yields. Optimum values of the most sensitive input variables were chosen by comparing modeled and observed yields. Correlation coefficients and linear regression coefficients between modeled and observed yields were calculated for each CRD. Finally, an independent test was run for the 1979-1990 period to test the accuracy of the adjusted modeled yield values.

The sensitivity tests revealed that the modeled yield variability was relatively insensitive to reasonable ranges in all of the input variables with the exception of potential plant available water (PPAW). This was varied by changing the maximum rooting depth. To determine the optimum maximum rooting depth in each CRD, model yields were generated for the 1979-1990 period using maximum rooting depths over a range of 0.50 m - 2.00 m. These simulations provided modeled yields for a wide range of PPAW values for each CRD. The maximum rooting depth producing the highest correlation between modeled and observed yields in each CRD was used in all subsequent model runs. Maximum rooting depths throughout the region ranged from 1.00 m to 1.50 m with the majority of CRD's having a maximum rooting depth of 1.25 m.

Model yields were generally well correlated with observed yields ($r > 0.6$); however, a 10-30% bias was observed in the modeled yields with the modeled yields being greater than the observed The bias is due in part to assumptions of optimal management, uniform soil throughout the region, and no pests or fertility problems. These assumed conditions do not exist in the real world; therefore, observed yields will be reduced more as the real world deviates more from the assumed conditions.

In addition to the systematic overestimation of yields by the models, the year-to-year modeled yields showed a greater variation than that observed in the USDA yields (Table 1). The larger variance in the modeled yields was

Table 1. Summary comparison of model and USDA yields (Mg/hectare).

	Corn		Soybean	
	USDA	Model	USDA	Model
Mean	6.6	8.2	2.1	2.3
S.D.	1.4	2.4	0.4	0.8
Max.	9.5	13.2	3.1	3.8
Min.	1.8	0.0	0.2	0.1

due to both a larger range in yields across the region through time and a greater interannual variability within CRD's.

The systematic bias revealed by the comparison between model and actual yields was removed by using the 1979-1990 calibration period to derive a linear correction factor using least-squares analysis. A time dependence was included in the relationship for corn because it was observed that the difference between modeled and observed yields was not constant but varied systematically with time, presumably the result of improvements in varieties. This same temporal dependence was not observed with soybeans.

The procedure to adjust model yield values with a linear correction was tested by sequentially estimating model yields for each year with a linear correction factor calculated by excluding the year being estimated. For example, yields for 1990 were estimated using regression coefficients calculated from model and observed yields for 1979-1989. This process was performed 12 times with each year of the 1979-1990 period being excluded from the linear regression analysis; the resulting coefficients were then used to estimate yields for the excluded year. Subsequently, the CRD model yields were combined, with an acreage weighting factor, to provide a regional yield estimate. Figure 1 gives a comparison between the model estimates and USDA estimates of actual yield for corn and soybeans for the nine-state Midwestern region.

The root-mean-square errors between modeled and measured values were 0.5 Mg/hectare for corn and 0.08 Mg/hectare for soybeans. However, there were a few years in which the comparison was considerably worse. For corn, errors of 0.8-1.0 Mg/hectare are present in 1983 and 1987. In 1983, actual yields were sharply reduced by a brief, but intense period of heat and dryness in July that coincided with the reproductive phase of corn. In the model, yields were reduced somewhat by moisture stress, but reductions were modest because large soil moisture values were present before the dry period began, the result of abundant late spring and early summer rains. In 1987, a dry summer reduced model yields due to soil moisture stress, yet surprisingly actual yields were not affected. Summer temperatures during 1987 were generally below the long-term average, particularly during the critical month of July. The model overestimate for the hot 1983 summer and the underestimate for the cool 1987 summer may be indicative of an improper temperature sensitivity in the model. For soybeans, the largest difference (0.20 Mg/hectare) occurred in 1988, the model yields being significantly higher. The reason for this discrepancy is not obvious.

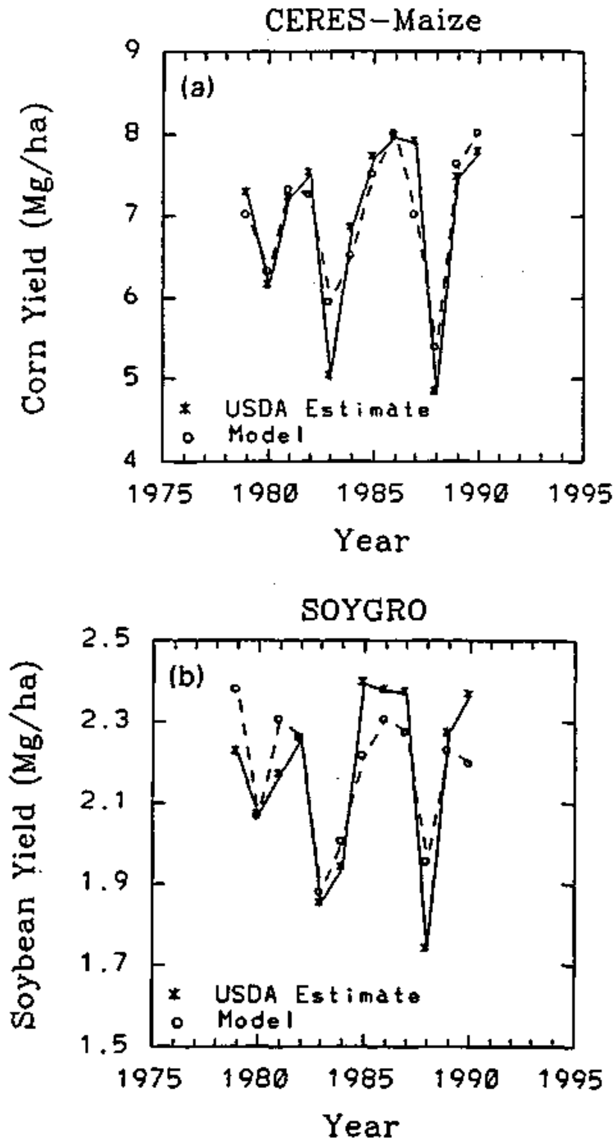

Figure 1. Comparison of regional average yields by CRD from observations and from the model with a linear correction applied for a) corn yields from CERES-Maize, and b) soybean yields from SOYGRO

3. WEATHER SENSITIVITIES

The relative sensitivities of the USDA yield estimates and the CERES-Maize and SOYGRO models to the weather variables can be examined by plotting the yield estimates as the dependent variable and the weather variables as the independent variables. These plots (not shown) revealed no predominant curvilinear relationships between the weather variables during various periods of the growing season and the modeled or USDA yield estimates. Therefore, we computed the linear relationship between each of the weather variables and the model yield (determined with a variable rooting depth) and the USDA yield estimates. The slopes and the coefficients of variation for these regressions are shown in Table 2 for corn and Table 3 for soybeans.

Table 2. Relationship between unadjusted modeled corn yields (Mg/hcctarc) and observed USDA yields with weather during the periods of May, June 1 • July 15, July 16 - July 31, and August.						
	Weather Variable					
	Max Temperature		Min. Temperature		Solar Radiation	
	USDA	Model	USDA	Model	USDA	Model
May						
Slope	0.02	-0.28*	0.12	-0.15*	-0.05	-0.46*
R^2	0.00	0.09	0.03	0.02	0.00	0.12
June 1 • July 15						
Slope	-0.25	-0.79*	-0.00	-0.36	-0.29	0.77*
R^2	0.12	0.40	0.00	0.08	0.10	0.24
July 16 • July 31						
Slope	-0.24	-0.56*	-0.11	-0.40*	-0.11	-0.41*
R^2	0.17	0.29	0.03	0.11	0.04	0.19
August						
Slope	-0.33	-0.68*	-0.32	-0.73*	-0.17	0.49*
R :	0.37	0.52	0.22	0.37	0.11	0.29

• indicates a difference in the actual crop yield and the model yield response to the weather variables. The differences are significant at α = 0.002, single tail t-test.

Table 3. Relationship between unadjusted modeled soybean yields (Mg/hcctarc) and observed USDA yields with weather during the periods of May, June 1 • July 15, July 16 - July 31, and August.						
	Weather Variable					
	Max. Temperature		Min. Temperature		Solar Radiation	
	USDA	Model	USDA	Model	USDA	Model
May						
Slope	0.00	0.08	0.01	0.13*	0.00	0.0S
R'	0.00	0.04	0.00	0.09	0.00	0.03
June 1 - July 15						
Slope	-0.07	-0.06	-0.02	005	-0.05	-0.30*
R^1	0.12	0.02	0.01	0.01	0.04	0.24
July 16 - July 31						
Slope	-0.05	-0.07	-0.02	0.02	-0.02	-0.11*
R^1	0.09	0.03	0.01	0.00	0.02	0.09
August						
Slope	-0.09	-0.13	-0.08	-0.10	-0.05	-0.13*
R^2	0.32	0.11	0.17	0.04	0.10	0.13

" indicates a difference in the actual crop yield and the model yield response to the weather variables. The differences arc significant at α = 0.002, single tail t-test.

The CERES-Maize model is more sensitive to each of the weather variables during each growth period than the USDA yield. This greater sensitivity would cause the observed increase in model yield variability vs. USDA variability. The analysis indicates a need to evaluate the temperature and solar radiation responses of the CERES-Maize model throughout the growing season. The temperature response during May for the model and USDA yields have opposite signs indicating a possible problem with the model during the early season. The response of the USDA yield estimates is not different from 0 for the maximum temperature and solar radiation during May, and the minimum temperature during the period June 1 to July 15.

The SOYGRO model does a better job of describing the relationship between temperature and yield. The only period where the slopes describing the temperature-yield response is significantly different is during May, when the model is too sensitive to the minimum temperature. The SOYGRO model shows a greater response to solar radiation and available soil moisture than the USDA yield estimates. These differences are similar to those seen in the CERES-Maize model.

The over-sensitivity of modeled yields to soil moisture could be the result of the method of parameterization of the soils of the region. Therefore, the errors may not be due to the model but to the accuracy of describing the rooting characteristics of the crop under different weather scenarios, as well as describing the water holding characteristics of the CRD soils.

Soybeans appear to be most sensitive to soil moisture and temperature during August, as seen by the largest coefficients of variations during this time period between the weather variable and USDA yield estimates. In this study, corn yields were most sensitive to temperature and soil moisture from July 16 through August.

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RESPONSE OF CORN YIELD COMPONENTS TO SIMULATED PRECIPITATION AUGMENTATION

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1. INTRODUCTION

Crop-weathcr regression relationships have been used frequently to estimate crop productivity under varying weather conditions. In Illinois, these models have shown that an increase in rainfall due to weather modification would result in increased returns for producers (Garcia ct a!., 1990). Such modeling relies upon spatially and temporally averaged historical data, and introduces uncertainties in the results. These models also fail to demonstrate the physiological response of the crop to the timing of enhanced rainfall (Changnon, et.al. 1989). Hence, we have sought, through field trials and controlled water applications, to define how various weather conditions and other management practices affect corn yields in Illinois.

Corn (Tea mays L.) yields are determined by a number of components that can be affected by management practices and weather at different times throughout the growth of the crop. The yield components include plant density, the number of kernel rows per ear, the number of kernels per row, and the kernel mass.

Plant density is determined to a great extent by the density of seeds planted. The density is modified to some extent by the soil moisture and temperature conditions during germination and emergence of the young plants. As plant density increases the yield of each plant will tend to decrease as the plants compete for water and nutrients. Generally, as plant density increases, yields over a large area will also increase. However, there is an optimum population above which higher plant densities begin to decrease area yields due to large reductions in the yields of individual plants. These yield reductions occur in the form of increased barrenness, reduced numbers of kernel rows per ear, reduced numbers of kernels per row, and reduced kernel mass.

The total number of kernels per plant (determined by the number of kernel rows per ear and number of kernels per row) and kernel mass can also be reduced by unfavorable weather during different parts of the growing season. For example, the number of kernel rows per ear is determined approximately 30 days after planting (Hollinger, 1981). Therefore, stresses due to weather and/or plant competition during this period may result in reduced numbers of kernel rows.

The potential total number of kernels per row, and thus the potential total number of kernels per car, is determined during the period beginning 30 days after planting until approximately 2 weeks after pollination. Before pollination, the plant is developing kemel primordia. The number of primordia developed determines the potential maximum number of kernels. If the plant experiences a stress during pollination the number of primordia fertilized will be reduced. Stress during the critical 2 weeks following pollination results in the abortion of kernels and a reduction in the number of kernels that mature (Grant et.al., 1989; Eck, 1986; Harder et.al., 1982).

During the grain filling period (2 weeks after pollination to maturity) the final mass of each kernel is bcine determined. Stress durine this period will not result in abortion of kernels, but will result in reduced kernel size which translates into reduced yields.

This paper reports the results of a 3 year study to determine the response of the various yield components to precipitation augmentation through weather modification. The yield increases experienced are related to the yield components to determine the growth period when precipitation augmentation is realized by the crop.

2. METHODS

Moveable shelters were used to preclude any natural rainfall from plots of corn during the summers of 1987, 1988, and 1989. Water to the crop was applied through a sprinkler system mounted in the moveable shelters that allowed the application of different amounts of water on each of the plots. Six rainfall treatments were applied to the 3x3m plots to simulate typical dry, normal, and wet summers and each typical year's rainfall augmented by 25% in central Illinois (Changnon and Hollinger, 1988). Totals of June, July, and August rainfall applied to represent the typical summers are shown in Table 1.

Corn (hybrid M017xB73) was planted on 28 May 1987 at a density of 83,980 plants/ha, 12 May 1988 at a density of 64,220 plants/ha, and 12 May 1989 and 26 May 1989 at populations of 64,220 and 83,980 plants/ha. Four rows at a spacing of 0.76m were planted in each plot. The crops were fertilized at normal recommended rates each year, and weeds removed from the plots by hand hoeing.

Table 1. Total June, July, and August rainfall applied to represent typical dry, average, and wet summers in cast-central Illinois.

Summer	Rainfall (mm)
Dry	160
Dry + 25%	200
Average	279
Average + 25%	349
Wet	381
Wet + 25%	476

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Table 2. Corn yield components and final yield for each rainfall and plant density treatment.

Yield Component	Rainfall (mm) 160	200	279	347	381	47S	Population Mean
Plant Dcnsity	65364	65.364	64.556	65,364	64,017	65,364	65.005
Banen Plants	1.346	808	1,346	1,613	808	808	1.121
Nubbins	3.498	4,308	3,228	1,077	808	2,151	2.511
Kernel rows/ear	15.0	15.4	15.0	15.7	16.0	15.8	15.4
Kernels/row	38.0	37.7	38.8	39.4	40.1	41.0	39.2
Kernels/plant	569.8	566.0	582.3	618.1	641.8	647.7	604.3
Kemel/weight (g)	0.283	0.289	0.296	0.296	0.300	0.299	0.294
Yield (mg/ha)	10.52	10.68	11.14	11.97	12.34	12.65	11.55
Plant Density	82,846	84,192	83,923	86,075	84.998	84,192	84.371
Barren Plants	7,800	7,262	10,759	6,993	4.303	3.498	6,769
Nubbins	8,608	7,262	5,380	5,380	1,882	3.498	5,335
Kernel rows/ear	12.6	13.1	12.7	13.3	14.8	14.4	13.5
Kernels/row	33.3	33.3	32.4	34.3	34.5	34.6	33.7
Kernels/plam	419.2	435.8	411.1	456.5	510.9	497.6	455.2
Kemet/weight (g)	0.243	0.246	0.247	0.245	0.243	0.245	0.245
Yield (mg/ha)	8.52	9.01	8.52	9.64	10.57	10.26	9.41

The center 2.4m of the 2 middle rows of each plot were harvested at maturity. The number of kernel rows per car and the number of kernels per row were counted. The total number of kernels per ear was computed by multiplying the number of kernel rows per car by the number of kernels per row. Kernel weight was determined by dividing the total weight of grain harvested from each plot by the total number of kernels in each plot.

3. RESULTS

Mean yields of the low plant density treatments (64,220 plants/ha) increased as the summer water applications increased (Table 2). The same trend of increasing yields occurs in the high plant density treatment (83,980 plants/ha), however, the increases are not as consistent as those observed in the low population. The stage of growth when water treatments affected final yield can be found by studying the yield components that comprise the final yield. The response of each yield component to the 6 rainfall treatments is also shown in Table 2. Plant density, number of barren plants, and number of plants with incompletely formed cars (nubbins) are expressed on a hectare basis. The number of kernel rows per ear was determined by computing the sum of the kernel rows per ear for each plot and dividing by the total number of plants in the plot (includes barren plants and plants with nubbins).

Plant density had the greatest effect on the various yield components. The higher plant density resulted in an increase in barrenness and number of nubbins, and a decrease in number of kernel rows per car, kernels per plant, and kernel mass". This effect is due to the increased plant competition for water, nutrients, and light at the higher plant densities.

Computing the car yield components (kernel rows per car and kernels per row) on the total plant population results in an underestimate of the actual number of kernel rows per car and kernels per row on fully fertile cars. The numbers of kernel rows per ear, number of kernels per row, and the number of kernels on the fertile cars are computed by dividing the number of kernels per plot less then number , of kernels contributed by the nubbins by the number of plants with fully developed ears (Table 3). The number of kernels per row on the fertile cars is slightly less than the number of kernels per row computed when the kernels on the nubbins are included.

Nubbins do not have any defined rows, therefore, in determining the number of kernel rows per car a nubbin was reported as having 0 rows and 'X' kernels, where X is the number of kernels on the nubbin. Therefore, the number of kernels rows per fertile ear (Table 3) is greater than the number of kernel rows per car reported in Table 2.

Barrenness, defined as plants with no ears on them and plants with only small nubbins as cars, decreased as water application increased regardless of population. The higher populations resulted in greater barrenness over all water application treatments. The fact that barrenness decreased with increasing water application indicates that the plants in higher populations and lower water application treatments were competing for the available water. Therefore, one benefit of precipitation enhancement by weather modification is healthier plants resulting in decreased barrenness.

The number of kernels per fertile plant increased with increased water application in the low plant density treatment (Table 3). This increase in the number of kernels is due to a corresponding increase in the number of kernels per row. The increase in kernels per row indicates that the

Table 3. Number of kernel rows per car, number of kernels per row on the fertile ears, and the number of kernels per nubbin.

Yield Component	Rainfall (mm) 160	200	771	349	381	475	Population Mean
		Low Plant Density					
Kernel rows/ear	16.2	16.3	16.1	16.3	16.3	16.5	16.3
Kernels/row	37.7	37.4	38.6	39.5	40.3	41.0	39.1
Kernels/plant	611.5	609.9	622.2	643.6	657.7	675.9	636.8
Kernels/Nubbin	69.5	56.8	82.0.	57.7	51.7	72.7	64.6
		High Plant Density					
Kernel rows/ear	15.7	15.8	15.7	15.5	16.0	15.7	15.7
Kemels/row	32.8	32.6	32.2	34.0	34.3	34.4	33.4
Kernels/plant	515.5	515.5	504.9	526.9	549.2	539.4	525.2
Kernels/Nubbin	56.1	107.0	51.3	85.1	76.5	72.9	75.4

response to the increased rainfall occurred during the period of silking to 2 weeks following silking.

The number of rows per car is determined when the plant is between the 5 to 10 leaf stage of growth (approximately 30-40 days after planting). During this early growth stage soil moisture is usually not a limiting factor in cast-central Illinois and the plants arc small enough that competition for sunshine is insignificant at the lower plant density treatment. The reduced number of kernel rows per car in the higher plant density treatments indicated that at these populations, there was some competition occurring for nutrients or sunshine. It is not likely that water was limiting during the early growth stages, because the number of kernel rows per ear are relatively constant across the rainfall treatments.

The different planting dates results in the application of different water amounts during the various growth cycles. Therefore, the data may provide some insight into the effect of water applications during different growth stages. The water application for cach growth stage was determined by computing the growth stage intervals using the modified growing degree day method (Cross and Zuber, 1972) and the estimates of the growing degree days necessary to reach the various growth stages (Table 4). The amount of water applied to the crop during each stage was determined by summing the water applied during the growth stage.

The effect of different water application amounts on corn ear yield components was determined by creating a linear correlation table (Table 5). All yield components were positively correlated with the quantity of water applied during the tassel initiation to ear initiation growth period. Vegetative mass was positively correlated with water application throughout the season. Final yield was negatively correlated with water application from planting to tassel initiation, and positively correlated with water application during all the other growth periods except for the growth period between car initiation and the end of row set.

The number of kernel rows per ear was positively correlated with the water application during the tassel initiation to car initiation growth period and the period from the end of row set to silking. The later correlation is due to the high positive correlation between the amounts of water applied during the period from tassel initiation and car initiation and the period from end of row set to silking. Because the number of rows is determined by the "end of row set" the significant correlation between the amount of water applied during the period from end of row set to silking and the number of kernel rows per ear is a spurious correlation and docs not have any physiological significance.

Table 4. Growing degree days required to complete the various corn growth stages (Adapted from Hollinger, 1981).

Stage	Growing Degree Days
Planting to Tassel Initiation	311
Tassel Initiation to Ear Initiation	81
Ear Initiation to End of Row Set	144
End of Row Set to Silking	208

Water amounts applied during the growth period from planting to tassel initiation were negatively correlated with the number of kernels per row and kernel mass. The number of kernels per row was positively correlated with the quantity of water applied during the tassel initiation to ear initiation, end of row set and silking, and silking to August 31 growth periods. It is impossible to determine which periods have the most effect on the number of kernels per row because of the high correlations of water application amounts during the various growth periods.

The effects of enhanced rainfall through weather modification on final yield can be further evaluated by studying the changes in the components that contribute to the actual final yield (mass and number of kernels per fertile plant, and mass and number of kernels per nubbin), and those components that reduce the final yield from a potential maximum yield. Maximum potential yield is the product of the total number of plants, the number of kernels per fertile car, and the measured kernel mass for each treatment. The effects of the rainfall treatments on barrenness and number of nubbins and the associated yield reductions are shown in Table 6. At the lower plant densities, increasing the typical summer rainfall by 25% in dry years reduced the barrenness, while increased rainfall in the average and wet summer rainfall treatments tended to cither increase or not change barrenness. At the higher plant densities, barrenness was reduced by increasing the rainfall by 25% during dry, average and wet summers.

The number of nubbins decreased in the average summer with increasing rainfall, while the increase in rainfall in the dry and wet summer treatments resulted in

Table 5 Correlation table of water applications between different corn growth stages and yield components.

	Water Application During Growth Stage					Yield Component				
	Plant to Tassel Init. S1	Tassel Init. to Ear Init. S2	Ear Inn. to End of Row Set S3	End of Row Set to Silking S4	Silking to Aug 31	Number Rows/ Ear R/E	Number Kernels/ Row K/R	Mass of Kernels KM	Vegetative Mass VM	Grain Yield YLD
S1	1.000	-0.212*	0.438*	-0.086	0.192*	0.053	-0.532*	-0.570*	0.324*	-0.456*
S2		1.000	0.387*	0.906*	0.728*	0.187*	0.590*	0.468*	0.395*	0.636*
S3			1.000	0.514*	0.881*	-0.096	-0.026	-0.158	0.584*	-0.007
S4				1.000	0.826*	0.315*	0.562*	0.439*	0.505*	0.659*
S5					1.000	0.001	0.290*	0.147	0.590*	0.310*
R/E						1.000	0.231*	0.028	0.275*	0.560*
K/R							1.000	0.744*	0.102	0.713*
KM								1.000	-0.036	0.597*
VM									1.000	0.405*
YLD										1.000

*Significantly different from 0 at $\alpha = 0.05$

Table 6. Effeets of enhanced precipitation on yield components and their contribution to final yield during typical dry, average, and wet summers. Numbers in the table have units of Mg/ha. (Note: Negative numbers indicate yield decreases and positive numbers indicate yield increases.)

	Rainfall Treatment								
	Dry	Dry +25%	Diff	Avg	Avg +25%	Diff	Wrt	Wet +25%	Diff
Low Plant Density									
Yield Potential	11.31	11.52	+0.21	11.89	12.45	0.56	12.63	13.21	038
Barrenness	-0.23	-0.14	0.09	-0.25	-0.31	-0.06	-0.16	-0.16	0.00
Nubbin number	-0.54	-0.69	-0.15	-0.52	-0.19	40.33	-0.15	-0.39	0.24
Nubbin size	0.07	0.07	0.00	0.08	0.02	-0.06	0.01	0.05	0.04
Kernel mass/ear	10.42	10.42	0.15	11.05	11.94	0.89	12.31	12.61	0.30
Actual Yield	10.54	10.69	0.15	11.13	11.96	0.83	12.32	12.66	0.34
High Plant Density									
Yield Potential	10.38	10.68	0.30	10.47	17.11	0.69	11.34	11.12	-0.22
Barrenness	-0.98	-0.92	0.06	-1.34	-0.90	0.44	-0.57	-0.46	0.11
Nubbin number	-0.96	-0.73	0.23	-0.60	-0.58	0.02	-0.22	-0.40	-0.18
Nubbin size	0.12	0.19	0.07	0.07	0.11	0.04	0.04	0.06	0.02
Kernel mass/ear	8.32	8.83	0.51	8.45	9.51	1.06	10.52	10.20	10.20
Actual Yield	8.44	9.02	0.58	8.52	9.62	1.10	1036	10.26	-0.30

more nubbins at the low plant density. At the high plant density, the number of nubbins was decreased in the dry summer, unchanged in the average summer, and increased in the wet summer when an additional 25% of rainfall was applied.

Increased rainfall resulted in larger fertile ear and nubbin size in all treatments regardless of the population with the exception of the average rainfall treatment with . low plant density and the high plant density treatment in the wet summer rainfall treatment. In the first instance, the size of nubbins was reduced while in the second the size of the fertile ear was reduced. In both cases, the reduction was due to reduced numbers of kernels on the ear or nubbin.

4. SUMMARY

Three years of controlled rainfall experiments in rain shelters were conducted in central Illinois to determine the effect of enhanced rainfall due to weather modification during typical dry, average and wet summers on final corn yields. Final com yields were increased by an additional 25% of rainfall in each of the typical summer scenarios at both high and low plant densities, except for the wet summer at high plant densities. Final yield increases were due to decreased barrenness, reduced numbers of incompletely formed ears, and increased fertile ear size. These responses indicate that the greatest effect of increased rainfall was felt at the time of pollination and the 2 weeks following pollination.

The experiments show that a benefit to Illinois agriculture could be realized by a reliable weather modification technology in all summers. The greatest benefits occur in the average years with lesser benefits in the drier and wetter summers.

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IMPACTS OF A CLIMATOLOGICALLY-UNIQUE YEAR (1990) IN THE MIDWEST

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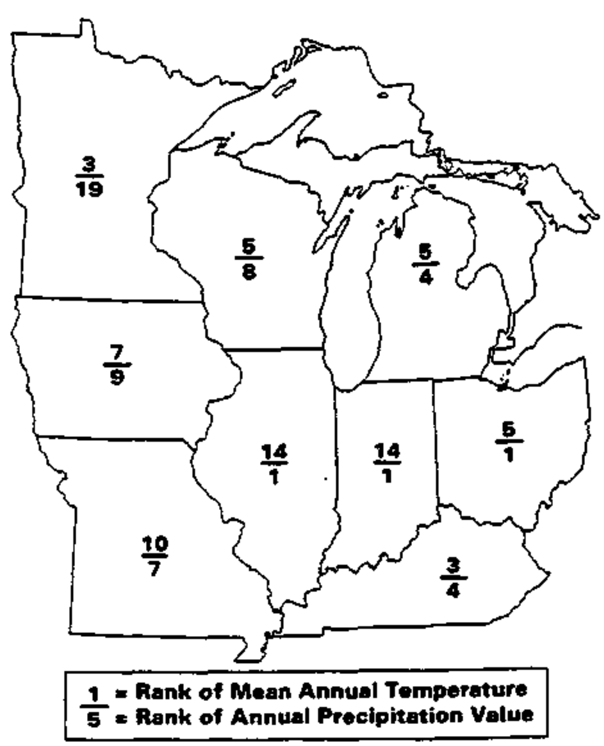
1. INTRODUCTION

In 1989 the Midwestern Climate Center (MCC) began a monthly documentation of the primary climate factors and resulting impacts in the 9-state midwest area which embraces the Corn Belt (figure 1). This was a cooperative project done in conjunction with the Climate Analysis Center/National Weather Service (NWS).

A primary thrust of the impact assessment was to gather quickly what was known at the end of each month, and to prepare a region-wide summary for rapid distribution to CAC and to regional clients of MCC including business and government agencies. Such a hurried assessment of impacts occurring within days after climatic events has limitations. The data are generally qualitative and represent impacts that result from more major weather extremes during the month, or from the culmination of conditions over a few months. Such analyses do not measure the more subtle effects from weather that occur over extended periods of time and reach deep into the fabric of society and the environment. Regardless, there is a need shortly after abnormal weather conditions occur for an "initial assessment" of the impacts. These impacts are believed to contain information worthy of a scoping investigation, and this is the purpose of this paper—to report on a study of these initially-measured impacts resulting from an unusual weather year, 1990.



Pig. 1. The Ranks of statewide Annual Temperature and Precipitation for 1990 (1 = warmest since 1895; 5 = fifth wettest since 1895).

1.1 Annual Weather Conditions for 1990

The annual temperature and precipitation values for 1990 have been shown to have been highly unusual globally and across the United States. LeCompte (1991) declared 1990 to be the globe's warmest year of the 20th century, and Heim (1990) rated 1990 as the nation's seventh warmest and fourteenth wettest year since 1895.

The climatic uniqueness of 1990 was even more marked in the 9-state midwest region. The year had extreme wetness and a high annual mean temperature, ranking 1990 as a singular combination, forming the "warmest-and-wettest" year since region-wide records began in 1895. No other year in the past 96 approximated the interesting mix of near-record high annual temperatures and record precipitation found in 1990.

The precipitation departure was +6.4 inches (16.3 cm), a value 17% above the long-term average and the region's wettest year on record. The annual temperature was 2.1F above average (+1.3C) ranking as the fifth warmest year on record.

An investigation of the primary impacts from weather conditions in such a year was seen as valuable. For example, the annual temperature and precipitation values for 1990 approximate some of those suggested for the region by certain global climate models, as a result of global climate change in response to a doubling of CO_2 (Grotch and MacCracken, 1991). one can consider 1990 an analog of the future and obtain a first approximation of the kinds of major impacts a warmer and wetter climate could bring to the midwest. Further, the storm losses experienced in 1990 set all-time records in dollars and lives lost, and the year's events represent a design challenge for severe-storm forecasting and for the weather-insurance industry and its re-insurance sector which must handle the catastrophic losses in such years.

2. 1990 WEATHER CONDITIONS

Table 1. General description of seasonal weather conditions in the midwest in 1990.

Season	Temperature	Precipitation	Storminess
Winter (J ,F,D)	very warm	very wet (below average snow	normal no. of winter storms, more thunderstorms, & increased fog
Spring (M, A, M)	near average	very wet	above average no. of severe storms and wind speeds
Summer (J ,J,A)	near average	very wet to average	extremely large no. of tornadoes and flash floods
Fall (S,O, K)	very warm	average to moderately dry	many tornadoes

The weather of 1990, which culminated in the extreme annual values, was assessed on a monthly and seasonal basis. A summary of the seasonal conditions is listed in table 1. This reveals that the annual high temperatures were a result of extremely high temperatures in the fall and winter seasons (with average values in summer and spring). The extreme wetness of 1990 in the midwest resulted from excessive precipitation in all but the fall season. Seasonally, 1990 did not mimic GCM outlooks calling for warmer midwestern summers, but who knows what such climate surprises lie ahead?

Table 1 also summarizes major storm anomalies and related weather conditions. All seasons experienced abnormally large numbers of severe convective storms. It was a record year for tornadoes with 267 in the midwest, a new high. Seventy were classed as violent, also a regional record high, and 39 persons were killed by tornadoes (Ferguson and Ostby, 1991). In different months, several midwestern states experienced record high numbers of tornadoes including March in Iowa (17 tornadoes), June (Indiana with 44 and Kentucky with 15) , September (Michigan with a record of 10), and November (Illinois with 7) . Note that months in all seasons experienced new tornado records somewhere in the region.

A major tornadic outbreak occurred on June 2 with 64 tornadoes in 7 states. Seven tornadoes rated as F4 and one traveled 100 miles. Then, an F5 monster occurred in Illinois on August 28 killing 29 and producing $113 million in insured property losses. Several very severe winter ice and snow storms occurred but not in record numbers. The warm/wet winter and spring months produced much above average numbers of days with widespread fog.

The dimensions of the increased storminess in 1990 are further revealed by property insurance loss data. All U.S. storm events producing more than $1 million in paid losses (equated to 1949 dollars when such storm accounting began) are classed by the insurance industry as "catastrophes." In 1990 there were 12 catastrophic events in the midwest, as shown in table 2. This number exceeds the midwestern average of 9 per year.

It is not the intent of this paper to delve into the atmospheric circulation anomalies that produced the unique temperature, precipitation and storm conditions in 1990. Wagner (1990) points out that during 1990, the 700-mb heights were generally below normal at the high latitudes and above normal at the low latitudes, a pattern that favors above-normal temperatures over the United States. Such a pattern typically moves the jet stream

Table 2. Catastrophic storms causing extensive property damages in the midwest during 1990.

Storm Conditions	Dates	Number of States	Loss $ in millions
Tornadoes and hail	6/1-2	4	31.2
	11/27-28	3	36.4
Hail and winds	7/7	1	15.0
Tornadoes, hail, rains, and floods	3/13-14	3	39.0
	5/14-15	4	52.0
	5/18-20	2	44.6
	6/6	3	235.0
	6/19	1	36.5
	8/28	3	113.0
	10/18-19	1	7.4
Winter storm	12/18-23	2	20.8
			630.9

(1) In 1991 dollars

and storm tracks farther north, and weather systems occur more often and move more rapidly. This situation produced the excessive variability found in the fall and spring weather conditions and the greater storminess in the midwest.

3. IMPACTS

Complete delineation of weather and climate effects on physical systems (e.g. the hydrologic cycle), and in turn, the resulting socioeconomic impacts and ensuing human responses is an extensive process since some effects take several months and even years to be realized. (Kates et al. 1985). It was not possible for our end-of-month impact assessments to pursue such definitive impact analyses, but rather to discern what could be learned and how useful our clients felt the information was. Many decisions about responses to atmospheric impacts must be made by private and public sector leaders with such hurried and often limited data on the real effects. Such impacts tend to be defined in lives lost and estimates of dollar damages. In essence, the economic impacts derived soon after a series of bad storms, or at the end of an unusually warm or cold winter month, are at best first approximations of the real impacts. Certainly one is safer to state that there were profits or losses in excess of a few million dollars without getting more specific. In essence, these impact analyses should be considered as largely qualitative.

Information on physical effects were derived from several state and federal agencies who routinely monitor certain parts of the hydrologic cycle such as lake levels, groundwater conditions, and streamflow. Data on economic impacts and responses were largely gathered from three sources: the news media, state climatologists, and from insurance assessments of loss. The physical effects, socioeconomic impacts, and responses identified as the end of each month in 1990 have been sorted and classified into several broad categories including water resources, agriculture, and energy use. The following text highlights findings in the major areas of impact during 1990.

3.1 Water Resources

The midwest entered 1990 with ample water supplies except in the northwestern portions of Iowa and Minnesota where effects of the 1988-89 drought persisted. The wet winter and spring of 1990 ended this lingering soil moisture shortage and water supply drought. Soil moisture was rated as "adequate to excessive" throughout the midwest by June 30.

The other major water-related impact was from flooding. Low winter (1989-90) snowfall did not yield major snowmelt floods, but the excessive rains from late January through March, coupled with the relatively high spring temperatures to melt the snow, produced early flooding along many rivers by March. Major riverine, urban, and extensive rural flooding followed during May and June, both months with near record rainfalls over large areas. Flooding resumed in parts of the midwest in October, November and December as heavy rains and low ET led to major river valley floods. Thus, all types of flooding were problems in all seasons of 1990.

3.2 Agriculture

Agriculture is the midwest's most weather-sensitive sector. The effects of 1990 weather were profound and surprising. The lingering drought in the northwest was an early worry but 1990 rains canceled any real effect on crops. The early winter and spring warmth led to early budding of fruit crops, but little harm occurred because the last spring freezes were not abnormally late even though May was a cool month (and the relatively coldest month in 1990).

The most important 1990 weather impact for production agriculture resulted from the wet winter-spring; it delayed planting of grain crops by several weeks. For example, at the end of April only 5% of the southern Illinois corn crop was planted as opposed to a normal of 85% planted by that date. This wet condition finally led to a major shift in planting of soybeans rather than corn over several million acres. The cool and wet April-May period also increased pest development, and then frequent higher-than-average winds in the spring and summer minimized opportunities to spray crops when needed.

The delayed planting also brought two major dangers for the region's corn and soybean crops; 1) greater vulnerability to heat-induced stress at critical times, and 2) potential damage from frost/ freezes occurring before the weather-caused late harvest. The "good news" was that excessively high daily temperatures did not occur during 1990 with its near average summer temperatures, and fall frosts were not early.

The heavy rains and flooding had other major impacts: fields were lost to any use and extensive soil erosion occurred. The heavy spring rains in Iowa caused a loss of 20 tons of soil per acre over more than 3 million acres, one fifth of the state. The spring flood-induced crop losses in Indiana were estimated to have produced $250 million in losses including the costs to replant ruined crops. The continuing series of violet thunderstorms during May, June and August not only produced field flooding but a large amount of hail and wind damage to field crops. Hail loss in Illinois in 1990 ranked as the third largest on record.

What was the net effect of the delayed planting, the non-stressful summer weather with adequate soil moisture, much above average storm damage, and above normal pests and fungus problems on production? The midwestern corn and soybean yields for 1990 were labeled as "above average," approximately those of 1989.

3.3 Energy Production, Use and Transmission

The use and responding production (and sales) of gas and electrical energy, and etc. transmission of electricity are very weather-sensitive activities. In general, consumers of electricity were winners in 1990. The warm winter reduced heating demands, and the near-average summer temperatures did not create high use of air conditioning. For example, the warm January led to savings in power purchases estimated at $100 million across the 9-state region.

Conversely, the power companies were not winners with reduced sales in both high demand seasons. Furthermore, the extreme storminess produced many power surge problems and power outages. Major outages due to severe storms (frequent very high winds, three major ice storms, and above-average frequencies of lightning outages) occurred in each month of 1990. This was particularly a problem in the large urban centers like Detroit (in February), Des Moines (March), Chicago (June and August), Cleveland (May), and Minneapolis (July and again in December).

3.4 Property Losses and Human Life

The total loss to insured property for the midwest in 1990 (table 2) was $630.0 million. The annual average (in 1991 dollars) is $413 million as calculated since 1960. The 1990 value exceeds all prior year totals except for $698 million caused by the record high of 14 catastrophic events in 1982.

Records on weather-induced deaths are among the better quantitative records but they often do not correctly estimate heat-induced deaths. Death-loss records are typically under-estimated. The severe tornadic outbreaks in the midwest, a record number for a year, led to 39 deaths. The abnormally stormy and foggy weather of 1990 also created plane crashes, boat accidents, and numerous auto accidents leading to 75 lives lost in weather-induced accidents. Lightning killed 10, 3 froze to death, and drowning due to flash floods claimed another 46 lives. The regional total was 173 deaths, a figure believed well above the region's annual average. Ninety died in 1989 due to weather causes, but more than 1,000 midwestern residents died due to heat stress during the hot summer of 1988.

3.5 Transportation

The major and frequent storm outbreaks caused several impacts on the movement of people and goods. Major airports had many closures due to adverse weather (storms, flooding, icing, and/or fog). O'Hare Field in Chicago had at least one weather-related closure in every month of 1990, the first year this occurred.

Most detrimental to surface transportation was the excessive amount of fog. It reduced or stopped surface and air travel in several 1-to 3-day periods, led to many accidents, and tremendous delays in urban-area travel. Flooding was also a serious problem at times.

3.6 Tourism

The below-average winter snowfall reduced winter sports participation in the northern portions of the midwest. Bad weather caused many events to be canceled in May and in the summer months, and summer storms caused excessive damage to pleasure boats in harbors, particularly those on Lake Michigan and Lake Erie. Conversely, the high water levels on all lakes allowed unrestricted pleasure boating. Flooding of campgrounds was a particular problem reported across the midwest in the summer. In general, tourists and tourist industry suffered from the 1990 weather.

3.7 Schools

An interesting aspect of the 1990 weather was the large number of school closings attributed to adverse weather, be it in winter or warm-season storm related. Flooding also compounded the problem of transporting students. Schools closed because it was too hot in September in Iowa, flooded roads in Ohio in March and May, too cold in Wisconsin and Minnesota in December, and too stormy at many other times and places. Damages to schools from storms were widely reported during the spring and summer.

4. RESPONSES

In the data we used, very little is known about most responses to weather impacts, particularly since many responses are delayed and occur weeks, months and even years after an impact. However, one measure of responses that do occur relatively quickly are those performed by government agencies.

The reported responses of federal government to the impacts of 1990 conditions in the midwest were not classed as major. President Bush responded eagerly to state-pleas for disaster area pronouncements (and low interest rate loans) resulting from the excessive storm damages. Most of these occurred as a result of the winter, spring and fall flooding in Indiana, Illinois, and Ohio and as a result of the widespread tornado damages in June and in August. The USDA, given the flooding and spring planting delays, agreed to alter their policy about planting of protected acreage and allowed this to occur.

State responses were largely aligned with actions due to storm damages. Several governors sought federal aid for disaster areas.

The major governmental impacts and responses noted occurred at the local level, and were typically actions of urban governments. As has been noted, major cities like Chicago experienced a wide range of major weather problems in 1990: there were numerous in-city floods affecting water treatment plants; polluted water had to be diverted at Chicago back into Lake Michigan twice due to excessive floods; bad weather (floods, storms, and fog) greatly affected commuter and airport transport; and metropolitan power outages were extensive and prolonged. (Chicago had four outages that each affected more than 150,000 people for many hours up to 4 days). Several small towns were severely flooded, some nearly destroyed, and a few had loss of life. Twenty-nine persons drowned at Shadyside, Ohio. One small Indiana town, after four major floods, gave up in October 1990 and began relocating to higher ground.

5. CONCLUSIONS

What does an extremely different weather year like 1990 cause? Basically, a different array of "winners" and "losers" than in other years. In table 3 we have tried to provide a single generalized assessment of the impacts for each section. The more major impacts of the unusual weather of 1990 were due to frequent and intensive storminess and to the wetness of January-June. The severe storms affected every activity — tourism, transportation, crops, and power availability, and produced near record numbers of property damages and deaths. The excessive wet conditions produced extensive flooding which impacted most sectors and more importantly hurt agricultural activities and delayed the growing season. The abnormally high temperatures in winter and fall had less major impacts but lessened power demands and altered the growing season.

Table 3. Generalized impacts from weather events in 1990 in the midwest.

Impacted sector	General rating of key impacts
Water resources	Mixed (water supplies positive, flooding negative)
Agricultural production	positive
Soils	negative
Energy producers	negative
Energy users	positive
Property owners	negative
Human safety and life	negative
Schools	negative
Tourism	negative
Federal/state impacts	marginal
Local government	negative (in selected cases)

From a sector viewpoint, the impacts were varied. The consumer benefitted from the abnormally high cold season temperatures (lower power bills) and the sizable crop yields (lower food costs), but suffered losses in property and lives, and many delays in travel. Residents of large urban areas and certain small towns suffered from a host of problems including major flooding. The weather insurance industry dealt with record losses. Farmers had increased expenses due to the wet spring conditions and storm damages, but still realized above average yields.

It is worth noting that the incidence of abnormally late spring frosts or early fall freezes in the midwest, which could have been disastrous to agriculture in 1990, are events independent of monthly average conditions. For example the cool October of 1990 was not accompanied by early fall frosts, nor did the cool May bring late frosts. This is one of the critical issues to consider for midwestern agricultural impacts from a future climate change leading to an altered growing season. Timing and relationship between certain critical weather events are very important.

Kunkel et al (1991), in a study of 3- to 10-day heavy rain events related to midwestern floods, found that the frequency of these did not relate to the degree of wetness or dryness of the pentad they occurred in. The rain events are random and not tied to seasonal or annual climatic conditions (e.g, wet, normal, or dry). Thus, altered future seasonal or annual climate conditions calculated to be hot and dry, wet and cold or whatever may not relate well to the many events critical to flooding and agriculture.

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Identifying Climate Variables That Are Important for Forest Growth and Health

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1. INTRODUCTION

The principles and concepts of forest development and management have largely evolved during this century and were formulated under existing climate conditions that were assumed to be "normal" and unchanging (Layser, 1980). However, as paleoclimatic research has shown, changes in forest extent and composition have accompanied past changes in climate. For example, Banlein et al. (1984) showed that Holocene pollen data in the midwestern United States indicated an eastward movement in the prairie/forest border in Wisconsin by 8000 B.P. and a subsequent westward retreat occurred after 6000 B. P.

There has also been recent concern with how forests might respond to possible future changes in climate due to increases in the atmospheric greenhouse gases. This concern is primarily based on experimentation with General Circulation Models (GCMs), using both modern-day CO_2 levels and doubled CO_2 levels. Several studies have sought to relate the climate changes suggested by the GCMs to likely changes in forests. One approach has identified the growing degree day isopleths that delineate current ecosystems or the current distribution of a given tree species. The changes in growing degree days suggested by the GCM climate scenarios are then used to predict the migration and extinction of particular species. An example of this approach is found in Emmanuel et al. (1985), where a Holdridge (1947) life-zone classification was applied to modem-day climate and the results were compared with the counterpart pattern obtained from the global temperature distribution given by a doubled CO_2 GCM experiment. Factors such as soils, precipitation, and competition were not taken into account.

The other approach is to link GCM climate scenario output to forest models, usually a "Gap" model. "Gap" models physiologicaly simulate the growth and mortality of individual trees on a small plot. The plot size is determined by the expected canopy size of the single largest tree in the plot. The death of this tree leaves a gap in the canopy, which strongly affects the processes in the plot (see Shugart (1984) for a more thorough discussion of "Gap" models). An example of this use of both climate and forest models is found in Pastor and Post (1988), who coupled the output of a GCM with a "Gap" model of forest dynamics to examine the ecological consequences of global warming in Eastern North America. Their conclusions were that, in the northern fringes of the taiga, white spruce and paper birch may come to dominate, while in the southern boreal forest the present species would be replaced by temperate deciduous species.

The weakness of these approaches is that they assume simple relationships between climate and trees, such as a sensitivity to degree day accumulations, while ignoring the more complex and secondary effects of CO_2 warming (e.g., changes in the nitrogen cycle, fire frequency, and leaf litter decomposition).

Unfortunately, the links between climate and forests are not well understood. A literature search shows that while some quantitative work has been published in this area, most of it is rather species and site specific. This may be due to several factors. As mentioned earlier, climate was traditionally considered to be a constant force in forest dynamics and was therefore "factored out" of the equation. Also, extensive, long-term forest monitoring programs have only recently been established to measure important forest variables. There has also been limited interaction between foresters and climatologists, resulting in the use of only coarse resolution monthly temperature and precipitation data sets in most forest studies. And, the most important climate factors may change from species to species and from site to site.

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In the absence of the needed quantitative research, some researchers have hypothesized the kinds of effects that a climate change may have on forests. For example, Sandenburgh et al. (1987) suggest that changes in "local" climate associated with greenhouse warming include shifts in: precipitation, evaporation, soil moisture, frequency of extreme weather events, total weather variability over the life of the stand, first and last frost, and the frequency of damaging storms. They also believe that higher levels of CO_2 may lower plant water requirements and allow soil microbes to fix greater amounts of nitrogen. Furthermore, there could be increases in tree stress due to more cold snaps or heat waves, and wanner and drier conditions would increase water stress, fire risk, and possibly increase pest populations.

Miller et al. (1987) have provided an excellent pilot study using the approaches that are needed to quantify the forest effects of climate change. Using loblolly pine in the southeastern U.S., they give detailed descriptions of the temperature and precipitation thresholds for various stages of tree growth, based on the large amount of field work on loblolly pine. In particular, it is suggested that height growth depends on how much rain is distributed between the cool season (October to March) versus the warm (April to September) part of the growing season. Provided the warm-season precipitation is less than 76 mm, increased height growth is noted with increasing cool-season precipitation. Otherwise, height growth decreased with increasing cool-season precipitation.

Unfortunately, there are not enough studies of this nature to form a comprehensive view of forest-climate interactions.

2. WORKSHOP

To help address the issue of what parameters and processes should be considered in climate studies that relate to U.S. forests, a workshop was organized by the Illinois State Water Survey and the U.S. Environmental Protection Agency (U.S. EPA). It was held on May 22-23, 1991, in Champaign, Illinois. Experts in the fields of dendroclimatology, forest modeling, entomology, forest hydrology, forest data bases, and climatology met to discuss the following issues:

I. Identify key relations between climate variations and forest development
- What climate parameters/processes affect forest development?
- What is the physical basis for these relationships?
- What stages of forest development are most sensitive to climate?

II. Identify data bases relevant for assessing climate impacts on forests
- What forest variables should be examined?
- What long-term forest data sets are available for those variables?
- What relevant long-term climate data sets are available?

III. Identify forest models that are appropriate for climate variation and change research
- What models are available?
- What are the strengths and weaknesses of each model?
- What climate parameters/processes are included in those models?
- What is the output of each model and how can it be interpreted?

The discussion at the workshop can be divided into five areas: data sets; analysis and modeling; water balance; dendroclimatology; and pests. We will now identify the speakers and main points in each area.

a. Data Sets

In this session, Michael B. Richman and James R. Angel (Illinois State Water Survey) discussed some unique daily precipitation and temperature data sets that cover North America east of the Rocky Mountains. The station network (Fig. 1) extends from approximately 55 * N in Canada southward to the Gulf of Mexico, and from the eastern edge of the Rocky Mountains to the Atlantic Ocean. In developing this network, the densest possible regular station spacing was found to be approximately 1 latitude-longitude; the distribution of the 766 selected stations approximates such a grid. One unique aspect of this data set is that each of the stations has complete records on a daily basis from January 1, 1949, through December 31, 1988, as missing values have been replaced by those from one of several nearby (generally within 10 km) stations. The climate variables available include daily precipitation and daily maximum and minimum temperature. These data sets thus contain good coverage in both time and space. The precipitation data set has already been used to address such questions as the spatial

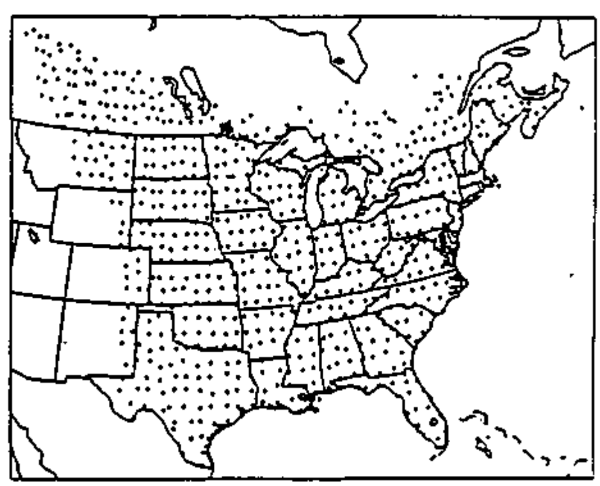

Fig. 1. Precipitation Station Network (766 locations).

coherence of precipitation at several time scales (3-day to seasonal), (e.g., Richman and Lamb, 1985, 1987), and the relationship between winter precipitation and mean storm tracks (e.g., Richman et.al. 1991). Other daily and weekly climate data sets (e.g., solar radiation, modeled soil moisture) are available for approximately the same time period, but they have a coarser spatial resolution and are for more restricted areas (e.g., upper Midwest).

H. Michael Rauscher (U.S. Forest Service, Grand Rapids, MN) discussed the status and availability of forestry data. For spatial coverage, the Forest Inventory and Analysis (FIA) data base may be the best available. This includes classifications and measurements of the following species, diameter class, disturbance history, site index, tree height, and crown class. Data collection started in the 1930s, with new samples being taken approximately every 10 years. The purpose of this assessment is to predict lumber production. The resulting data set is not suitable for the long-term monitoring of panicular sites, since the measurement techniques and the plot locations have changed over time. While there are also long-period research data sets for particular sites, many of these lack adequate documentation and are not widely available. Currently, there is no national archive for the safekeeping and distribution of the forestry data sets. This presents an obstacle, since researchers are potentially faced with dealing with several public institutions for data that are heterogenous in many respects. Despite its limitations, however, the available forest data base is potentially valuable for not only the investigation of forest-climate relationships, but also the calibration and verification of some forest models.

b. Analysis and Modeling

Michael B. Richman (Illinois State Water Survey) reviewed some recent applications of multivariate statistical techniques (Principal Component Analysis and Procrustes Target Analysis) to the aforementioned daily precipitation data set. Particularly germane to forestry are the coherent regionalizations obtained for 3-day precipitation totals for each season. An example for spring is shown in Fig. 2. Related methodological issues are addressed in Richman and Lamb (1985, 1987) and Richman and Easterling (1988).

Margaret R. Holdaway (U.S. Forest Service, St. Paul, MN) used a regional tree growth model without climate parameters and compared the results with stand data from Michigan, Minnesota, and Wisconsin. The model employed (STEM/TWIGS) was developed for the Great Lakes region and incorporates biologically based growth and mortality schemes. The differences between the modeled and the stand data were assumed to largely reflect the influence of climate. Among the results obtained, based on correlation analysis, are that fall precipitation is beneficial to conifers, summer precipitation to cold season hardwoods (e.g., basswood, sugar maple), and spring precipitation to warm season hardwoods (e.g.,

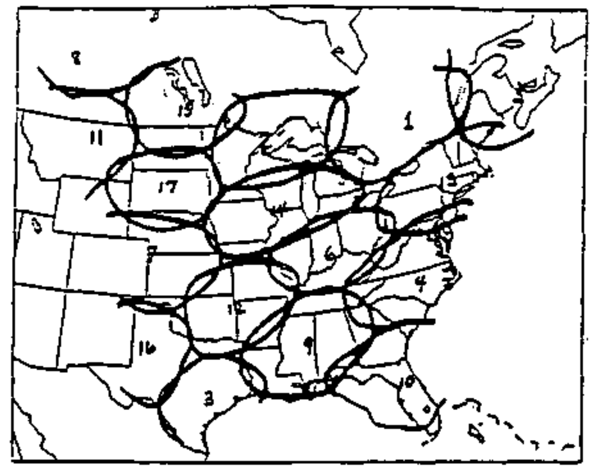

Fig. 2. Regionalization of eastern North America for three-day spring (Mar, Apr, May) precipitation on the basis of the Harris-Kaiser obliquely rotated Principal Component patterns. The regional boundaries are the 0.4 loading isopleths for individual PCs.

elm, red maple). Conifers appear to need a higher proportion of the total precipitation in the fall for soil moisture recharge, while cold season hardwoods need more in the summer. Cold winters are apparently beneficial to conifers and cold season hardwoods, whereas warm winters favor to warm season hardwoods. This work is reported in Holdaway (1988).

Ellen J. Cooter (U.S. EPA, Research Triangle Park, NC) discussed research on climate-ecosystem interactions conducted under the Environmental Monitoring and Assessment Program (EMAP) of the U. S. EPA. Climatological averages and ranges provide one set of physical boundaries on the ecosystem (Fig. 3 and Fig. 4) with year-to-year variability acting as ecosystem disturbances. These disturbances may be reflected by changes in health, growth, system energetics, plant populations and species characteristics. She identified broad categories of stress based on the size, frequency, and magnitude of events such as fire, drought, tornadoes, ice storms, insects, lightning, floods, hurricanes, and freezes. The goal is to gain an understanding of the interactions of climate, climate variability (disturbances), and forest health.

Gordan B. Bonan (National Center for Atmospheric Research, Boulder, CO) provided insight into the effects of air temperature on tree growth from an ecological standpoint. As already noted, there is little quantitative knowledge about the effects of climate on tree growth. The traditional view of ecologists is that this situation results from there being too few data on which to base the needed studies. The counter-argument (advanced by Bonan) is that enough is known about basic tree processes to construct more physiologically-based models, which can then be integrated over larger space-

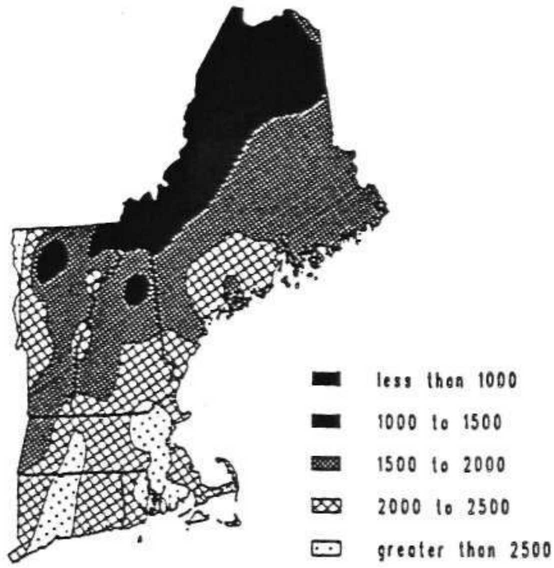

Fig. 3. Median annual growing degree days for the northeastern United States (Cooter, personal communication).

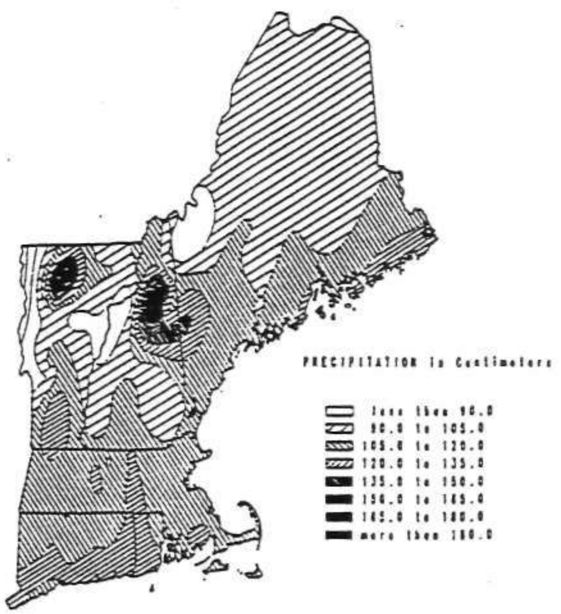

Fig. 4. Mean annual precipitation, 1961-1990, for the northeastern United States (Cooter, personal communication).

scales. Using this approach, Bonan showed evidence to suggest that the northern and southern pine forest boundaries in the southeast U.S. may not be due to growth limitations (as suggested by the "Gap" models), but possibly to limitations on reproduction. In other words, two entirely different processes can give the same final result. This illustrates the potential pitfalls of trying to narrowly relate a single forest process with climate change.

c. Water Balance

William Massman (U.S. Forest Service, Fort Collins, CO) discussed the physical processes governing interception and evapotranspiration. The climate variables used to model interception are mean rain rate, storm duration, and mean evaporation rate. Although interception is a significant component of the general forest water balance, most of the relevant research has been done in England and the Pacific Northwest. Evaporation was suggested to be a more complex process and requires 20 parameters (using a resistance approach) to model as compared to the 6 parameters for interception. The two factors affecting evapotranspiration are the boundary-layer resistance and stomatal resistance. Research indicates that the large-scale boundary - layer resistance is related to the leaf area index (LAI), and canopy architecture. LAI, which can be readily measured in the field, is a variable useful for scaling between leaf level processes and canopy level processes.

d. Dendroclimatology

Rosanne D'Arrigo (Lamont Doherty Geological Observatory of Columbia University, Palisades, NY) pointed out that the forest response to future climate change and related feedbacks are key issues in the greenhouse gas debate. She suggested there is a substantial amount of tree-ring information that can improve our understanding of the relations between forests and climate, as well as enhance and validate forest growth models. Her work in the Boreal forest of Canada showed that tree-ring reconstruction matches the annual mean temperature curve for the Northern Hemisphere for 1880-1990. Interestingly, several sites showed greater tree growth in recent years. It is not certain if this is due to more favorable growing conditions, CO_2 enrichment, or some other factor. While northern forest growth was found to be limited by temperature, the eastern deciduous forests showed a greater dependence on moisture availability.

Lisa J. Graumlich (Laboratory for Tree-Ring Research, University of Arizona, Tucson, AZ) reported on research that has focused on the Great Lakes region. "Gap" models have not performed well in terms of predicting species distributions in this area. Graumlich's work suggests that climate could have an impact on all phases of the forest growth cycle (regeneration, thinning, mortality). Preliminary results suggest that the responses to climate might be broken down according to the function and structure of trees, regardless of species. For example, the response to summer temperature of ring-porous species such as oaks is different from that of ring-diffuse hardwoods. This type of result would allow the development of more physically-based relationships between climate and tree physiology. An example of the complicated relationship of temperature and precipitation for western juniper is shown in Fig. 5.

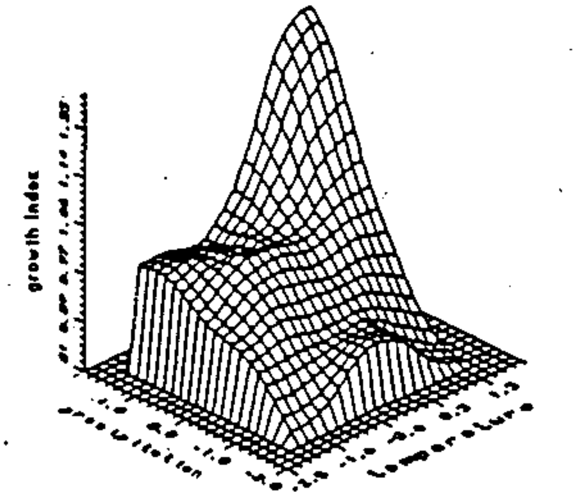

Fig. 5. Response surfaces relating tree growth indices to summer (July-August) temperature and winter (previous October to current June) expressed in standarized units (Graumlich, personal communication).

e. Pests

Michael E. Irwin (Office of Economic Entomology, The University of Illinois, Urbana, IL), with input from David Wood (Department of Entomology, The University of California, Berkeley, CA) and Stewart Gage (Department of Entomology, Michigan State University, East Lansing, MI), provided an overview of pests in forest systems. Pests can cause additional stress to forests through defoliation (Lepidoptera), piercing-sucking (Homoptera), cambium feeding (bark beetle), root feeding (Curculionid weevils) and flower and seed feeding. Climate can influence pests in two ways, either directly on the insect itself or indirectly through changes in the plant characteristics. For example, climate stress may predispose a tree to attack by insects, alter an insect's ability to damage the tree, alter an insect's biology and behavior, or provide competitive advantage for one insect over another. Drought can induce pest outbreaks (e.g., bark beetles). Drought can also cause some physiological changes in trees, such as mobilizing nitrogen, which induces outbreaks of piercing-sucking pests. Temperature variations can affect pest metabolism rates, survivability, developmental rate, and generation time. They can also alter plant physiology to change its susceptibility to pests through nutritional quality and natural defense mechanisms. Lightning strikes predispose trees to attacks by bark beetles and serve as "brood" trees from which epidemics can come. It was suggested that climate sensitivity of forests might be more easily assessed using measures of pest population dynamics, since pest population directly affect forests and are themselves highly sensitive to climatic conditions.

3. Concluding Remarks

This workshop highlighted several points. Fine-resolution precipitation and temperature data sets, with added quality control, are becoming available for forest-climate research. The most appropriate forest data sets, on the other hand, are not widely available and lack documentation. These data sets may not be so useful for cb'mate change research due to changes over time in measurement practices, sites, and parameters collected. Current forest models allow a preliminary examination of tree growth interactions with climate; however, newer and more physiologically based models will be more appropriate for that research. Dendroclimatology, traditionally used to reconstruct past climates, can be used to identify climate sensitivities by species, location, and tree structure. Climate factors strongly affect pest populations and the vulnerability of trees to pests.

The workshop discussions also emphasized that forest systems-are complicated, as are climate systems, and the interaction of the two will require more cooperative research. The forest system contains long-lived species, large amounts of organic matter, with very complex and interacting biological sub-systems. Because of this, it is presently very difficult to single out particular climate factors that influence forest growth and health. This workshop underscored the need for more basic research on tree physiological processes, their interaction with the environment, and role of stresses related to changes in climate.

ACKNOWLEDGMENTS

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RELATIONS BETWEEN THUNDER REPORTS AND CLOUD-TO-GROUND LIGHTNING FLASHES FROM LIGHTNING NETWORKS

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1. INTRODUCTION

This study is seeking to define time and space relationships between thunderstorms and cloud-to-ground (CG) lightning flashes in the United States. Incidence of thunderstorms at first-order stations (FOS) have been recorded since 1897, but the systematic, area-wide reporting of cloud-to-ground lightning only began in 1983 in parts of the nation. This study of thunder events and lightning flashes features the 1983-1985 period when the lightning networks in the Western Mountains and along the East Coast provided suitable data. Data for 1986-1989 from across the nation are under analysis.

There are several applications for information about the relationships between thunderstorms and CG lightning. In the absence of lightning data, thunderstorm statistics have been used to assess the lightning threat to structures. A change in the means of recording thunderstorm incidence at weather stations is under consideration in the modernization of the National Weather Service. In the event that lightning data becomes a future substitute for human observations of thunderstorms (the hearing of thunder), the results of this comparative analysis should prove valuable.

2. DATA AND ANALYSIS

The data came from two sources: 1) thunder event data from 1983-1985, and 2) the CG lightning flash data for 1983-1985 from two networks of lightning sensors, one in the Western Mountains and one in the Eastern U.S. The thunder event data were from 25 FOS of the National Weather Service. Thunder audibility is effected by atmospheric and local topographic conditions and is heard typically 8 to 15 km from the point of discharge. A thunder event is a period of one or more thunder peals; an event is recorded as beginning at the time of first peal with the ending time recorded as 15 minutes after the last peal of thunder.

Lightning detecting systems are subject to three forms of error that can affect the locational accuracy of the flashes. First is the angular accuracy of the direction finders (the mean error is 0.5"); second, is the detection efficiency of flashes (typically a function of distance between sensing stations); and third, are local site problems that can affect the direction and magnitude of the incoming waveform. Detection efficiency was seen as less than 100% for several reasons and generally was 70% for all lightning in the east. The western sensing network, with a greater spacing between the direction finder stations than in the eastern network, had a lesser detection efficiency, ranging from 50% to 70%.

Since the range that thunder can be heard varies due to surface and atmospheric conditions, the comparative analysis was based on the incidence of lightning flashes within varying ranges from each FOS. Since thunder audibility is typically between 8 to 19 km, we selected three ranges to study, 5-km, 10-km, and 20-km, to bracket the audibility. Circles with these ranges were drawn around each FOS, and the incidence of flashes within each circle were determined through locational analysis of the individual flashes.

Comparison of the time of thunder events with the times of flashes (for each of the three ranges) revealed that many flashes did not occur during thunder events, and this was particularly true at the 10- and 20-km ranges. The flashes during thunder events were counted to derive the total frequency of flashes and average flash rate. Inspection of the flashes occurring during periods without thunder revealed three general types of flash events.

One type of flash event identified was called "isolated." These were single flashes occurring many hours or days away from any thunder event or any other flashes. These were considered indications of noise (locational errors) in the electronic sensing-location system.

Another frequently observed class of flashes not occurring during thunder events were those in "extended flash periods." An extended period contained 3 or more flashes within at least 60 minutes. The extended period could, and often did, persist for more than 1 hour.

Furthermore, to qualify, such multi-flash periods had to have beginning and ending times (as defined by the first and last of the series of Hashes) more than 3 hours from the beginning time or ending time of a thunder event. The definition was selected to be restrictive and to represent sufficient lightning activity to emulate a thunder event. They are indicative of missed thunder events at a FOS.

A third type of Hash frequently not occurring within thunder events was labeled as a "prethunder event Hash." Examination of the individual flash data revealed that one or more flashes frequently occurred in the periods just before thunder was listed as beginning. These preevent periods reflected under-estimates in the duration of thunderstorms recorded at a weather station. This and the other two criteria for categorizing flashes not occurring within thunder events accounted for >95% of the flashes that did not occur during thunder events.

Certain terms and phrases are used in the text, and to facilitate understanding and to shorten the text, abbreviations were established as follows:

F1	Flash(es)
F1 5	Flash(es) within 5 km of a FOS
F1 10	Flash(es) within 10 km of a FOS
F1 20	Flash(es) within 20 km of a FOS
T	Thunder
TE	Thunder event
ExFLP	Extended flash(es) period without T
IsoF1	Isolated flash(es) without T
FlPreT	Flash(es) before thunder event began

3. FINDINGS

The assessment of T and Fl data revealed both datasets had certain quality problems (TE data is poorer than lightning Fl data). The information is considered useful to gaining a better understanding about the use of thunderstorm records to study the global atmospheric circuit. The other relates to utilizing TE data to assess risk of CG lightning.

One major area of analysis involved the temporal relationships between the TE and Fl. The analysis of "between year" changes showed general agreement: that is. the percentage changes in TE between years were of the same general magnitude, and sign, as the between-year changes in F1 frequencies. Furthermore, large changes in annual events related to large changes in annual Fl frequencies. Correlation analysis of TE and Fl, based on their annual totals, produced coefficients of +0.83 for all eastern stations, and +0.67 for all stations in the Western Mountains. Correlations of annual durations of TE and Fl produced a coefficient of only +0.39. Storm durations and their F1 frequencies at all 25 FOS revealed poor relationships. The event Fl frequencies had skewed distributions with a few events containing great numbers of Fl. Thus, thunderstorm durations are not a good predictor of CG F1 frequency. Annual TE frequency is a better predictor of the annual Fl, but firmer conclusions await study of more data.

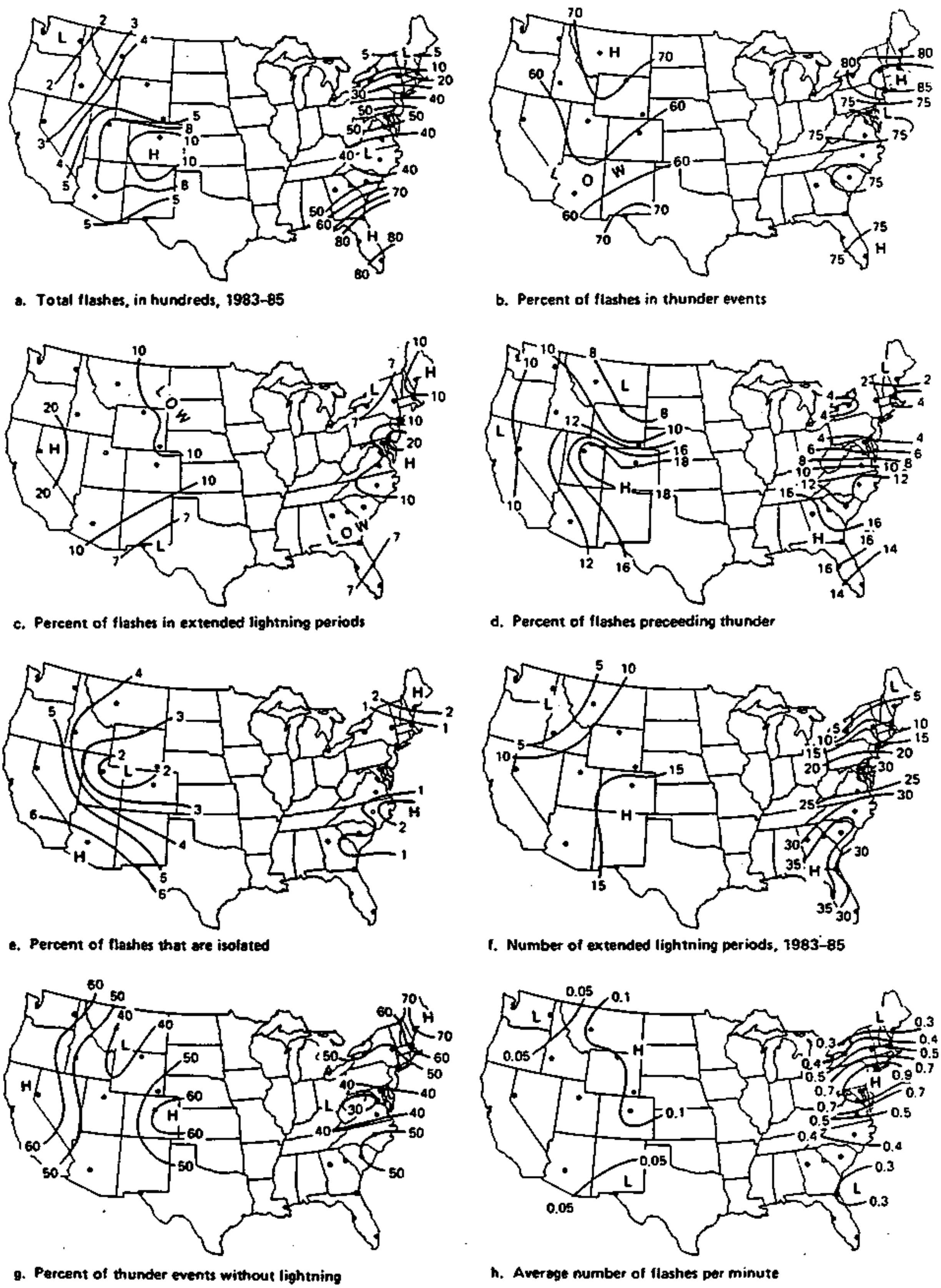
Reasons for the non-close relationship between TE and F1 frequencies at a point largely relate to the percent of F1 not occurring in events. Based on F1 10, FOS in the west showed that 28% to 44% of all F1 were not during events, whereas eastern stations had values between 13% and 28%, as shown in Fig. 1b. Thus, many F1 were missed by recorded TE. Conversely, consideration of TE with one or more F1 10 at the eastern stations shows that the point value range from 29% up to 70% (Fig. 1g). That is, many thunderstorms occur without CG Fl. Both results indicate why the statistical relationship between events and CG F1 is not strong.

Results relating to the broad geographical and small-scale spatial relationships between thunderstorms (events) and *CG* fl were grouped into five general classes. First, Euclidian cluster analyses based on 12 characteristics of F1 and T periods at the 25 FOS indicated six regions that were geographically and climatically consistent. The regions included two in the west (5 intermontane FOS, and 5 FOS along the Rockies), and four regions along the East Coast. These were the Northeast (upper New York and New England), the Mid-Atlantic states, the Southeast (Georgia and South Carolina), and Florida.

A second set of spatial findings concerned the types of shifts in thunder-lightning relationships due to the size of the sampling area around a weather station. Most areal relationships (number of Fl, percent of TE with Fl, etc.) fit a logarithmic distribution (Fig. 2). Furthermore, five of the six regions had straight line distributions with the same slope, revealing similar functional relationships with changing sampling area. Only the intermontane region displayed spatial relationships with a different slope than that of the other regions. This difference was found to be related to thunder audibility problems for lightning at the longer ranges of 10- and 20-km.

The frequency of Fl increased at the same rate as sampling area size, but other characteristics (Fl rate per TE, number of ExFIP, TE with Fl, etc.) changed less with expanding area than the area size would predict. These differences were partly due to audibility decreases with distance. However, for the three definitions of F1 not in TE (ExFIP, FlPreT, and isolated), it was discovered that the definitions at the longer ranges were sometimes confounded and less often met the defined qualifications than did F1 within 5 km. Thus, the values based on F1 within either 10 or 20 km are recommended to discern 1) the number of TE missed (ExFIP); 2) the frequency and lengths of abbreviated TE (preevents F1 periods), and 3) the frequency of isolated Fl. The reader is cautioned however, that the F1 frequencies of the western area are biased due to recording and detection problems and represents underestimates of the actual frequency of CG F1 around FOS.

Several findings revealed that many thunder and lightning characteristics exhibited latitudinal distributions. These included the total number of F1 (Fig. 1a), frequency of TE, duration of TE frequency of ExFIP, frequency of



a. Total flashes, in hundreds, 1983-85

b. Percent of flashes in thunder events

c. Percent of flashes in extended lightning periods

d. Percent of flashes preceeding thunder

e. Percent of flashes that are isolated

f. Number of extended lightning periods, 1983-85

g. Percent of thunder events without lightning

h. Average number of flashes per minute

Fig. 1. Patterns of thunder event and CG flash characteristics based on flash data within 10 km of first-order stations (dots), 1983-1985.

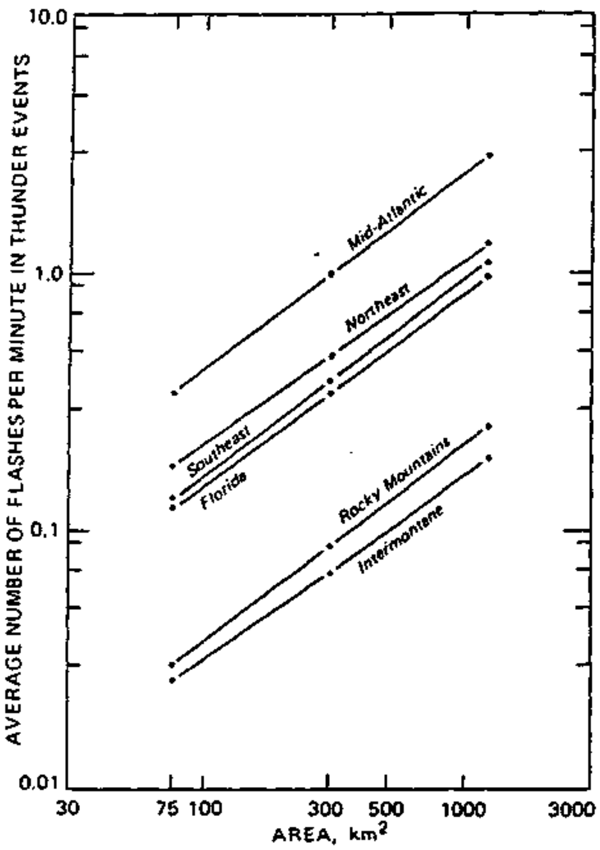


Fig. 2. Regional mean frequency of *CG* flashes per minute during thunder events (at a point) for varying sized areas.

preevent F1 periods and number and percent of FIPreT periods. Two explanations partially account for these spatial differences. Some conditions (TE, their durations, and total F1) increased from north-to-south, as expected for convective activity. However, the various expressions of missed F1 (not in TE) also increased from north-to-south. This suggests that the average atmospheric conditions in the northern portions of the United States (above 40°N) are more conducive to audibility of T over longer distances than are conditions farther south (30° to 35°N).

Comparison of east and west results for T and lightning conditions does not reveal climatic differences because of the greater data problems in the west. However, the west vs. east differences help reveal the magnitude of the errors in the western FI data. The East Coast values for the percent of total FI occurring during events were higher than in the west. That is, thunderstorms recorded in the west missed more nearby flashes than were missed in the east. Thus, on the average, the audibility of thunder at western FOS may be much poorer than at eastern FOS. The amount of the intracloud lightning causing TE appears to be much higher in the west than in the east (based on TE without CG FI), but this may be partly an artifact of the western FI recording problems.

The fifth set of spatial findings related to small-scale, either local or mesoscale, features in the patterns of certain lightning-thunder values. For example, the Mid-Atlantic region had many more FI than the adjacent eastern areas (Fig. la). The sampling vagaries related to the 3-year database may well explain the large numbers of FI found in the Mid-Atlantic region in 1983-1985. The intermontane region had fewer FI, both during events and in the number missed at the longer ranges, than the Rocky Mountain areal relationships would predict. Problems in the TE data were detected at Denver and Baltimore. Some small-scale changes in relationships were partly a result of audibility problems for T, established as the principal reason for the differing values in the intermontane region, at Denver, and at Baltimore.

The results raise several interesting questions and recommendations for additional research. We are now analyzing data for 1986-1989 for 70 FOS across the U.S.

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POTENTIAL WIND AND SOLAR POWER RESOURCES IN ILLINOIS

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1. INTRODUCTION

The recent conflict in the Persian Gulf has resulted in renewed interest in alternative energy sources in the United States. Wind and solar energy arc two alternative energy sources. However, the potential benefits of utilizing these resources is unknown because of a lack of networks designed to monitor the solar radiation received at the earth's surface and the potential for generating energy from the wind.

Eighteen automated weather stations have been established in Illinois to monitor the weather throughout the state. These stations have instruments to measure solar radiation, wind speed and direction, air and soil temperature, rainfall, and relative humidity (Hollingcr and Rietz, 1990). The first station was established in 1988, and the last station in August 1990. Currently, weather data from these stations are used to monitor conditions throughout the state for agricultural purposes. However, as the data record from these stations increases in length, the data base will become valuable in designing solar and wind alternative energy facilities.

The most commonly used length of record for computing statistics on weather variables is 30 years. However, alternative energy designers and users need and are requesting the data now. The density of the Illinois Climate Network (ICN) and hourly observations of wind and solar radiation provide data valuable for energy resource assessment even with a data set of only 1 or 2 years of record. Therefore, we have developed a computerized statistical data base for solar and wind energy resources in Illinois. This paper discusses the statistics used to describe the solar and wind energy resources and the computer software developed to present the data to the user. The data base is designed so that new data may be added to it each year, which will gradually improve the stability of the statistical parameters.

2. STATISTICAL ANALYSIS

Hourly solar radiation and wind speed and direction data from the 18 ICN sites have been quality controlled for the period from the start of the station record or 1 January 1989 (whichever is later) through 31 December 1990. For the most part the data were quality controlled a minimum of 3 times a week so that any instrument problems were discovered early and corrected as soon as possible. The quality control of the data was accomplished using computer programs (Rcinkc and Hollingcr, 1990) that identified data exceptions. The data exceptions were reviewed by a data technician who accepted or rejected the flagged data values.

The hourly quality controlled data were used to compute mean hourly and daily solar and wind statistics for each climatological week and month. The solar data were assumed to be normally distributed, therefore, the mean and standard deviation were used to describe the solar radiation distributions. Because of the extreme skewness of the wind data, the Gamma distribution was used to describe the wind speed and power distributions.

2.1 Solar Radiation Computations

In addition to the global radiation received on a horizontal surface, as measured by a pyranometer, the energy received on a vertical wall and on a surface with a slope equal to the latitude of the station were estimated. The vertical wall and sloping surface energy was computed for 5 different aspects (15° cast of south, south, 15° west of south, 30° west of south, and 45° west of south). The means and standard deviations of the measured and estimated solar energy were stored in a data base.

Accurate estimation of the energy received on non-horizontal surfaces requires partitioning the measured global-radiation into its diffuse and direct components. These computations are necessary in order to account for the diffuse and reflected radiation received on a sloping surface whenever the sun is positioned so that the face of the surface docs not receive direct radiation. The percent of global radiation in the diffuse component was estimated by computing the optical thickness (τ) of the earth's atmosphere

$$\tau = \frac{E_g}{E_t} \qquad (1)$$

where E_g is the global radiation measured at the earth's surface, and E_t is the computed energy from the sun at the top of the earth's atmosphere. The diffuse component of solar radiation (E_{dif}) is a function of the optical thickness (from Liu and Jordan, 1960). For an optical thickness ≤0.777

$$E_{dir} = 0.995 + 0.048T - 3.467T^2 + 2.577T^3 . \qquad (2)$$

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For τ>().777, E_{dif}=0.155. The direct beam component (E_{du}) is given by

$$E_{dir}=1-E_{dif} \quad (3)$$

The largest errors in this computation occurred at sunrise and sunset when the direct solar rays were parallel with the surface of the pyranometer. These errors, however, were small compared to the potential energy received during most hours of a day.

The solar energy available at the top of the atmosphere was based on the solar constant (1353 Wm^{-2}), the declination of the sun, and the distance of the sun from the earth. The declination of the sun (δ) on any given day was computed using the fourier scries (Spencer, 1971)

$$\delta = 0.00618 - 0.39912\cos D + 0.070257\sin D - 0.006758\cos 2D + 0.00907\sin 2D - 0.002697\cos 3D + 0.001480\sin 3D \quad (4)$$

where D is given by

$$D=2\pi\left(\frac{d+\left(\frac{h-0.5}{24}\right)}{365}\right) \quad (5)$$

and d is the day of year (1-365) and h is the hour of the day. Subtracting 0.5 from the hour in equation 5 caused the computation of solar radiation at the top of the atmosphere to occur on the half hour and correspond with the time of the measured surface data. The measured data arc recorded on the hour and represent the average radiation intensity for the previous hour.

The distance of the sun from the earth (S_d) was computed using

$$S_d=1.0+0.03144\cos\left[\pi\left(\frac{d-3}{182.5}\right)\right] \quad (6)$$

where d is the day of year.

The total energy received on a sloping surface (E_T) was computed as the sum of the direct (E_{dir}), diffuse (E_{dir}), and reflected (E_1) radiation.

$$E_T=E_{dir}\cos i+\frac{1}{2}E_{dif}(1+\cos\theta_T)+\frac{1}{2}rE_r(1-\cos\theta_T) \quad (7)$$

where θ_T is the angle of the sloping surface from horizontal, and r is the albedo of the earth (assumed to be 0.2, representative of a grass surface). The angle of incidence of the solar rays and the normal to the surface is given by

$$\cos(i)=\cos(a)\,\cos(90-\theta_T)\,\cos(\alpha-\alpha_s) + \sin(90-\theta_T)\,\sin(a) \quad (8)$$

where a is the solar altitude above the horizon, a is the solar azimuth from north, and α, is the azimuth angle of the slope from north.

The energy available on each surface slope and aspect was computed each hour and the statistics were computed from these hourly values. Procedures used to compute the statistics are described below.

2.2 Wind Power Computations

The wind speed and direction are measured at a height of 10m at the ICN stations. Potential wind power at the 10m height was computed by

$$E_w=\frac{1}{2}\rho w_s^3 \quad (9)$$

where E_w is the wind power in $Wm^{"2}$, p is the air density, and w, is wind speed in ms^{-1}. This equation provides an estimate of the maximum potential energy and docs not account for any inefficiencies in the wind generators. Air density was computed using

$$\rho=\frac{m_d P}{RT^*} \quad (10)$$

where m_d is the mass of dry air in kgm^{-3}, p is the atmospheric pressure in pascals, R is the universal gas constant and T* is the virtual temperature. Atmospheric pressure (p) was assumed to be 100 kPa. Virtual temperature was computed by

$$T^*=\frac{1+1.608w}{1+w}T \quad (11)$$

where T is the air temperature. The mixing ratio (w) was computed by

$$w=\frac{\varepsilon e_s}{p-e_s}R_h \quad (12)$$

where E is the ratio of the molecular weight of water to dry air, and R_h is the relative humidity. The saturation vapor pressure (e_s) was computed using the Clausius Clapeyron equation

$$e_s=611\exp\left[\frac{m_v L_e}{R}\left(\frac{1}{273}-\frac{1}{T}\right)\right] \quad (13)$$

where c, is in pascals, m_v is the molecular weight of water, L_e is the latent heat of evaporation, R is the universal gas constant, and T is the air temperature.

The effect of including air temperature and relative humidity in determining air density in the wind power computation are shown in figure 1. If a standard atmosphere were assumed, with T=20°C rather than the actual air temperature, the error introduced at an actual air temperature of 30°C would be 3%. At 0°C the error would be 7%. Assuming a relative humidity of 100% introduces an error of 0.7% if the actual relative humidity were 50%. Both temperature and relative humidity were included in the wind power computations. The error introduced by neglecting relative humidity was small but the computing cost of including it was not significant so it was included. Although the effect of assuming a standard atmosphere temperature of 20°C is only 7%, and appears small, the effect of the error on computing the actual energy for a given hour and day can be significant. For example, an error of 7% will result in the energy computation for an hour of 252 J for each Wm^{-2} of potential in wind power.

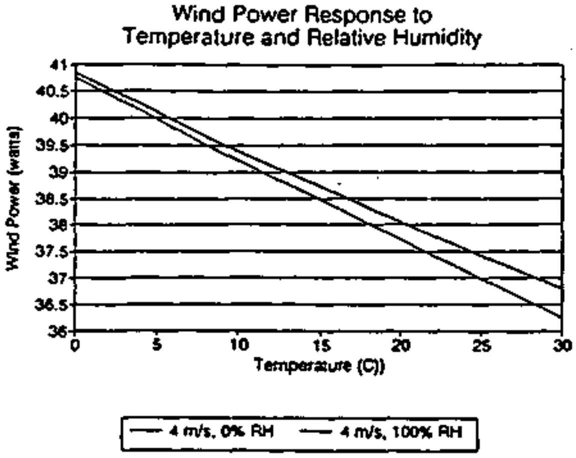

Figure 1. Effect of air temperature and relative humidity on the computation of wind power.

2.3 Statistical Computations

The mean $(\bar{X})$ and standard deviation (s) of the solar radiation received on a horizontal surface, and the 10 slope and aspect combinations were computed using (14) and (15), respectively,

$$\bar{X}=\frac{\Sigma x_i}{n} \tag{14}$$

$$s=\frac{\Sigma x_i^2-\Sigma \frac{x_i^2}{n}}{n-1} \tag{15}$$

where n is the number of observations. The mean, standard deviation, and number of observations were stored in a computational data file and are updated each year with the new year's data. A mean, standard deviation, and number of observations is stored for each hour of the day on a weekly and monthly basis. The data base is updated by computing a mean and standard deviation for each time period of the new year then combining them with the corresponding time period in the computational data base. Before the new sums and sums of squares are added to the old mean and standard deviation, the mean and standard deviation are decomposed into the old sums and sums of squares using the number of observations stored in the computational data base. After the old and new sums and sums of squares are added together, a new mean and standard deviation arc computed for the entire length of record.

Computation of the wind statistics was not as simple as for the solar data. The computation of the mean and standard deviation of the wind direction (w_d) required the computation of a vector mean and standard deviation. Vector components of the wind direction were obtained using

$$u=w_s\cos w_d \qquad v=w_s\sin w_d \tag{16}$$

where w_s is the wind speed, u is the east-west component of the wind direction and v is the north-south component. The mean and standard deviation of the wind components were computed using (14) and (15). The value stored in the computation data base is the mean wind direction in degrees (ϕ), computed by

$$\phi=\tan^{-1}\left(\frac{u}{v}\right). \tag{17}$$

The wind speed and power are both bounded by zero. This characteristic results in their distributions being highly skewed. Therefore, the normal distribution can not be used to determine the probability of different wind and wind power thresholds, an important parameter needed in determining risk. The gamma distribution is easy to use in fitting such skewed distributions (Haan, 1971) and can be described by the scale (λ) and shape (H) parameters. Values of H≤1 result in an exponential distribution, values greater than 1 give distributions that will approach a normal distribution. λ determines the maximum probability p(x) of the distribution where

$$p(x)=\frac{\lambda^{\eta}x^{\eta-1}e^{-\lambda x}}{\Gamma(\eta)} \tag{18}$$

where x is either the wind speed or wind power.

The maximum likelihood estimators for λ and H were obtained for each of the time periods in the data base using

$$\eta=\frac{1+\sqrt{1+\frac{4y}{3}}}{4y}-\Delta\eta \tag{19}$$

where

$$y=\ln\bar{x}-\overline{\ln x} \tag{20}$$

and

$$\lambda=\frac{\eta}{\bar{x}}. \tag{21}$$

where x is the mean wind speed computed using equation 14. The variables stored in the computational data base arc x and $\overline{\ln x}$ and n the number of observations. These first 2 variables are used to compute the λ and TJ estimators stored in the solar-wind atlas data base. λ and H are used by the atlas computer subroutines to compute the mean, standard deviation, probability density function (pdf) and cumulative density function (cdf) for each of the time periods. The pdf and cdf can be used to find the mode and the probability of the wind speed or wind power begin less than or greater than a specified value.

3. SOLAR WIND ATLAS DEVELOPMENT

Traditionally, information products describing the climatology of a location or area have been distributed as hard copy, printed materials. The main problem with hard copy products is that they become dated as soon as they are published. With the limited length of record currently available for ICN solar and wind data, it would be an additional 10 or more years before publishing a hard copy alias of the solar and wind statistics could be justified. Even then, only a limited number of tables, maps and graphs could be feasibly printed. By capitalizing on available computer technology, a computerized climatological solar and wind atlas based on an annually updated database could immediately provide useful, timely information to users.

A computerized atlas can present the solar and wind statistics in an essentially unlimited number of tabular and/or graphic screen displays. For example, by accessing the solar wind statistics database described in section 2.3, approximately 26,000 different contour maps and 58,000 different graphs can be generated and displayed.

3.1 Alias Requirements

The computerized solar wind atlas is a compiled C[2] program designed to: (1) be interactive and user friendly, (2) use pop-down menus, (3) run on 80286 and 80386 based microcomputers with an EGA or VGA color monitor, (4) be able to display solar and wind data in tabular and graphic forms, and (5) contain comprehensive on-line help.

3.2 The Illinois Solar Wind Atlas Program

The Illinois Solar Wind Atlas is a menu driven program. Six choices are accessible from the main menu: (1) Reports, (2) Graphs, (3) Maps, (4) Wind Roses, (5) System Help and (6) Quit. Submenus pop-down after each main menu choice except 'Quit', which exits the program. The user must proceed through a scries of data entry screens which define the product to be displayed. The data entry screens allow the user to select a data type (i.e. solar or wind) and parameters of interest (i.e. radiation on a vertical wall with an aspect of 165°), a station (or stations), a statistical summary period (i.e. week, month, season or year), and the hourly and/or daily summary value of interest. The data entry screens arc intuitive with user input limited to simple, explicitly stated keystrokes. After the selections are made, the program retrieves and displays the data without any further interaction from the user.

The 'Reports' option generates tabular displays of solar or wind means and standard deviations for any station or time period. The wind speed and power mode and probability can also be retrieved into a table. Tabular summaries arc useful when the user is interested in the actual numbers in the database for use in calculations or for detailed numeric comparisons between stations.

The 'Graphs' option generates x-y plots (Fig. 2) of solar or wind data versus time. These plots give the user a visual picture of time trends which are often hard to pick out of tabular summaries. The wind speed and wind power probability density distributions can also be viewed using the graphs option.

The 'Maps' option produces contour plots (Fig. 3) that show the spacial variation of solar or wind data for a specific time period across the state of Illinois. Such maps are very useful for quickly identifying the most

[2]The program was written using Microsoft C version 6.0.

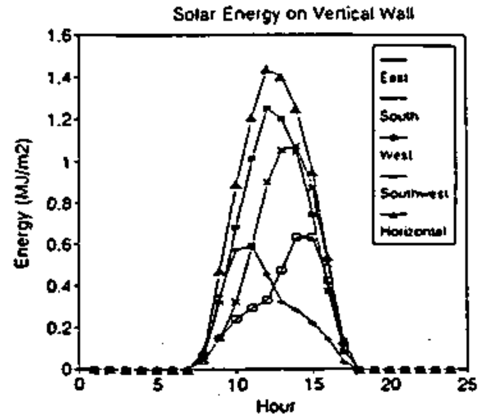

Figure 2. Graph generated by the solar-wind atlas program demonstrating temporal variation of solar energy recieved by a vertical wall facing different directions.

suitable location for wind or solar power generators during a specific time of year.

The final data display option, 'Wind Roses', generates a graphic frequency distribution of wind speed and direction for a specific station during a specified time period (Fig. 4).

The 'System Help' option is an on-line user manual and consists of a scries of text screens describing the menu options and how to use the computerized atlas. Also available are context sensitive help windows accessible from any menu option or data entry screen by pressing the F1 function key.

4. SUMMARY

A computerized Illinois Solar-Wind Atlas has been developed to make use of a short record of solar and wind data in Illinois. The atlas data base can be updated as additional years of data are obtained. Accompanying the computerized atlas will be a hard copy document describing how the atlas products were developed, showing examples of the products available, and

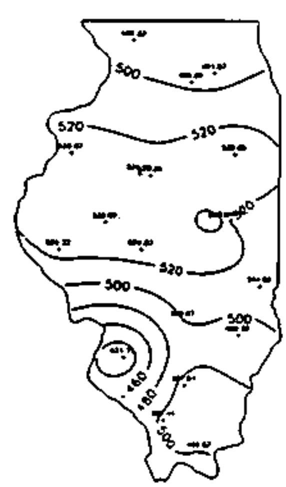

Figure 3. Map generated by the solar-wind atlas program demonstrating spatial variation of solar data.

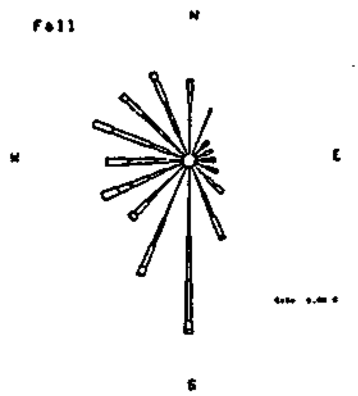

Figure 4. Example of wind rose generated by the solar-wind atlas program.

describing how the products generated may be used to evaluate the suitability of a location for using wind and solar power as alternative energy sources.

ACKNOWLEDGEMENTS

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OPERATIONAL CLIMATE INFORMATION DISSEMINATION: PRODUCTS, PROBLEMS AND PROGRESS

by:

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1. INTRODUCTION

The Midwestern Climate Information System (MICIS) provides access to regularly (daily) updated climate information which is used by a variety of organizations with a need for up-to-date information on climate conditions (Kunkel et. al., 1990). After two years of full operation, we find that midwestern agribusinesses comprise a large proportion of the frequent users although these are also significant numbers of users in other categories. The main purpose of MICIS is to provide a source of information on the current status of the climate of the midwest, particularly as it may affect agriculture and water resources. To this end, the following features characterize the system:

a. Full regional coverage of a 9-state area in the midwest is provided. Partial coverage of other areas (including Canada) which are within the Great Lakes drainage basin is also provided.
b. Daily updates to the climatic database are made utilizing reports from various National Weather Service networks and some state-run networks.
c. Large historical databases of daily data are on-line. Temperature and precipitation data are available for about 1500 stations.
d. Specialized products are derived from the climate data with the use of models. These include regional soil moisture estimates and corn and soybean yield risk assessments using crop development models.
e. Telephone and Internet access to the system are available.
f. A large variety of standard climatic products are available on-line.

2. DATA PROBLEMS AND CHALLENGES

Real-time updates of the climatic database are obtained, in large part, from the Domestic Data Plus Service of Zephyr Weather Information Services. When utilizing an operational data source (such as Domestic Data Pius) for climatic applications, problems of missing and erroneous data arise. This requires the implementation of estimation and quality control procedures.

With regard to precipitation, missing and erroneous data are difficult to identify and correct because of the high spatial gradients in convective precipitation patterns; we have yet to find a universally satisfactory solution. We have found that some stations persistently report erroneous precipitation values (as evidenced by frequent large differences compared to surrounding stations). In a few cases, the frequency of these erroneous reports has forced us to eliminate stations from the real-time database. We also eliminate values of daily precipitation for all stations when those amounts exceed 7 inches, thereby addressing the worst problems with erroneous precipitation data. Problems with missing precipitation data are very difficult to address, particularly for stations which are event or criterion reporters (that is, they report only when precipitation exceeds some threshold value). In these cases, the station totals for any recent time period tend to be systematically low. An option is available to fill in missing precipitation data with the climate division average. These problems generally disappear once we receive preliminary data from the National Climatic Data Center (about five weeks after the end of a month).

Handling of temperature data problems is conceptually easier because of the spatially coherent nature of temperature fields. Therefore, we have incorporated an objective analysis program into the system, which allows us to calculate gridded temperature fields on a daily basis. Erroneous values are automatically screened when they exhibit large differences from surrounding temperature values. The gridded data sets also allow us to estimate missing values by interpolating among the nearest gridpoint values.

Gridded temperature fields are calculated each day around mid-morning once the majority of morning reports have been received. In this manner, the gridded data are also a near real-time source allowing current assessments of climatic conditions. We have also generated an historical gridded data set by performing the objective analysis on daily data for the period 1948 to the present. This allows us to estimate missing data for. that entire period.

The gridded data set provides a major advantage compared to station data since it inherently has no missing data. It allows us to look at spatial temperature patterns for any period to assess the anomalies. As an example, Figure 1 shows gridded data values for the summer of 1988, illustrating the spatial anomaly patterns for that very warm summer. This also allows us to quickly determine anomaly patterns for recent periods, such as the last week, last month, or seasons.

3. SPECIAL PRODUCTS

To address the specific needs of the midwest, we have developed several special data sets which are used

Figure 1 - Gridpoint temperatures (°F) expressed as deviations from normal (1951-1980) for summer (June 1-August 31) 1988.

both internally and by a small number of our more sophisticated users. In addition to the gridded temperature data set, other special data sets of interest include:

a. A daily solar radiation data set has been generated for 53 stations for the period 1948-present. This has been done using a semi-physical model (Petersen, 1990; Petersen et al., 1991) which utilizes hourly observations of cloud cover, humidity and temperature.

b. A daily potential evaporation data set has been developed for the same 53 stations and the same time period as above, using hourly wind, dewpoint, cloud cover and temperature data. (Both of the above data sets are essential input to the operational soil moisture and crop yield models. Table 1 shows an ex-ample of a month of daily solar radiation and potential evaporation data in addition to other variables calculated from the hourly data at Chicago).

c. The soil moisture model (Kunkel, 1990) has been used to generate a weekly soil moisture data set for the period 1949-present. This data set allows a historical perspective on the current operational soil moisture estimates. For instance, Figure 2 shows soil moisture values for mid-July of 1988 expressed as anomalies based on this historical data set.

d. The objective analysis program has been used to generate climate division values (daily) of solar radiation and potential evaporation using the data from the 53 stations. Since the soil moisture and crop yield models are implemented on a climate division basis, this allows direct input into these models.

4. SUMMARY

This system has demonstrated its usefulness to agribusinesses and other weather sensitive users in the Midwest, including the scientific community. Some of the problems with real-time data availability, particularly missing erroneous data, diminish the attractiveness to potential users. Although we have addressed these problems for temperature, precipitation presents a more challenging problem given the convective nature of summertime rainfall. We are continuing to investigate ways to partially solve this problem using statistical studies of precipitation spatial coherence. Nevertheless, this problem will remain until more sophisticated technologies such as NEXRAD provide more spatially and temporally complete estimates of precipitation.

Table 1 - Daily Averages of hourly surface observation data from Chicago for July 1990

Station: (ORD) CHICAGO_OHARE_WSO_AP

yyyymmdd	Air Temp (F)	WetB Temp (F)	DewP Temp (F)	Min RelH (per)	Max RelH (per)	Wind Speed (mph)	Wind Direc (deg)	SeaLev Press (mb)	Solar Radiat (MJ/sq m)	Pot Evap (in)
19900701	68	61	57	55	90	12	27	1017	29.7	0.25
19900702	72	64	59	46	93	6	162	1016	29.1	0.22
19900703	81	71	67	50	81	16	198	1011	28.5	0.31
19900704	87	77	74	50	87	14	236	1011	29.2	0.32
19900705	72	65	62	43	90	11	7	1017	26.1	0.22
19900706	63	56	51	48	90	11	38	1022	30.1	0.23
19900707	70	61	56	44	93	11	165	1019	20.5	0.20
19900708	84	73	68	43	71	14	213	1013	29.0	0.34
19900709	80	71	67	42	84	8	0	1015	22.4	0.20
19900710	71	66	64	63	97	9	12	1018	19.0	0.14
19900711	66	62	59	60	96	13	48	1016	21.2	0.17
19900712	66	59	55	56	90	18	23	1019	23.7	0.25
19900713	62	57	53	60	86	16	30	1021	21.9	0.19
19900714	62	59	58	75	96	10	30	1012	10.4	0.07
19900715	64	62	61	60	96	5	223	1012	21.8	0.13
19900716	71	67	65	61	96	11	218	1016	23.1	0.18
19900717	77	68	64	35	87	13	211	1019	26.0	0.28
19900718	75	69	67	54	93	10	207	1019	23.4	0.21
19900719	74	71	69	60	97	10	209	1017	22.8	0.18
19900720	69	67	67	75	97	9	329	1014	17.4	0.11
19900721	69	62	58	43	100	8	30	1015	20.9	0.17
19900722	67	64	62	68	96	10	61	1013	23.0	0.16
19900723	69	62	58	48	100	8	286	1016	26.8	0.20
19900724	70	63	60	46	93	6	187	1019	26.0	0.19
19900725	74	66	62	48	96	6	200	1022	25.9	0.20
19900726	76	67	62	43	90	9	138	1023	23.5	0.22
19900727	76	68	64	54	87	8	160	1021	21.0	0.18
19900728	79	72	69	56	87	10	176	1017	10.5	0.12
19900729	78	73	71	62	97	9	237	1012	21.7	0.18
19900730	70	66	63	59	93	12	11	1015	23.2	0.19
19900731	62	56	51	50	93	10	10	1021	27.4	0.21

Figure 2 - Soil moisture (inches) expressed as deviations from average for mid-July 1988. Averages are calculated from a modeled historical soil moisture data base for the period 1951-present.

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IMPLEMENTATION OF A SEMI-PHYSICAL MODEL FOR EXAMINING SOLAR RADIATION IN THE MIDWEST

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1. INTRODUCTION

Publication of solar radiation (SR) data was stopped by the U. S. Weather Bureau in 1972 when it became clear that its network's routine observations contained errors of ±5 to ±30% (Thekarhara 1976). The available hourly radiation data were subsequently rehabilitated by the National Oceanic and Atmospheric Administration (NOAA) for 26 stations by applying a correction that largely accounted for a slow instrument deterioration. These stations, for which rehabilitated hourly radiation data are available for 1952-1975, are known as the SOLMET (SOLar METeorological) stations. The data from this sparse network of United States stations have been used extensively in SR research, even though their accuracy is somewhat uncertain because they contain adjusted observations. Nevertheless, in the Midwest region only two SOLMET stations exist.

In order to examine SR in the Midwest, a long-term SR data set needed to be created, since the network of available SR measurements, be they the SOLMET data or those from other localized networks, is either sparse or lacking in longevity. A semi-physical SR model was used to generate daily values of SR for 53 locations in 9 agriculturally important states (Minnesota, Iowa, Missouri, Illinois, Wisconsin, Michigan, Indiana, Ohio, Kentucky) for the 40 year period 1948-1987. These data were then analyzed to provide information on the spatial and temporal variability of SR throughout the Midwest

2. METHODOLOGY

The SR received at the earth's surface is given by

$$I = I_o (\cos Z)\, T_R T_g T_w T_a T_c \qquad (2.1)$$

where I_o is the extraterrestrial flux density at the top of the atmosphere on a surface normal to the incident radiation, Z is the solar zenith angle, and T_i denotes the transmission coefficients after Rayleigh scattering *(R),* absorption by permanent gases (g) and water vapor (u'), absorption and scattering by aerosols *(a),* and cloud attenuation (*c*). A complete description of the model can be found in Petersen (1990) or Meyers and Dale (1983).

The input parameters required by the model are: time of day, day of year, latitude, longitude, surface pressure, dew point temperature, cloud height and fractional sky coverage, and the presence or absence of snow cover. The TD-3280 Surface Airways Hourly data were acquired on magnetic tape from the National Climatic Data Center (NCDC 1986) for the time periods available for each of 53 Midwest stations. Care had to be taken when using these data since 1) the reporting times and intervals for each station were not constant during its period-of-analysis. and 2) close examination indicated that the absence of the sky condition element during an entire day indicated no clouds to report that day rather than missing data.

A significant effort was made to calculate the most accurate possible SR value for each day of a station's period-of-analysis. For the time period previous to 1 June 1951, as much cloud information as possible was obtained from the general sky condition element, which included fractional amount of the higher layer, fractional amount of the lower layer, and the height of the lowest scattered layer. However, preliminary tests indicated that the literal use of this information led to unrealistically low values of SR for this time period; in addition, the quality of this element is marred by many missing values. Subsequently, an attempt was made to use ceiling height in order to estimate cloud heights. This approach was found to be successful and is described in detail in Petersen (1990).

Considerable examination of the surface hourly data suggested that there was a mixture of reporting (or perhaps archiving) procedures between the stations concerning cloud information after 1 June 1951. Three possible combinations existed concerning the cloud elements: 1) both sky condition and cloud heights reported; 2) sky condition only reported; and 3) neither reported. Most of the time, both elements were given; however, on occasion neither element was given. In this instance, it was assumed, based on examination of the data, that neither element was recorded/archived because there were no clouds during the day or hour to report. For some stations, however, the cloud height element was not given whether there were clouds or not. This situation led to the development of the similar, successful approach using the ceiling height to determine cloud heights as was done for data prior to 1 June 1951. A comprehensive description of this method is also given in Petersen (1990).

Ideally, a SR value was calculated for each hour during the day, and then summed to produce the total SR for that day. However, if any input parameter was missing for a given hour (with the exception of sky condition as described above), the SR value for that hour was initially also set to be missing. Even though most of the time both the sky condition and cloud height elements were reported during a day, the cloud heights were rarely reported every hour, as the sky condition usually was, but rather every 3 hours. This resulted in periodic hours of missing SR. To fill in these hours, interpolation was needed. Due to the discontinuity in the location of clouds from one hour to the next, which encompasses the fact that, at one hour, the cloud height of layer 1 may be the height of last hour's layer 2 since layers can disappear from hour to hour, the T_e variable was interpolated between given hours rather than the layer's cloud height or the transmission coefficient for that particular layer. A linear interpolation scheme with step interpolation at the ends was used, but if more than 2 consecutive daylight hours were missing, those hours were left missing/unknown.

It was found that frequently when a station reported the sky condition to be partially obscured, the corresponding height was reported as unknown/missing. To minimize the possible number of interpolations and perhaps missing daily SR values, the cloud height was set to 900 feet when the sky condition was given as partial obscuration, since phenomena which partially obscure the sky occur close to the ground.

On occasion, the reported sky condition did not match the reported cloud cover for the same hour [clear (CLR) = 0 tenths, scattered (SCT) = 1 to 5 tenths, broken (BKN) = 6 to 9 tenths, overcast (OVC) = 10 tenths]. For example, the 7:00 am observation on 5 July 1951 at Springfield, Illinois reported the cloud information shown in Table 1. Clearly, the sky condition and tenths of cloud coverage for layers 2 and 3 do not match. Thus, it was assumed that when a sky condition other than CLR was reported at the same layer as 0 tenths cloud coverage for a given hour, the sky condition was taken to be that of the next higher layer. In other words, in the example in Table 1, it was assumed that layer 1 was SCT (2/10) at 7000 ft, layer 2 had no clouds (0/10), and layer 3 was -OVC (8/10) at 25000 ft (i.e., 2 layers total of clouds for this hour).

Actual snow cover data were used for each day at each station, if available. If it was not available at that station on a given day, the next closest station with available data was used. If no other nearby station had data, a climatology of snow cover for the station was used. That is, for a given day of a given week, snow cover was assumed if climatology (based on the years 1948-1987) indicated 50% or more of the time there was snow cover for that week.

It was somewhat common for missing hours of dew point temperature and surface pressure to occur which potentially resulted in missing daily totals of SR. Separate tests of the model's sensitivity to dew point temperature and to surface pressure indicated that substituting an average dew point temperature or an average pressure, whether they were an average of the available hours of a day or a monthly climatological average for missing temperature/pressure data, resulted in non-detectable biases in the SR data.

The model generated SR values were compared and validated against several sets of measured SR data, including SOLMET and regression-extended SOLMET values. Comparisons indicated that the model generally tends to over-predict daily totals of SR on average, but more so in the cooler months (October-March) than the warmer months (April-September). The mean absolute error was approximately 1.6 MJ m^{-2} day^{-1}, which translates to differences from 8-12% of the measured averages. Comparisons of modeled data with regression-extended SOLMET data suggested that the regression-extended SOLMET data should be viewed with caution, which is in agreement with findings of the Solar Energy Research Institute (1990).

3. RESULTS

Calendar monthly means were calculated for each of the 53 stations for its period-of-record. Analyses of the resulting spatial patterns for the four mid-season months are presented in Fig. 1.

The most basic feature of these SR fields is a northward decrease in SR, as one would expect, with the strongest gradient in October and weakest in March. For most months, however, the SR isopleths cross the latitude lines at a slight angle rather than running parallel to them. This northwest to southeast orientation is due to increasing frequencies of cloud cover from west to east, and may in part be due to the increasing altitude towards the west, which results in a shorter air mass path length for the sun's rays, and atmospheric humidity.

The SR pattern for the Midwest is less smooth and more meso-scale in character from the late spring into the summer months. One prominent feature evident during these months (April -August) is an area of low SR over northern Wisconsin extending into the Upper Peninsula of Michigan and over northern Lake Michigan into northern Lower Michigan. The stations in this area are Eau Claire and Green Bay (Wisconsin) and Gwinn and Traverse City (Michigan). The quality of the data at Green Bay is believed to be very good. Although the data quality for the other three stations

Table 1. Example of cloud information reported for one hour.

	Sky Condition	Actual Tenths Coverage	Height of Layer (ft)
Layer 1:	SCT	2/10	7000
Layer 2:	-OVC	0/10	18000
Layer 3:	CLR (no clouds/unknown)	8/10	25000
Layer 4:	CLR (no clouds/unknown)	0/10	unknown

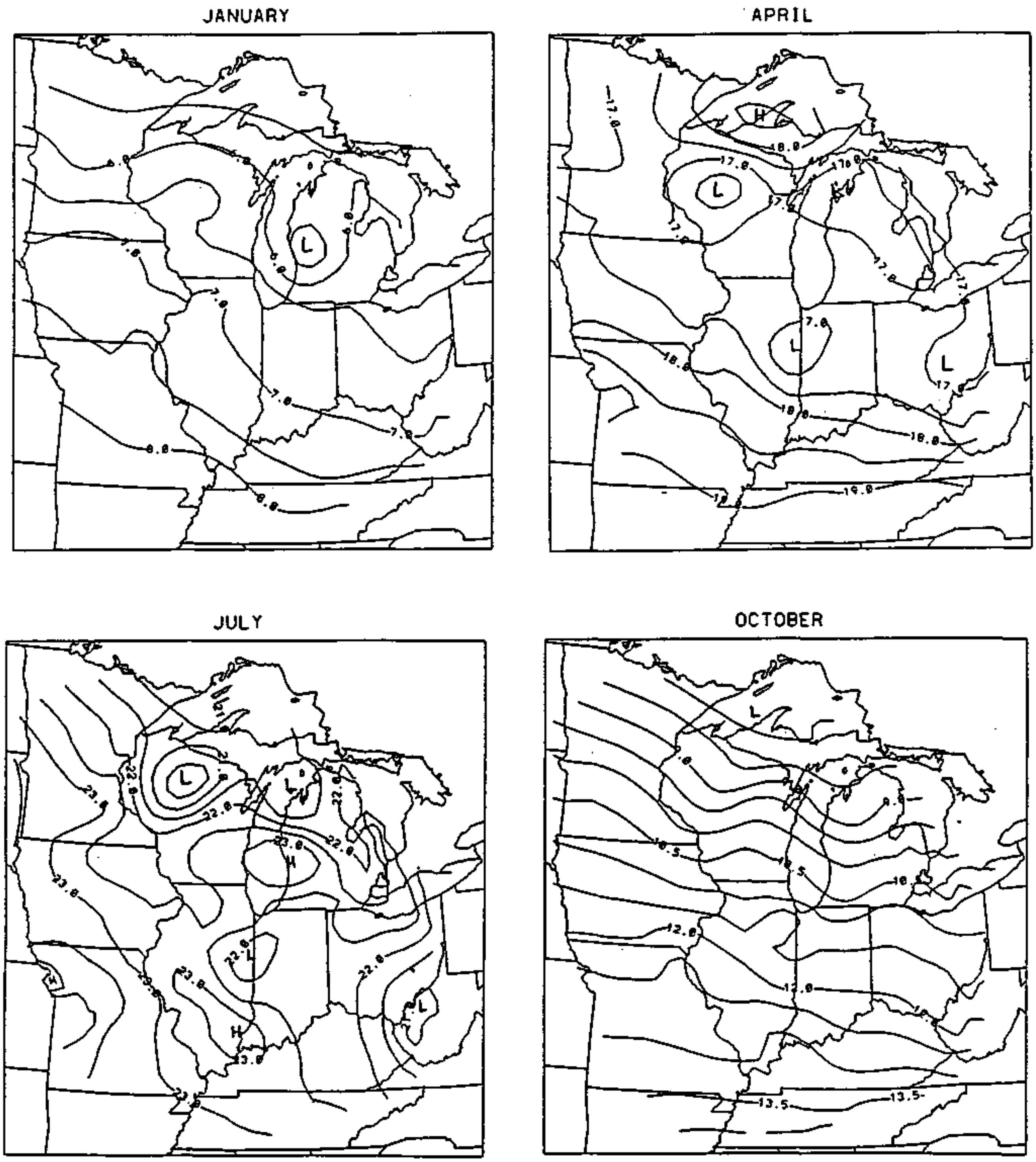

Fig. 1. Spatial variations in mean daily totals of SR for the mid-season months (January, April, July, and October) over the midwest region. Contour interval is 0.5 MJ m^{-2} day^{-1}.

is less certain, the pattern is believed to be correct. Total sky cover statistics for the period-of-analysis at Eau Claire show a lower percentage of clear sky hours by 2 to 5% than at either Minneapolis or Green Bay. Eau Claire also shows a higher percentage of overcast hours by as much as 5% compared to these other 2 stations.

Another evident meso-scale feature is that Kansas City's Downtown Airport (lower SR) and more-removed International Airport (higher SR) differ in their June and July means. A possible explanation for this discrepancy might be the heat-island urban effect; the International Airport is located just outside the metropolitan area to the north and would thus be less affected by the urban-induced cloud cover to which the downtown airport would be subjected.

All months show the thermal effect of the Great Lakes. In summer, the predominantly southwesterly winds (Eichenlaub *et al.* 1990) blowing across the relatively cool water will suppress convection and cloud formation over and along the eastern shore of Lake Michigan, for example, as is evident by the SR maxima over the Muskegan (Michigan) vicinity during these months (seen in July in Fig. 1).

During September/October through March/April, the Great Lakes are warmer than the surrounding air or land (Eichenlaub *et al.* 1990). The predominantly westerly winds over the Lakes carry warm, moist air across to the eastern side, causing clouds to form there, as was found by the progressive appearance of low SR over Lower Michigan from October through January and February. A further characteristic of the fall SR pattern is the return to the smooth northwest-southeast oriented isopleth pattern in September from the weak gradient character of July and August. This smooth pattern continues into October, November, and December with the large gradient of October continuously weakening into November and December.

Time series of mid-season individual monthly mean SR values for 1948-1987 were found. A linear regression line was fitted to each time series, and the slopes of these regression lines were subjected to the Students *I* test to determine their statistical significance. Fig. 2 portrays the spatial coherency of these trends for the Midwest.

Figure 2 shows a strikingly coherent temporal trend pattern for October. That is, the October trends for all stations are negative, and most are highly (>95%) or extremely (>99%) significant. The October trends significant at the >99% level are generally located at stations in the central part of the region. Thus, the spatial coherency of these trends is extremely high. Only 16 October trends are not significant at the >95% level. Half (or 8) of these stations have shorter than 40 year periods-of-analysis, ranging from 14 years at Gwinn (Michigan) to 33 years at St. Cloud (Minnesota). These shorter periods result in smaller degrees of freedom which, in turn, are reflected in the significance value (i.e., the smaller the degrees of freedom, the larger the *t* value must be in order to be significant). The other 8 stations with <95% significant October trends have anywhere from 39 to 43 years of data for each station. Four of these stations (International Falls, Des Moines, Sault Ste Marie, and Covington/Cincinnati) are significant between the 90-95% level. The other 4 stations with about 40 years of data each are farther south and east, and have trends that are <90% significant.

The January results show a swath of significant (>90%) upward trends in the central Midwest, generally oriented in a south-southwest to north-nonheast direction, with more than half of these trends highly significant (>95%). Additionally, six of these trends were found to be >99% significant and are spatially coherent in eastern Illinois and western Tennessee, with the exception of Toledo.

The stations with positive trends for April tend to be in the eastern portion of the Midwest, while those with negative trends for that month are largely in the western pan of the region. Only a few (11) stations have significant trends, and only 5 of those are highly significant (>95%). There is little spatial coherency in the stations with highly significant trends, except for Fort Wayne and Cleveland which are near Toledo, whose tendency is 90-95% significant. Most April trends, however, are not (>90%) significant

The July trends show less spatial coherence throughout the region than those for the other mid-season months. About two-thirds of the trends are positive, and not quite half of these trends are significant (>90%) or highly significant (>95%). The negative trends are found mostly around the Great Lakes and in Ohio, with a few exceptions (Alpena, Muskegan, and Toledo show positive trends). Positive trends prevail elsewhere. The most significant ones are located in the central part of the region, but they are interspersed with some insignificant positive and negative trends. These significant positive trends are somewhat coherent in the southwest quadrant of the Midwest. Springfield, Evansville, and Memphis show the highest significance (>99%) of the positive trends in this area.

4. SUMMARY

This study arose from the need for a detailed documentation of the solar radiation (SR) climate of the Midwest region. Previous SR climate studies have been contradictory in establishing the SR climate of the Midwest region, partly due to the lack of available data. Because the network of SR measurements for this region is either sparse or lacking in longevity, a semi-physical SR model based on Meyers and Dale (1983) was implemented and used to create a 40-year (1948-1987) data base of daily SR values for 53 stations in the Midwest.

Techniques employed to insure the most complete possible SR data base for each station included: 1) using ceiling height to estimate various cloud layer heights when cloud heights were missing; 2) interpolation of modeled parameters over one or two consecutive hours with no data; 3) substituting climatological values of dew point temperatures and surface pressure when one of those elements was missing for all hours of a day; and 4) using nearby stations with snow cover or a climatology of snow cover when a particular station's daily snow cover value was missing. As a result, the daily SR data set generated is 93% complete for the 53 stations for 1948-1987.

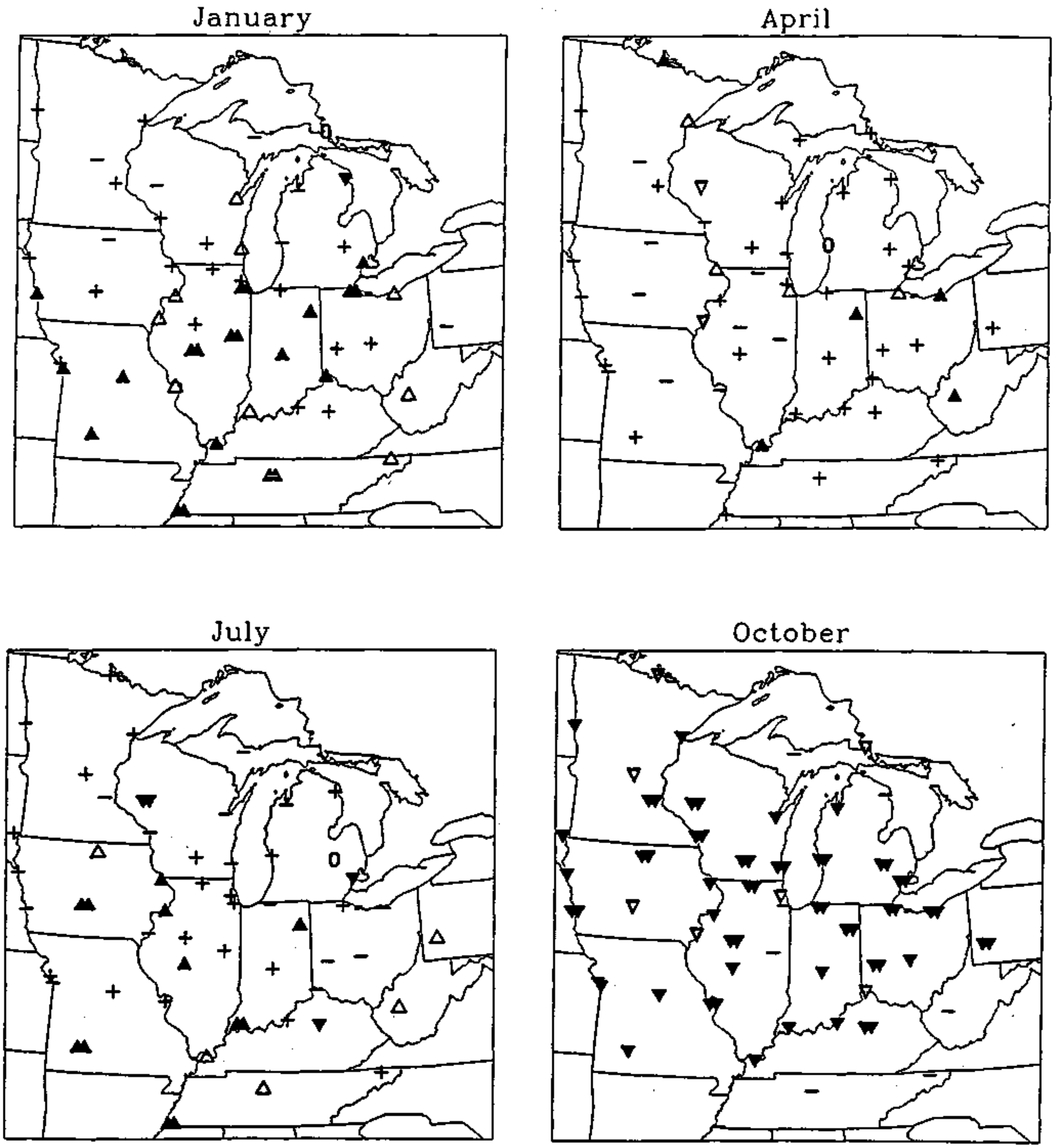

Fig. 2. Spatial coherency of SR trends for 1948-1987 for January, April, July, and October months. Relatively insignificant (<90%) positive and negative trends are shown with a + and -, respectively; significant (90-95%) positive and negative trends display a Δ and v, respectively; and highly significant (>95%) positive and negative trends are shown as Δ and v, respectively. Double solid triangles indicate significance at the >99% confidence level. No trend is signified by a 0.

The monthly mean spatial patterns obtained from the data set exhibited some pronounced characteristics. The most dominant feature is a northward decrease in SR, with the strongest gradient being in October and the weakest in March. For most months, however, the SR isopleths have a slight northwest-southeast orientation rather than running parallel to the latitude circles. This near-zonal SR pattern is most pronounced during the fall and winter months. However, the pattern becomes more meso-scale in character from the late spring into the summer months.

Investigation of the temporal SR variability during 1948-1987 revealed that long term (40-year) trends for the Midwest region show a strikingly coherent pattern for October: all 53 stations have downward trends and most are highly (>95%) or extremely (>99%) statistically significant. This strikingly coherent pattern was less visible for the other mid-season months, which displayed mostly positive trends.

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ESTIMATIONS OF A CHANGED CLIMATE ON HEAVY RAINFALL FREQUENCIES

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1. INTRODUCTION

The growing concern over projected climate change due to the Greenhouse Effect has impacted the hydrologic community. There is broad consensus that study of the climate effects on the hydrologic cycle is of paramount importance. Shifts in average seasonal temperatures and precipitation values derived from global climate models have been assessed for their hydrologic importance in the Great Lakes Basin (Smith and Tirpak 1989). However, many other important climate change questions are facing hydrologists who design water resource structures that have 10- to 100-year lifetimes and must accommodate climate variability (Nemec and Schaake 1982). One of these concerns relates to possible changes in extreme precipitation conditions such as droughts or heavy rainfall events (Gleick 1989).

The outputs of existing global climate models arc not considered adequate to specify the regional precipitation conditions for many applications (Schneider, 1990), including data for addressing the extreme rainfall issue. To obtain a first approximation of possible shifts in heavy rainfall conditions under varying climatic conditions in the central Midwest, we utilized data from historical analogs.

We did follow the prevailing expectations from the global climate models for midwestern conditions in defining our potential scenarios. The models suggest a climate that, in both winter and summer, will be 1° to 3°C warmer on the average, with seasonal precipitation that varies from -10% to +20% of current averages (Jenne 1988).

We used temporal and regional analogs drawn from the past 100 years as a means to estimate possible shifts in extreme rain events, an approach used by others to investigate possible effects of climate change on water resources (Glantz 1989). To examine for the possible shift in design events with a climate warmer and wetter than current conditions, we compared rain events between areas in Illinois which have average conditions that differ sufficiently to represent a 3° to 4°C increase in temperature and a +20% change in precipitation. We then compared the heavy rainfall frequency relations in these areas to define differences considered reflective of possible changes.

To estimate the potential effects of a warmer and drier regime on heavy rainfall conditions, we selected the extremely warm and dry periods of the past 100 years in Illinois and compared their heavy rainfall frequencies with those based on all data since 1900. Hansen et at. (1988) calculated shifts in droughts using global climate models and found an increase in droughts due to climate change. The major drought periods studied in Illinois occurred during the 1930s and early 1950s.

2. POTENTIAL EFFECTS OF WARMER AND WETTER CLIMATIC CONDITIONS

The effect of the climate becoming warmer and wetter was investigated for the distribution of heavy rainstorms in the Midwest This was done by comparing the frequency distribution of such storms between the ten climatic regions of Illinois. Each has a homogeneous rainfall regime, and they are shown in Figure 1. These regions were defined by a study of heavy storm characteristics during the period 1901-1987. A relatively wide range exists in the regional temperature and precipitation normals in Illinois due to a north-south extent of more than 600 kilometers. For example, the annual mean temperature varies from approximately 9.4°C (49°F) in the NW region (Fig. 1), to 14.0°C (57°F) in the South region. This spatial difference in warming of 4.6°C approximates some climate model-related projections for future temperature change in the Midwest Similarly, the annual average precipitation increases southward across Illinois from 90.2 cm (35.5 in) in the NW region to 112.3 cm (44.2 in) in the South. This spatial difference represents an increase of approximately 25% from the extreme northern to the extreme southern parts of the state. Again, this difference approximates the GCM estimates for the central United States. In essence, we used the differences between the NW and S regions as an estimate of what would occur in the NW region under a warmer and wetter climate.

Table 1 shows the frequency distribution of heavy storm rainfall events of 24-hour duration in the NW and S regions. Rainfall values are shown for selected recurrence intervals and represent relations for any selected point in each region. Columns 4 and 5 show the S-NW differences. The relations shown in Table 1 are typical of those found for shorter and longer storm durations, and incorporate the type of information essential to the design and operation of various water control structures (storm sewer systems, dams, spillways, etc.).

The differences reflect the effect of warmer temperatures which are normally associated with a longer convective rainfall season in the South and consequently, more thunderstorm rainfall. Heavy rainfall events in the Midwest are often associated with thunderstorm activity. Thus, if the northwestern Illinois climate was altered to closely represent the warmer and wetter climate now existing about 600 kilometers southward, we would estimate the net effect to be an increase on the order of 10% to 15% in the intensity of heavy storm events, as shown in Table 1. This difference would result in an increase in failures of many flood control structures in the north that were designed on present-day rainfall relations. For example, a rainfall amount rated as a once in 5-year event in the NW area occurs twice as often in the South (2.5-year occurrence). Similarly, the 10-year, 25-year, 50-year, and 100-year events in the NW are experienced in 5, 15, 30, and 60 years, on the average, in the South, as revealed in figure 2. Of course, the opposite effect might well occur in southern Illinois if a similar climate shift to cooler and drier conditions occurred.

The foregoing analysis provides one estimate of the magnitude of changes that could occur in the distribution of heavy storm rainfall events in NW Illinois with a change to a warmer and wetter regime than presently exists. It appears that the spatial comparative technique used here could be used for obtaining first estimates of the consequences of potential future climate changes on the distribution of other meteorological events involving precipitation and temperature.

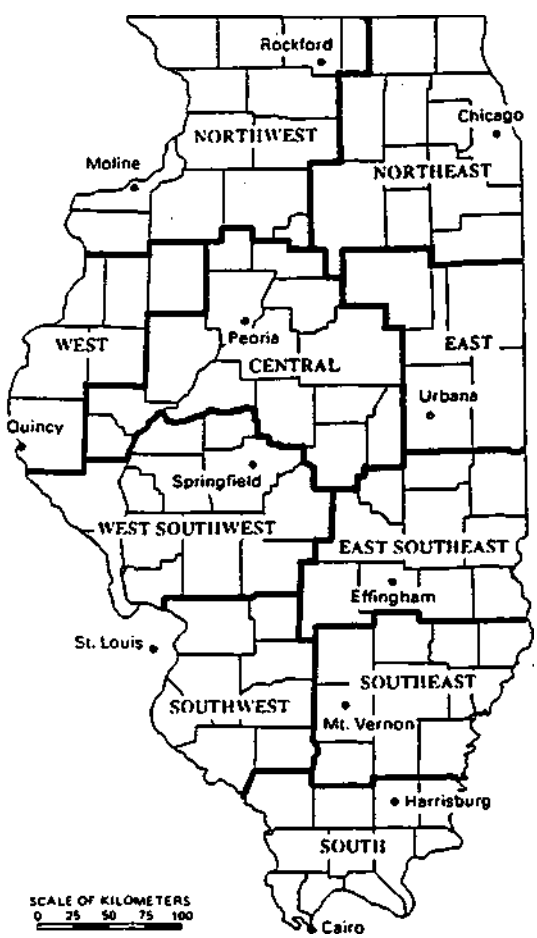

Figure 1. Climate regions defined lor Illinois rainfall frequency relations and stations used in the analysis of the 1930-40 warm and dry period.

TABLE 1. Comparison of Average Frequency Relations from Northwestern and Southern Illinois for 24-Hour Storms.

Recurrence Interval (Yrs)	Rainfall (cm) for Given Section		S-NW Difference	
	NW	S	Centimeters	Percent
2	7.9	9.2	1.3	16
5	10.0	11.5	1.5	15
10	11.8	13.2	1.4	12
25	14.2	15.8	1.6	11
50	16.2	18.2	1.6	10
100	18.7	21.1	2.4	13

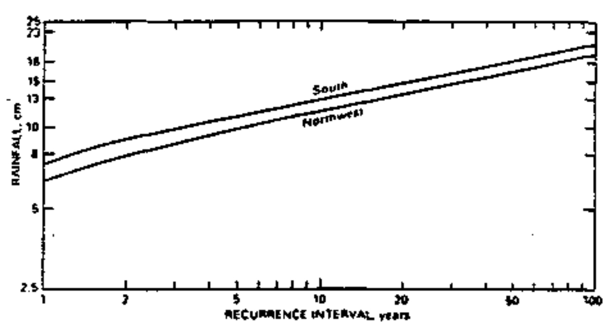

Figure 2. Frequency distribution of 24-hour rainfall values in the Northwest and South climatic regions of Illinois.

3. POTENTIAL EFFECTS OF WARMER AND DRIER CLIMATIC CONDITIONS

To obtain an estimate of the effects of a climate that was considerably warmer and drier than current average conditions on the distribution characteristics of heavy rainstorms, we used as two analogs, both prolonged periods of abnormally warm and dry conditions. The rainfall frequency distributions (at individual points) based on long-term data (1901-87) were compared with those obtained from data for 1930-40 and 1951-55. These were periods that encompassed the two worst prolonged droughts in the central Midwest (Easterling and Changnon 1988).

Such temporal differences in rainfall frequencies were used to provide an estimate of the effects on heavy rainfall distributions with a change to a warmer and drier climate than now exists in Illinois. During the 1930-40 period, the statewide average precipitation was 9% below the 87-year average and the mean temperature was 1.1° C above average. In the 1951-55 period the statewide precipitation was 13%

below average and the mean temperature was 0.9°C above average.

Comparisons of frequency distributions were done for 12 stations (Fig. 1) selected to sample conditions throughout Illinois. Comparisons were made of rainfall amounts with recurrence intervals of 2, 5, and 10 years. The two analog periods were considered too short to derive comparisons for longer recurrence intervals.

3.1 The 1931-40 Period

Table 2 shows the results of certain comparisons of the 1930-40 drought. For each station, the differences in millimeters and percent of the long-term average are indicated for the three recurrence intervals. The negative values are those for which the drought frequency curves indicated larger amounts during 1930-40 than the long-term, 87-year curves. To illustrate use of the table, note the Springfield values. At all three intervals, the drought period values were less, being 0.7 mm less at 2 years, 10.7 mm at 5 years, and 19.8 mm at the 10-year values. Results for most stations indicate a decided trend for the differences to increase with increasing recurrence interval. That is, during the 1930-40 warm-dry period, the magnitude of the more intense storms w'as suppressed to a greater degree than in the more moderate heavy storms. For example, at Chicago the suppression effect increases from a 2% decrease at the 2-year frequency to a 27% decrease at the 10-year recurrence interval.

TABLE 2. Comparison of Rainfall Frequency Relations Based on Long-Term Data (1901-87) with those Derived from 1930-40 Drought Period, for 1-Day Rainfall.

Difference (millimeters and %), Long-Term Average - Drought Period Value, for Given Frequency (years)

Station	2-year		5-year		10-year	
	mm	%	mm	%	mm	%
Chicago	1.3	2	15.5	18	27.2	27
Rockford	2.3	3	18.8	19	8.4	16
Moline	8.9	13	12.7	21	17.0	16
Quincy	10.1	13	15.5	16	14.9	14
Peoria	1.8	3	9.4	11	22.1	21
Springfield	0.7	1	10.7	12	19.8	21
Urbana	2.1	4	10.2	12	14.7	16
Effingham	-1.8	-3	2.5	3	7.9	8
Mt. Vernon	-3.0	-4	-4.3	-5	-2.3	-2
St. Louis	-13.5	-18	-2.3	-2	5.6	5
Harrisburg	9.4	11	8.9	8	13.2	10
Cairo	-0.7	-1	-9.4	-9	-9.9	-8
Median	1.0	+ 3	9.1	+ 9	8.1	+ 15
Range (%)	13 to-18		21 to -9		27 to -18	
Mean		+ 1		+ 7		+ 10
Regional Means	mm	%	mm	%	mm	%
North & Central	3.8	6	13.7	16	18.3	18
South	-1.9	-3	-0.9	-1	2.9	2

The effect was found most pronounced in northern and central Illinois, the 7 stations listed in the upper part of the table. The five station values at the bottom of Table 2, those for southern Illinois, show lesser effects, generally less than 10% at all intervals. The average for the seven northern and central stations (Chicago, Rockford, Moline, Quincy, Peoria, Springfield, and Urbana) increased from 6% at 2 years to 16% at 5 years, and to 18% at 10 years. The averages for the southern stations were -3%, -1%, and 2% for the 2-, 5-, and 10-year recurrence intervals, respectively. This areal difference was related to the drought's pattern which was relatively more severe in the north and central sections.

The annual precipitation during the 11-year drought period had a median departure from 87-year average of -10.5 cm (-8%) in the north. In the central part of the state, the median was -53 cm (-6.4%), and in the south the median departure was -3.4 cm (-3.2%). In the north, 8 of the 11 years had below average precipitation, whereas in the central and south, 7 years were below average. The precipitation drought was least severe in southern Illinois during this 11-year period, and its effect on the frequency distribution of heavy rainfall was least in this region.

Additional information on the magnitude of the heavy rainfall change during the unusually warm and dry conditions of 1930-40 is shown in Table 3. The frequency of storm rainfalls equalling or exceeding the long-term (1901-87) values for various recurrence intervals is shown for 1-day rainfall values during the 1930-40 period, using the same 12 stations. The frequency of occurrence during the drought period can be compared with the expected number in a normal 11-year period, as based on 1901-87 data, shown in table 3. The average frequency of 2-year maximum amounts was slightly less than the normal expectancy (4.2 vs. 5). The total number of 5-year amounts was 14 compared with a normal of expectancy of 24 for the 12 stations. The number of 10-year events (6 vs . 12) was only 50% of the expected number. Values for the 25-, 50-, and 100-year values are shown to reveal that none occurred at any station in Illinois during this 11-year period.

The analyses performed on the 1930-40 heavy rain data indicate that a change from the 20th Century's average climate to warmer and drier conditions would likely have a significant effect on the distribution characteristics of heavy rainstorms, particularly with respect of those of hydrologic significance. The effect to fewer events became more pronounced with increasing storm intensity.

3.2 The 1951-55 Period

The heavy rainfall characteristics during the drought of the 1951-55 period, which was the most severe on record in the southern half of Illinois, were similarly investigated. Inspection of the annual precipitation for each of the five years of the drought indicated that two-thirds or more of the state experienced below average precipitation in 4 of the 5 years.

TABLE 3. Frequency of One-Day Rainfall Amounts lor Various Recurrence Intervals During 1930-40.						
Number of Times 1930-40 Daily Rainfalls Equalled or Exceeded Given Recurrence Interval Amounts						
Station	2	5	10	25	50	100
North Rockford	4	0	0	0	0	0
Chicago	4	0	1	0	0	0
Moline	3	2	0	0	0	0
Central Peoria	5	0	0	0	0	0
Quincy	3	0	0	0	0	0
Urbana	4	4	2	0	0	0
Springfield	5	0	0	0	0	0
South Effingham	6	1	0	0	0	0
St. Louis	4	1	0	0	0	0
Mt. Vernon	7	3	1	0	0	0
Cairo	3	2	2	0	0	0
Harrisburg	3	1	0	0	0	0
TOTAL	51	14	6	0	0	0
Average	4.2	1.2	0.5	0	0	0
Median	4	1	0	0	0	0
Normal Expectancy	5	2	1	-	•	-

Figure 3 shows percent of average annual precipitation for this 60-month period. The number of occurrences of 1-day storms that produced values equal or greater than the average 2-year frequency value at each station is also shown. It is notable that the five stations where the 5-year precipitation was ≤90% of average, had either 0 or 1 of the 2-year events, whereas the areas with more than 90% of average had between 2 and 3 events at the 2-year return interval. In the southern half of the state, this drought was more severe than that of the 1930s, but in northern Illinois precipitation was near normal during 1951-55. This situation allowed for spatial comparisons during this warm and dry period of the northern and southern Illinois values. The greatest negative departures were found in the south central part of the state. For example, at Effingham, the 5-year deficiency was 45.5 cm, but at Peoria (in the north central part of the state), only 5.1 cm.

The 1930-40 results would suggest that there should have been a suppression in the frequency and/or intensity of heavy rainstorms during the 1951-55 period in southern Illinois. This supposition receives support from the 1951-55 period statistics including the values shown in figure 3. Table 4 shows the number of times that the average 2-year and 5-year extreme rainfall events for 1-day storms were equaled or exceeded at each of the 12 stations across Illinois.

In a normal 5-year period, 2 to 3 occurrences of the 2-year storms could be expected at each station. Table 4 indicates that 7 of the 12 stations experienced two or more of the average 2-year events. However, five stations (Urbana, Effingham, St. Louis, Mt. Vernon, and Harrisburg) experienced a low frequency (0 or 1) in the 1951-55 period, and all these stations were in the major drought area (precipitation ≤90% of average).

In an average 5-year period, a station would be expected to experience one or more 5-year events. Table 4 indicates that four stations (St. Louis, Springfield, Mt. Vernon, and Harrisburg) had no 5-year rain events in the 1951-55 period. All four stations were within the most severe drought region of the 1951-55 period (Fig. 3).

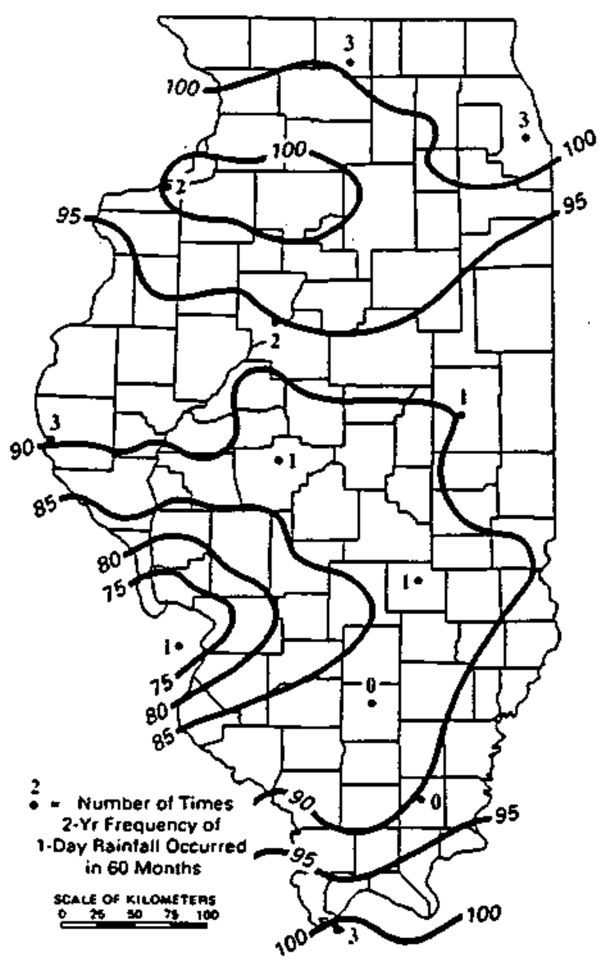

Figure 3. Pattern of percent of long-term average precipitation during 1951-55, and the number of 1 -day rainfall events ≥ 2-year frequency at selected stations.

TABLE 4. Frequency of 2-Year and 5-Year Extreme Rainfall Events lor 1-Day Storms During 1951-55.			
Stations	2-Year	5-Year	% of Long-Term Average Precipitation
Chicago	3	2	103
Rockford	3	1	102
Moline	2	1	100
Peoria	2	2	95
Quincy	3	2	90
Springfield	2	0	85
Urbana	1	1	91
Effingham	1	1	86
St. Louis	1	0	75
Mt. Vernon	0	0	86
Harrisburg	0	0	89
Cairo	3	1	100

4. SUMMARY

To obtain estimates of possible effects during a warmer and wetter regime than the 1901-87 period, regional values were compared. Results indicated that NW Illinois with warmer and wetter conditions, such as the GCMs predict (and as found in extreme southern Illinois), could be accompanied by increases of 10 to 15% in heavy rainstorm events with return intervals of 5- to 50-years. Such a change could result in the failure of many flood control structures designed on present-day rainfall frequency relations.

Two major warm-dry periods occurred in Illinois in the 1930-40 and 1951-55 periods. These analyses indicated that a change from the average climate of 1901-87 to a substantially warmer (+1.5°C) and drier climate (-10%) would have a significant effect on the distribution of heavy storms, particularly with respect to hydrologic applications of rainfall data. The general effect would be to suppress the frequency and intensity of extreme storm events. The suppression effect also increased with increasing storm intensity; that is, the suppression of events would be greater in the longer recurrence-interval storms. For example, analysis indicated that if the 1930-40 conditions became the normal climate in northern and central Illinois, present-day 2-year events would be suppressed by only about 6%, but the decrease would be a more substantial 18% for 10-year events.

The general relationship between total precipitation shifts studied and the heavy rain shifts noted is of interest. The spatial comparison revealed that a 25% increase in total average precipitation was associated with a 10% to 15% increase in heavy rain events ranked at the 5- to 50-year recurrence intervals. The temporal analogs used to assess effects of warmer and drier conditions revealed that 9% (1930-40) and 13% (1951-50) decreases in statewide precipitation were associated with 12% and 8% decreases in the number of 5-year events, respectively. These comparisons suggest that the relative magnitude of the shift in total average precipitation generally approximated the shifts found in the number of heavy rain events at 2-year and longer return intervals.

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EXTREME PRECIPITATION EVENTS: THE LINK TO TEMPORAL VARIABILITY IN SEASONAL PRECIPITATION

by

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1. INTRODUCTION

The Committee on Earth Sciences (CES, 1989) has identified the study of "Climate and Hydrologic Systems" as having the highest scientific priority in the U.S. Global Change Research Program. The critical role played by water in all three phases in the energetics and dynamics of the earth's climate system accounts for this emphasis. Any changes in the hydrologic cycle will also have major impacts on water resources. In this study, we have investigated the nature of extreme precipitation events associated with stream flooding. In particular, we have looked at the frequency of occurrence of extreme multi-day precipitation events, and their relationship to interpentadal fluctuations in total seasonal precipitation. Results of the research presented here have major implications for the estimation of hydrologic impacts from the results of General Circulation Models (GCM's).

2. DATA ANALYSIS

The period 1921-1985 was chosen for analysis. Streamflow data were used to identify those precipitation events which are most closely related to flooding. To this end, we identified 69 streamgaging stations in the midwestern U.S., which obey the following criteria:

a. No significant control structures upstream of the station.
b. Less than 20 percent missing data over the 65 year period of record.

For each of these basins, daily streamflow data' were obtained from the EarthInfo Hydrodata CD-ROM. For each time series of streamflow data, partial duration series of daily streamflow values were constructed. Based on knowledge of midwestern flood events and factors causing floods, we chose two seasonal time periods of interest:

a. Warm season (May through November).
b. Cold season (December through April).

Each part of the analysis was performed independently on the two seasonal periods. For each season, those events exceeding the threshold for a one-year recurrence frequency were chosen and identified as the flooding events.

It is obvious that floods occur as the result of the combination of several climatic elements. These elements include short-term precipitation totals, short-term precipitation rates, and antecedent soil moisture conditions in the basin. For the purposes of this study however, we chose to look only at short-term multi-day precipitation totals because this largely controls the incidence of floods of the magnitude we investigated. For this element, long-term records (daily precipitation) are available for many stations. By contrast, soil moisture measurements are not widely available, and short-term precipitation rates requiring at least hourly data are also not widely available prior to around 1948.

Daily precipitation data were obtained for approximately 230 stations with records covering the period 1921-1985. Precipitation totals were calculated for various intervals, including 1-day, 3-day, 5-day, 7-day, and 10-day events. A partial duration series of these short-term precipitation events was constructed. Similar to the analysis of the streamflow data, these were separated into warm season and cold season events. Those events exceeding the threshold for a one-year recurrence frequency were identified and used for subsequent analysis.

3. RESULTS

The first step was to identify the precipitation event lengths that were most closely related to flood events. A precipitation event was considered to cause a flooding event if it occurred on the day of the flood, or within 6-15 days prior to the flood event, depending on the length of the precipitation event. This analysis indicated that, at the longer precipitation intervals (three days or greater), about half of the precipitation events were related to specific flood events with little relational difference across the range of intervals. However, at the shortest interval, one day, the number of related events was less. This relative behavior was true across the region. Therefore, for subsequent analysis, only the longer interval precipitation events were considered.

The primary question of this study is: do extreme precipitation events occur more frequently during climatic periods of general wetness? To address this, we aggregated precipitation events by five-year periods (pentads) from 1921-25 through 1981-1985. For each pentad, the total precipitation was calculated for each station. A comparison for the warm season between the total pentad precipitation and the number of extreme precipitation events revealed a general trend toward increasing precipitation amounts as the number of extreme precipitation events increased. Fig. 1 summarizes these data; the points in this figure represent the average precipitation for all station pentads with similar values for the number of precipitation events. Also shown are plus and minus one standard deviation values. The correlation between the two variables is quite obvious. The correlation coefficient between the individual values of the number of events and total precipitation is + 0.65.

This graph, however, is somewhat misleading since the precipitation events themselves make a significant contribution to the total seasonal precipitation. Fig. 2 is similar to Fig. 1 except that, for each pentad, the total precipitation from the extreme events has been subtracted from the total seasonal precipitation. It is clear in Fig. 2 that there is little relationship between the number of extreme precipitation events and the total non-event precipitation ($r = -0.12$). The relationship between cold season events and total cold season precipitation (not shown) is similar to the behavior illustrated in Figs. 1 and 2.

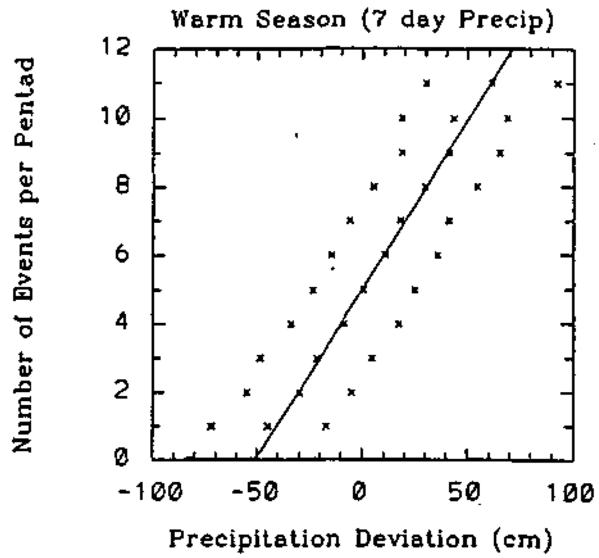

Figure 1 - Number of warm season 7-day extreme precipitation events (magnitude greater than the threshold for a 1-year recurrence interval) as a function of the pentad precipitation deviation. Each set of three points at discrete values of the number of events represents the mean and ± 1 standard deviation of the values for all station-pentads with an equal number of events. The solid line is a least-squares fit to the mean values.

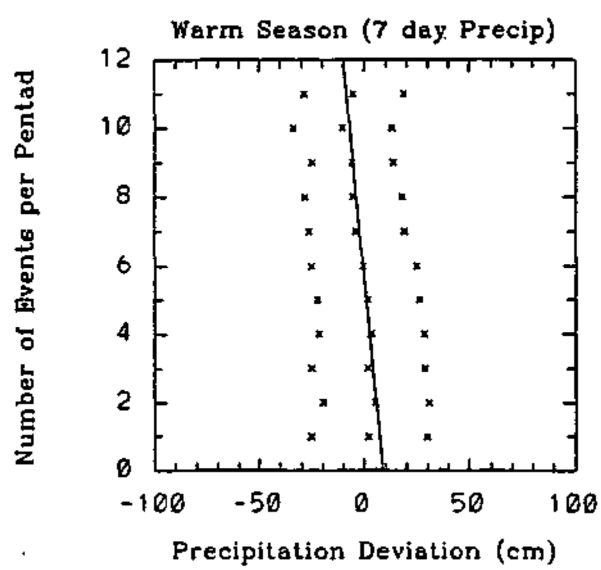

Figure 2 - Same as Figure 1 except that the total event precipitation was subtracted from the total pentad precipitation.

To shed further light on this situation, weekly precipitation was calculated for each station for its period of record. For each pentad, the frequency of occurrences were calculated for ten categories of weekly totals. Table 1 gives a summary of the frequency distributions averaged over all stations and sorted by the number of extreme precipitation events for the warm season. This table indicates that there is little relationship between the number of events and frequency of occurrence of weekly precipitation totals for all categories up to 50 mm. Strong correlations are present only for the categories greater than 75 mm. This probably represents almost entirely the extreme events themselves. (Although the average threshold for a 1-year recurrence interval event is about 100 mm, the weekly precipitation totals are calculated over fixed dates. Therefore, events will often be split and distributed over two adjacent weeks, resulting in some effect on the frequencies in categories less than 100 mm). An analysis of variance indicated that these extreme events account for 42% of the inter-pentadal variance in total precipitation for the warm season and 49% for the cold season.

Table 2 shows the frequencies of occurrence as a function of pentad precipitation deviation for the warm season. For the higher precipitation categories (greater than 75 mm), there is a significant positive relationship between the frequencies and the precipitation deviations. This reflects that portion of the inter-pentadal variance caused by extreme events. There are relatively small variations in the intermediate categories (1-50 mm). However, larger changes are apparent in the dry week (0) and 51-75 mm categories.

4. DISCUSSION

Figs. 1 and 2 imply that there is no relationship between extended (in time) wet spells and the frequency of occurrence of extreme precipitation events. It would appear from these results that these extreme precipitation events are in fact random and may not be tied to any particular long-term circulation anomalies. From another perspective, these events contribute nearly one-half of the inter-pentadal precipitation variance. The remaining variance is due largely to differences in the frequencies of dry weeks and large events (50-75 mm) which are somewhat smaller than the extreme events.

The implications for global climate change impacts assessments are significant. These results suggest that GCM estimates of precipitation changes for months or seasons will not be adequate for estimation of hydrologic (flooding) impacts if they do not adequately model the frequency of occurrence of these extreme precipitation events. Since these events are often mesoscale in size, they cannot be modeled directly by the current generation of GCMs. The question which then arises is: do the precipitation parameterization schemes used in these models properly represent the frequency of occurrence of extreme events? These results also may place in doubt

Table 1 - Frequency of occurrence (# of weeks/year) of weekly precipitation totals for May-November as a function of the number of extreme precipitation events (greater than 1-year recurrence interval) for 5-year periods. These values represent averages for all 230 long-term precipitation stations.

	Precipitation Total (mm)									
Number of Events	0	1-6	7-12	13-25	26-50	51-75	76-100	101-125	126-150	greater than 150
0-1	5.8	6.6	4.3	5.8	5.2	1.6	0.3	0.1	0.0	0.0
2-3	4.9	6.7	4.4	5.9	5.4	1.8	0.5	0.1	0.0	0.0
4-5	4.7	6.6	4.3	5.9	5.6	1.9	0.6	0.2	0.1	0.0
6-7	4.5	6.4	4.3	5.9	5.5	2.0	0.7	0.3	0.1	0.0
8-9	4.4	6.2	4.2	5.7	5.7	2.1	0.9	0.4	0.2	0.1
10-11	4.1	6.2	4.1	6.0	5.5	2.2	1.1	0.5	0.2	0.1
>12	4.9	4.1	3.8	5.9	5.9	2.5	1.7	0.8	0.3	0.1

Table 2 - Frequency of occurrence (# weeks/year) of weekly precipitation totals for May-November as a function of the precipitation deviation for 5-year periods. The values represent averages for all station-pentad's in that category.

	Weekly Precipitation Total (mm)									
Pentad Precipitation deviation (cm)	0	1-6	7-12	13-25	26-50	51-75	76-100	101-125	126-150	greater than 150
-76 to -100	7.8	5.9	4.0	5.2	4.7	1.5	0.5	0.1	0.0	0.0
-51 to -75	6.3	6.7	4.2	5.5	4.8	1.6	0.5	0.2	0.1	0.0
-26 to -50	5.3	7.0	4.5	5.8	5.1	1.5	0.5	0.2	0.1	0.0
-1 to -25	4.8	6.8	4.4	5.9	5.3	1.8	0.6	0.2	0.1	0.0
0 to +25	4.3	6.5	4.3	6.0	5.7	2.0	0.7	0.2	0.1	0.0
+ 26 to +50	4.1	6.1	4.2	5.9	6.0	2.2	0.8	0.3	0.1	0.1
+51 to +75	4.0	5.8	4.0	6.9	6.2	2.4	0.9	0.4	0.1	0.1
+76 to +100	4.2	5.1	3.6	5.7	6.4	2.7	1.2	0.4	0.2	0.1
> 100	4.8	5.0	3.6	5.1	5.5	3.0	1.5	0.7	0.4	0.1

the GCM predictions of precipitation changes, since our study indicates that these extreme events account for almost half of the inter-pentadal variance. This is clearly a major challenge.

In summary, it appears that the results of the current generation of GCMs are inadequate for use in the estimation of changes in flooding frequencies. This problem can perhaps be solved by the coupling of regional models with GCMs. This has been done in the western part of the U.S. This would provide the spatial resolution necessary to directly model these events. Another approach would involve an exhaustive study of the types of synoptic situations which cause extreme events. The frequency of occurrence of synoptic events can be obtained from GCM data.

Acknowledgements

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Development of New Rainfall Frequency Relations for Nine Midwestern Stales

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1. Introduction

Rainfall frequency analysis provides a means to predict the average time interval between the recurrence of storms of a given duration and size. At the Midwestern Climate Center, a comprehensive re-evaluation and updating of heavy rainstorm frequency has been made for nine states (Illinois, Indiana, Iowa, Kentucky, Michigan, Minnesota, Missouri, Ohio, and Wisconsin). This project meets current needs in climatology, hydrology, engineering, and other related fields. A special effort is made to determine the existence of climatic fluctuations and trends in heavy rainfall distributions since 1901, and their significance on frequency distributions which are a major input in the design and operation of flood control systems and other hydraulic structures. A second major objective is to provide a better definition of spatial variations in extreme rainfall events within the region due to small-scale variations in topography, Great Lakes effects, and urban-related influences when discernible.

Analytical methods and techniques were initially developed in a detailed investigation of Illinois frequency relations (Huff and Angel, 1989). These were then used in the other eight states since there are no major variations in precipitation climate across the region -- a humid, continental climate exists throughout. Our basic philosophy is that a combination of appropriate statistical techniques, guided by available meteorological and climatological knowledge of atmospheric processes, provides the best approach to the problem.

In this paper, we will discuss the analytical techniques developed and the patterns of heavy rainfall at various recurrence intervals across the nine states. Also, comparisons will be made between this and earlier studies.

2. Data and Analytical Approach

This study relied upon 275 daily reporting stations of the NWS cooperative network with records greater than 50 years. These data were provided in digital form by the National Climatic Data Center and, in some cases, keypunched by us from the written records. The coverage, by state, ranged from very good in Illinois, to sparse in Minnesota, Wisconsin and Kentucky. These data were supplemented by 134 cooperative stations with shorter records (1948 to present) to fill in gaps in the analyses. Figure 1 shows the complete coverage. Because the data from the cooperative network provides for only daily amounts of rainfall, an empirical factor developed by Herschfield (1961) was used for converting calendar-day rainfall to a maximum 24-hour rainfall. It is an average value that may vary considerably between storms, but it should result in only small errors when applied to a large sample of storms. The conversion factor for 1 day to 24 hours is 1.13. For durations of less than 24 hours, another set of empirical relations was applied (Table 1). These relations are based on a study of recording raingages in Illinois and surrounding states for 1948-83, and a similar study in the Chicago area (Huff and Vogel, 1976), as well as Herschfield (1961).

Frequency relations were developed for recurrence intervals of 2 months to 100 years and for storm periods ranging from 5 minutes to 10 days. The rainfall frequency analysis can be broken down into two parts: the time

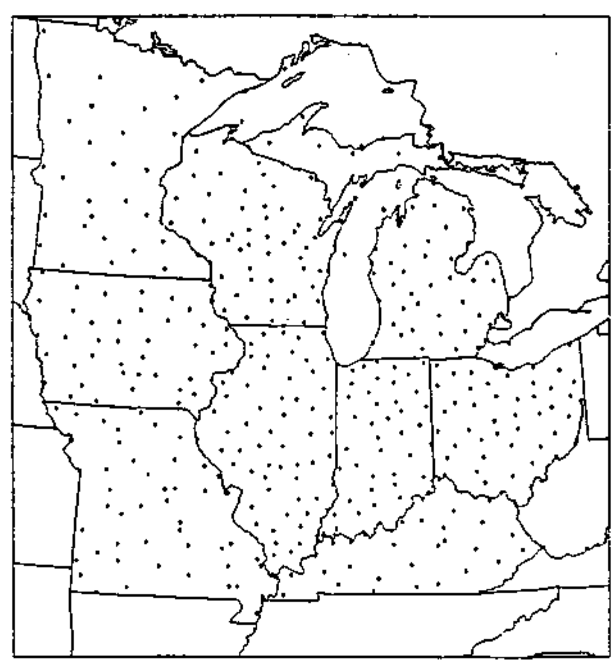

Fig. 1 Cooperative network stations.

Table 1. Average ratios of less than 24 hours to 24-hour rainfall.

Rain Period	Ratio
5 minutes	0.12 .
10 minutes	0.21
15 minutes	0.27
30 minutes	0.37
1 hour	0.47
2 hours	0.58
3 hours	0.64
6 hours	0.75
12 hours	0.87
18 hours	0.94

distribution for individual stations and the spatial distribution for all stations.

a) Time Distribution

The daily precipitation data was used to find the annual maximum time series, that is, the highest precipitation amount for a given duration for each year. These sample time series are typically fitted with some statistical distribution to provide an unbiased estimate of the true population and allow some extrapolation beyond the original data. Sevruk and Gieger (1981) made an extensive appraisal of distribution types for extremes of precipitation for the World Meteorological Organization (WMO). Their worldwide appraisal did not reach a conclusion concerning the superiority of any particular distribution. They point out that "some distributions, however, may be superior to others under given seasonal and/or geographical conditions." This agrees with the earlier Illinois findings which indicated that the Frechet distribution was most applicable to annual, spring, and fall data, but the log-normal distribution provided the best fit for winter data (Huff and Neill, 1959b).

In this study, it was found desirable to determine frequency relations for precipitation periods ranging from 5 minutes to 10 days and for recurrence intervals varying from 2 months to 100 years. No distribution was found to adequately fit the data throughout these wide ranges. For example, the Frechet, Log-Pearson type II, and log-log methods provided the best fit most often for recurrence intervals exceeding 2 years, but these methods produced unsatisfactory estimates of rainfall values for recurrence intervals of 2 months to 2 years. For these shorter intervals, log-normal and semi-log fittings of the data often closely approximated the values indicated by graphical plots of the ranked observational data.

A log-log graphical analyses was selected for final derivation of the frequency relations. This method resulted in smooth curves, such as illustrated for the sectional curves in Figure 2. This figure shows the frequency distribution of 24-hour maximum rainfall amounts for recurrence intervals varying from 2 months to 100 years. A major change is reflected in the distribution

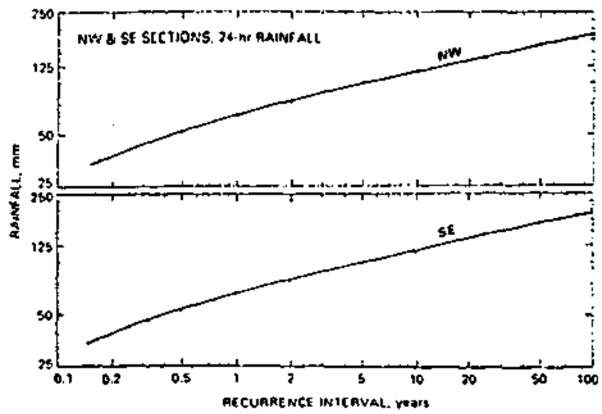

Fig. 2 Example of time distribution relationships for Illinois.

characteristics for the sections near the 2-year recurrence interval. Similar curves were obtained for the other sections and for individual sampling points.

The foregoing method does place a cutoff on extrapolation at or near the 100-year frequency, since the data are not fitted to a specific mathematical distribution. However, extrapolation of any frequency relation much beyond the limits of the data sample (80+ years in this case) is not recommended. As pointed out by Huff and Neil (1959), this is a dangerous practice, since nature is not governed by any particular statistical distribution. Furthermore, climatic and physiographic variations can cause the "best-fit" distribution to vary within the state, as shown by Huff and Neill in their 1959 study.

b) Spatial Distribution

The next problem encountered is how to develop the frequency relations to provide maximum accuracy and reliability for the user. A major source of sampling error results from poor raingage exposure, inadequate gage maintenance, plus data entry and data reduction errors (man-induced errors). Nonrepresentative spatial variability may be introduced by rarely experienced severe rainstorms (outlier events) which do not properly reflect the average frequency distribution to be expected within the time frame covered by the study (100 years in this study). While the time distribution analysis may dampen outliers with respect to that station, it will be much harder to remove systematic biases such as poor exposure or improperly maintained equipment.

Most frequency relations in the past have used isohyetal maps to present the frequency distribution (Yarnell, 1935; Herschfield, 1961). However, this approach can be susceptible to considerable subjectivity and sampling errors. On the positive side, this approach is useful and familiar to most users. It also allows for smaller-scale features to be accounted for in the design process. An example of small-scale features is the increase in rainfall found downwind of large urban areas

(Huff and Changnon, 1973) or changes associated with geographical features (Huff et. al., 1975). In this project, only features supported by two or more stations are incorporated into the maps.

The second approach is to pursue a method used by Huff and Neill in an earlier Illinois study to alleviate the problem of spatial variability. It involved the division of the state into regions of approximately homogeneous climate with respect to heavy rainstorm events. Average relations were then developed for each division. Consideration of available climatic information on the distribution of heavy rainfall along with climatological-meteorological knowledge of storm system characteristics indicated that the well-established climatic divisions could be used for dividing the states. The only exception was Illinois where a slight change was made in the established divisions to more accurately reflect a combined effect from the Ozark Hills and the Mississippi River in the western part of the state. While the climate division averages are recommended by the authors, some hydrologists still prefer the use of isohyetal maps (e.g., working with basins that cover two or more climate divisions). In this case, a limited set of isohyetal maps are provided.

The foregoing technique does not eliminate the potential sampling errors in the data samples, but it does moderate their effect in regions of similar precipitation climate, and should produce better estimates of the true time-space distribution of heavy rainstorms across the 9-state region. However, unless the divisions are properly selected, the averaging technique may mask real small-scale effects, such as those induced in the vicinity of the Great Lakes. This problem could become more acute in regions incorporating major changes in topography, such as the Rocky Mountain states.

3. Temporal Changes in the Frequency Distribution of Heavy Rainstorms

Earlier work by Huff and Changnon (1987) showed significant changes in heavy rainfall events in Illinois between two 40-year periods. This was followed by a regional study by Huff and Angel (1990) which documented changes across the midwest. The basic analysis is to divide the raw precipitation data into two 40-year periods, do the frequency analysis, and compare the values at selected recurrence intervals and storm durations. The changes are expressed as a ratio between the later 40-year period and the earlier 40-year period with a value greater than 1 indicating an increase over time. Figure 3 shows the ratio for a 5-year, 24-hour storm. There is a large area of increased values in northwest and west-central portions of Missouri and a large swath from St. Louis to Chicago and extending up into northwest Indiana and into Michigan and northern Ohio. Decreased amounts can be found in Missouri, Wisconsin, and along the Ohio river valley. There is some degree of spatial coherency to the area of increased values which suggests it is something more than random

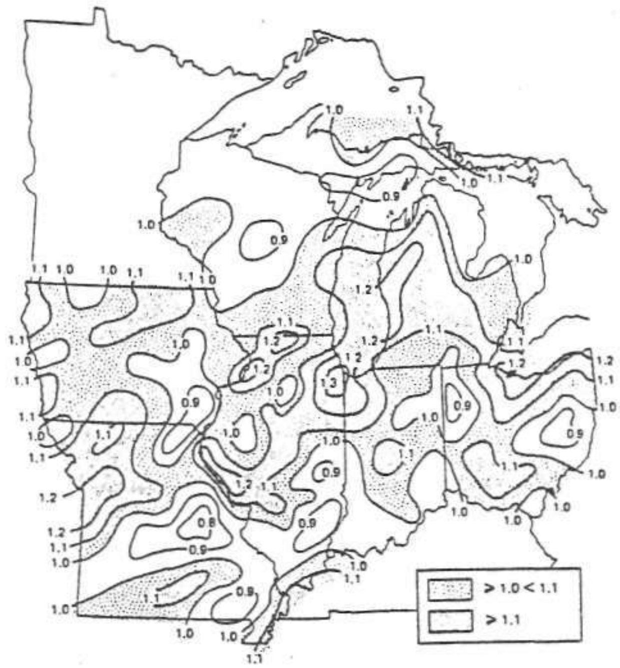

Fig. 3 Ratio for the two 40-year periods for the five-year, 24-hour storm.

variation. These results also suggest that the assumption of a stationary time series for fitting statistical distributions to historical precipitation data may be invalid. It also suggests that rainfall frequency values need to be updated on a regular basis.

4. Results

Here are examples of the two formats chosen to present the data. Table 2 shows the rainfall amounts expected for a 24-hour duration at selected recurrence intervals for selected states. Figure 4 shows the isohyetal map for the 5-year, 24-hour storm. Note that this shows much more spatial detail than Technical Paper 40 (Herschfield, 1961).

5. Problems with Technical Paper 40

Technical Paper 40 (TP40) was the designed standard in the midwest for most hydrological structures. It has been observed that the 100-year, 24-hour values from TP40 have been exceeded on a frequent basis in certain regions. Table 3 gives a breakdown on the number of times this value was exceeded and the number of times it is expected to be exceeded for the given period of record. Remember, at a given point each year, there is a small probability of exceeding the 100-year, 24-hour rainfall value. As table 3 shows, this value was exceeded too often in Illinois, Michigan, Ohio, and Wisconsin. The values were considerably over estimated for Missouri.

There are several reasons for the problem of too many storms exceeding the TP40 100-year, 24-hour storm. First, it has not been updated in 30 years (1961). It was

Table 2. 24-Hour Rainfall Amounts for Kentucky and Minnesota at Selected Recurrence Intervals.

	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
Kentucky						
Western	3.75	4.66	5.39	6.38	7.19	8.09
Central	3.49	4.34	5.30	6.22	7.09	7.96
Bluegrass	3.05	3.76	4.36	5.15	5.78	6.44
Eastern	3.09	3.73	4.26	5.06	5.74	6.53
Minnesota						
Northwest	2.16	2.94	3.69	4.57	5.41	6.11
N-central	2.41	3.06	3.58	4.39	5.10	5.88
Northeast	2.31	2.88	3.36	4.08	4.64	5.20

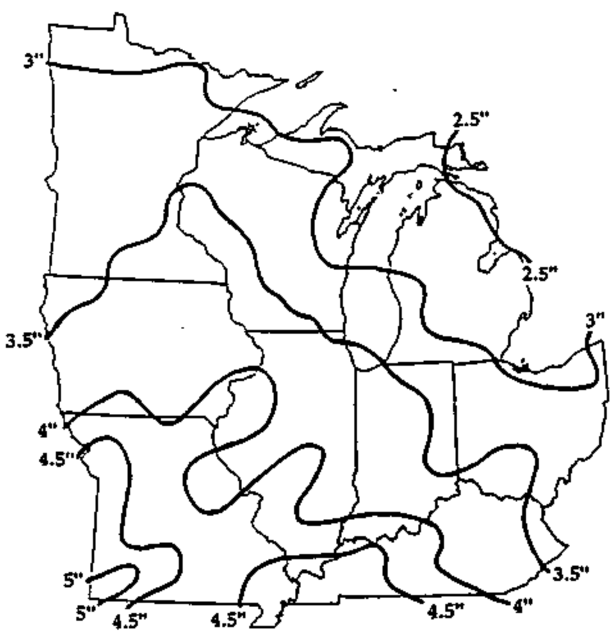

Fig. 4 Five-year, 24-hour rainfall maps for the Midwest (preliminary).

also during the more recent times that Huff and Angel (1990) found major shifts in heavy rainfall for parts of the midwest. TP40 relied primarily on first-order stations which number about 200 in the U. S. Although TP40 states that it used supplementary data from 1600 climate stations, it is not clear how this was done. These first-order stations used tipping bucket gages, which are known to underestimate heavier storms. Also many of these stations moved from locations downtown out to the airport around World War II with corresponding changes in exposure.

6. Summary

Rainfall frequency values are updated for the first time in 30 years for the nine states of the Midwestern Climate Center. Results are presented in the form of isohyetal maps and tables that cover the entire range of recurrence intervals from 2 months to 100 years and rain durations from 5 minutes to 10 days. Climatic division means for each state are presented in table form only. Overall, the combined use of first-order and cooperative station data yields a logical distribution of rainfall values

Table 3. Number of times the 24-hour, 100-year value from Tech. Paper 40 is exceeded by state.

	(a) # of stations	(b) Average length of record	(c) # of times exceeded	(d) # of times expected	ratio (c/d)
Illinois	61	87	69	36	1.92
Indiana	41	64	17	20	0.85
Iowa	43	80	20	24	0.83
Kentucky	25 .	67	11	12	0.92
Michigan*	46	60	71	21	3.38
Minnesota	25	67	14	12	1.17
Missouri	44	62	4	20	0.20
Ohio	41	60	27	19	1.42
Wisconsin	13	78	13	7	1.86

*Sorrell and Hamilton, 1989

through the nine states. The new relations show much more detail than was presented in previous publications, which employed shorter records and concentrated on first-order stations.

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SOIL MOISTURE/EVAPORATION/PRECIPITATION FEEDBACK: A CASE STUDY OF THE 1988 DROUGHT

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1. INTRODUCTION

The 1988 drought was the worst since the 1930's in the midwestern part of the United States (Kunkel and Angel, 1989). The most notable feature of that drought was the extreme dryness in late spring/early summer. The period May-June was easily the driest of this century in a large area of the midwest. As a result, soil moisture reserves were very low by mid-summer. This situation provides a possible analog to explore the soil moisture/evaporation/precipitation feedback mechanism that appears to cause mid-continental drying in some General Circulation Models (GCM's).

Kunkel (1989) reported on eddy correlation measurements of latent and sensible heat fluxes taken at an east-central Illinois field site during the drought. At times during that summer, midday Bowen ratios of greater than 1 were measured compared to potential values (if soil moisture had not been limited) of 0.2 • 0.3. Mid-summer evaporation rates were estimated to be only two-thirds of normal while sensible heating rates were 2-3 times greater than normal. Analysis of the atmospheric water vapor budget during other years suggested that local evaporation may be a dominant source of water vapor during mid-summer when circulation patterns are weak.

Kogan (1990a) used a variation of the Normalized Difference Vegetation Index (NDVI) to investigate the intensity of the drought. He compared the satellite data with Illinois county corn yields and found good qualitative agreement.

The objective of this study are a) to investigate the extent of soil moisture shortages and associated evaporation decreases through use of several data sets and b) to explore the use of satellite data for monitoring the status of soil moisture through its effects on vegetation. Four data sets were available for this analysis: a) the eddy correlation measurements mentioned above which were available for 17 days during the period June 30-August 17; b) semi-monthly soil moisture measurements at depths of 0-15 cm, 15-50 cm, and 50-100 cm; c) weekly model soil moisture estimates for several layers to a depth of 2 m; and d) weekly NDVI measurements. Because the soil moisture measurements were only available for Illinois, this study is mostly limited to Illinois.

2. RESULTS

The Illinois State Water Survey obtained semi-monthly measurements of soil moisture under grass at 18 sites in Illinois using the neutron probe technique. The soil moisture model of Kunkel (1990) was used to estimate soil moisture at an additional 101 sites in Illinois where complete daily precipitation data for 1988 were available. These estimates assumed com as the cover crop. The NDVI measurements were available at a 16 km x l6 km resolution and were normalized relative to the range of their change for each location during the period of available satellite records (Kogan, 1990b); this modified NDVI is named the Vegetation Condition Index (VCI) and has a range of 0-100%. Approximately 60% of the state's area is covered by com and soybeans. Therefore the VCI data are expected to generally be representative of those crops. Since grass will begin transpiring in early spring while corn and soybeans will not emerge (and therefore begin transpiring) until mid to late spring, the early summer soil moisture depletion as indicated by the under-grass soil moisture measurements is expected to be earlier than under corn and soybeans. The VCI may also lag the change in soil moisture due to a lag in the response of the vegetation to soil moisture changes.

Fig. 1 shows the time dependence of all four data sets at the one common site, Champaign. The soil moisture data are expressed as % plant available water, defined as 100% (SM-WP)/(FC-WP) where SM = soil moisture measurements/estimates, WP = soil moisture at the wilting point, and FC = soil moisture at field capacity. The behavior of all four are generally consistent. The model soil moisture estimates and the VCI decrease rapidly over the same time period. As expected, the decrease in the soil moisture measurement data occurs earlier. The midday Bowen ratio measurements are already high at the onset of their availability, consistent with the plant stress suggested by the VCI and soil moisture data. The temporary decrease in the Bowen ratio during mid-late July in response to a few rain events is reflected by small increases in the soil moisture data, but not in the VCI.

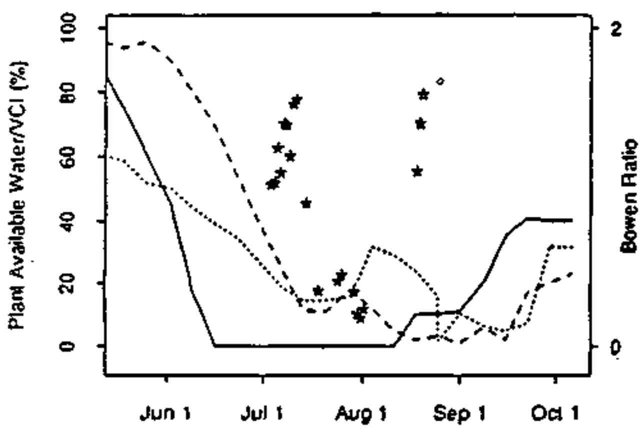

Figure 1 - Temporal behavior during 1988 of the following data at Champaign, Illinois: a) model soil moisture estimates (dashed line), b) soil moisture measurements (dotted line), c) VCI (solid line), d) Bowen ratio measurements (asterisks).

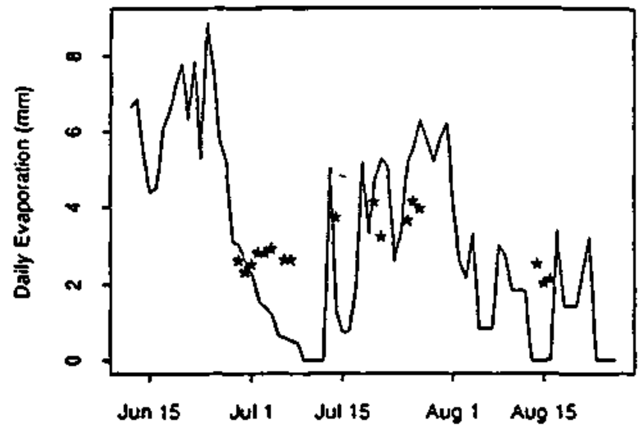

Figure 2 - 1988 evaporation at Champaign: a) estimated from the soil moisture model (solid line) and b) from the eddy correlation measurements (asterisks).

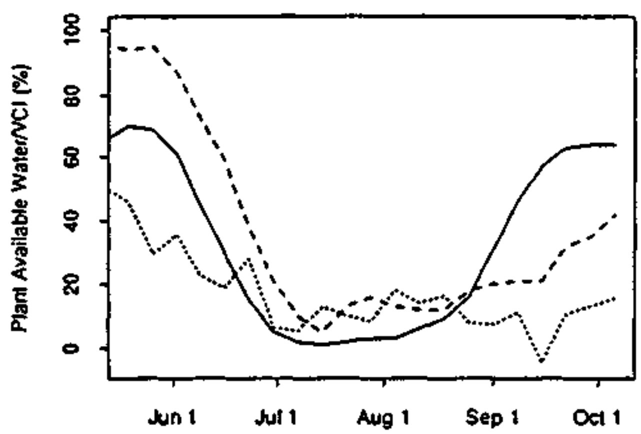

Figure 3 • Temporal behavior during 1988 of modeled soil moisture estimates (short dashed line), soil moisture measurements (dotted line), and VCI (solid line) for Illinois averaged over all available stations or pixels.

Fig. 2 shows a comparison of measured evaporation at the Champaign field site and evaporation estimates from the soil moisture model (assuming a maximum rooting depth of 1.25 m). The model estimates of evaporation remain high in the early part of summer despite extreme drought since soil moisture reserves are still available. However, by late June the reserves are depleted and evaporation decreases rapidly. The evaporation measurements are in general agreement with the model estimates, although they do not coincide exactly. This agreement provides some confidence in using the soil moisture model for large area evaporation estimates.

Fig. 3 shows the time dependence of the soil moisture values and the VCI averaged over all available stations and pixels in Illinois. Once again, very similar behavior is observed. The rapid early summer decrease in the soil moisture estimates and the VCI occur simultaneously. The decrease in the soil moisture measurements is similar, but begins earlier. The widespread coverage of low soil moisture/NDVI values indicated by Fig. 3, of a magnitude similar to that observed at Champaign, would suggest that the evaporation decreases measured at Champaign were also widespread and of similar magnitude throughout the state. Table 1 shows the distribution of measured VCI values for the four weeks of July 1988. About 92% of the pixel-weeks were in the lowest category, further indication of the severity and areal coverage of vegetation under severe stress.

The general similarity of all four data sets provides the motivation for using the soil moisture model of Kunkel (1990) to make large-area estimates of evaporation. This

Table 1 - Frequency of occurrence of VCI pixel values in Illinois for weeks 27-30. A total of 714 pixels were available for this analysis

VCI (%)	Frequency (%)
0-10	91.7
10-20	2.3
20-30	1.3
30-40	1.3
40-50	1.3
50-60	0.4
60-70	0.5
70-80	0.4
80-90	0.2
90-100	0.6

model covers the nine-state area of Illinois, Indiana, Iowa, Kentucky, Michigan, Minnesota, Missouri, Ohio, and Wisconsin and provides soil moisture estimates on a climate division scale. The purpose of this model is to provide real-time assessments of soil moisture conditions for the two dominant crops in the region, corn and soybeans. Since it makes no attempt to model the heterogeneous nature of soils and surface cover, the following evaporation estimates should only be considered suggestive of actual conditions in 1988. Daily precipitation data were available from the National Weather Service's cooperative observer network (1500 stations). Potential evaporation was estimated from the Penman-Monteith (Monteith, 1965) formula using hourly wind, water vapor, temperature, and cloud cover observations from 53 stations. A maximum rooting depth of 1.25 m was assumed. Historical estimates of total July evaporation (soil evaporation plus plant transpiration) were generated by running the model for the period 1949-1990. Fig. 4 shows the results of this analysis. Interannual variability over the period is quite small with most estimates in the range of 120-150 mm. The major exception is 1988, with an evaporation of 103 mm, about three-fourths of the period average. These results are suggestive of the possible significant changes in the energy budget in 1988.

In a slightly different vein, we investigated the response of the VCI to short-term soil moisture recovery. Significant precipitation occurred in southern Illinois during the last two weeks of July. Amounts at some locations exceeded 100 mm. The resulting response of the VCI lagged the precipitation by about 3-4 weeks and was not entirely coincident with the area) coverage. Fig. 5 compares the July precipitation patterns with the VCI distribution for week 34 (late August). The east-west strip of higher VCI across south-central Illinois coincides with a portion of the significant precipitation area. However, the significant precipitation in extreme southern Illinois is not entirely reflected in the VCI pattern. We can only speculate on the reason for this mixed behavior. That region of Illinois has a much higher proportion of forested land than the rest of the state; the location of these coincide in a general way with those areas in which the VCI did not respond. Perhaps trees were unable to take significant advantage of the recovery of near-surface soil moisture supplies because of their deep root systems. The terrain in this area is also rather hilly which may result in increased runoff from these rain events (which were quite heavy and occurred in very short time periods) and less soil moisture recharge. By contrast, the area to the north and east where the VCI did respond is flat, generally planted in corn or soybeans, and characterized by soils with poor drainage (an advantage in this situation). The lag in response of the NDVI has also been observed in the Sahel (Kerr et al., 1989). In that study, they found a lag of about 2 weeks.

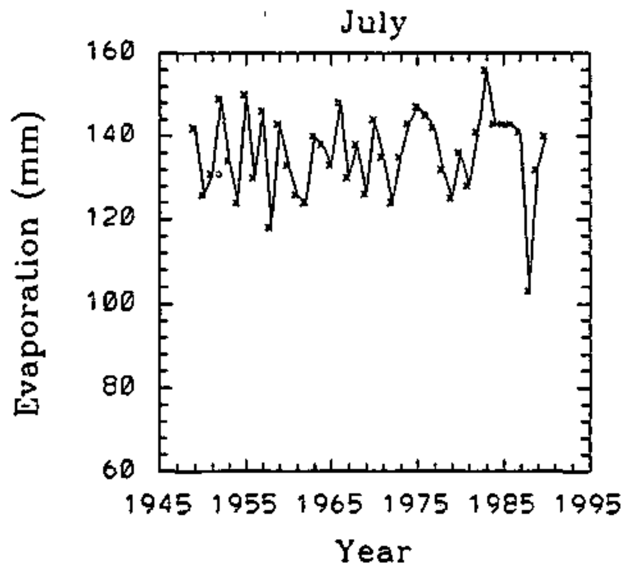

Figure 4 - Model estimates of actual July evaporation for 1949-1990 for a 9-state midwestern area.

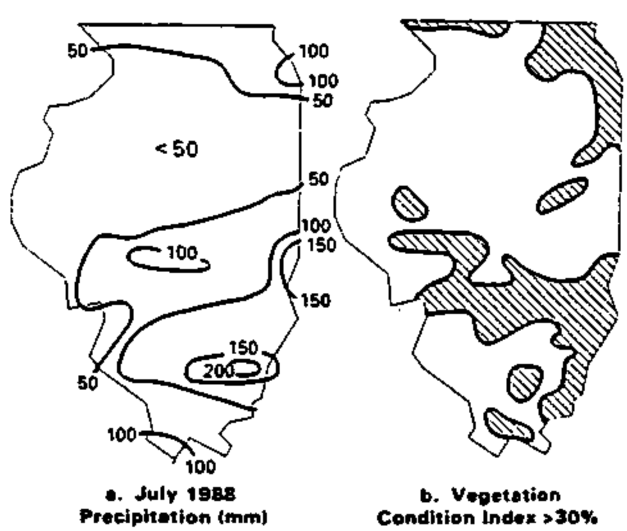

Figure 5 - a) Total July precipitation (mm) in Illinois. b) Smoothed VCI distribution with shaded areas indicating values greater than 30%.

3. CONCLUSIONS

This analysis suggests that soil moisture depletion . in the 19SS drought was of sufficient magnitude and areal extent to significantly reduce surface evaporation and ' (perhaps) affect precipitation in the midwest during mid-summer. This event provides an excellent case study of aspects of the hydrologic cycle under extreme conditions. Since some General Circulation Models (GCM's) show both reduced soil moisture and precipitation in the midwest in summer for doubled CO_2 conditions (presumably a result of this process), it is of considerable importance to quantitatively study this process. The present analysis indicates that such a process can operate in the present climate, albeit only under rather extreme conditions.

This study also indicated that the soil moisture changes (and presumably changes in evaporation rates) can be monitored remotely by satellite NDVI data, as expressed in the VCI. Short-term shallow soil moisture recovery may not be detectable under some circumstances.

ACKNOWLEDGEMENTS

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APPLIED CLIMATOLOGY: ATMOSPHERIC SCIENCES BIGGEST SUCCESS STORY FACES MAJOR NEW CHALLENGES**

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1. BASIC FUNCTIONS OF ATMOSPHERIC SCIENTISTS

What are the fundamental activities that atmospheric scientists can perform for mankind? I claim they fall within three broad areas.

First, we can describe and access the weather conditions and the climate so that society can design its structures, plan its operations, and assess adverse conditions. This area has been the purview of applied climatologists for more than a century.

Second, we can predict the weather or climate for hours, days, weeks, and months ahead. Predictions have enormous societal value, but the amount of value depends on the accuracy of the forecast. This has been the purview of physical meteorologists and facilitated by modeling.

Third, we can conceivably modify the weather to lessen storms, enhance visibility, and alter precipitation. This area has involved the cloud physicists and dynamists, largely attempting to modify cloud and precipitation processes.

I have had the good fortune to pursue research in all three fields, and with 40 years experience I have tried to assess them. If you examine these three areas with some objectivity, or by talking about the products they generate with non-atmospheric scientists and the public, 1 claim you will find the following general reactions.

2. RATINGTHEPRODUCTSOFATMOSPHERJC SCIENTISTS

The applied climatologists have succeeded. Climatological data and information and those who provide it have credibility. Our society with its technological world functions successfully based on our established ability to measure and describe the climate and how it relates to the design of bridges, communication systems, water supply systems, military operations, farm equipment, highway construction, and an almost endless list of activities and structures. We can reliably analyze and describe a drought or heavy rainstorm to explain its relative magnitude and statistical likelihood. To do these things successfully, we have identified the linkages between the climate conditions and many physical reactions such as soil erosion, crop yields, flooding, and highway disintegration. We have further begun to explore the social costs of some climate conditions and particularly those due to abnormal events.

The forecasters receive mixed reviews by society. Our science has attained, I claim, success in short-term forecasting although improvement is needed in precipitation forecasting. Climate predictions covering months and seasons ahead exhibit some skill but are of marginal value to society. Specialized sectors like transportation and certain forms of agriculture gain major benefits from short-term forecasts, but in general, weather forecasting does not have the credibility that suppliers of climate data and information have in the user community. Our studies of the use of climate predictions by U.S. agribusinesses show that 75% buy predictions, but no company uses them in making key decisions. Agribusinesses use recent climatology as a predictor because that is all they trust.

Farthest down the credibility scale of the atmospheric sciences is planned weather modification, quite possibly the most difficult "product" or achievement facing our field. Unfortunately, early promise, coupled with bureaucratic mismanagement, led scientists to tackle the issue too soon, and therefore often clumsily, without knowledge of the atmosphere or the instruments to measure critical conditions. We conducted too much futile experimentation. However, we must not ignore modification research, as is the current case, and we can now approach it intelligently as we better understand and measure how the atmosphere works.

Ironically, the weather/climate-sensitive sectors have long recognized the high value of our fields' most uncertain deliverables: climate predictions and weather

**Invited.

modification. The demand has driven many to use the limited, uncertain capabilities offered. Poor performance of the products has lessened the credibility of these two fields. ,

The major point of this product assessment is to say that the field of applied climatology is the oldest and by far the largest success story of the atmospheric sciences. It is not the global modelers, the weather modifiers, or weather forecasters who have most effectively served our society for 100 years and gained the greatest credibility the atmospheric sciences possess. It is the applied climntologist. Ironically, I believe that too few in our discipline realize this and many care little for applied climatology; it certainly is not seen as the core of the field. Have we become too successful? Why are there only 65 papers at this conference? Are we too old? Has the field disappeared into the realms of the allied disciplines? Has the field lost its identity? Should the field lose its identity?

3. WHAT ARE THE PROBLEMS AND CHALLENGES FACING APPLIED CLIMATOLOGISTS

The central problem that applied climatologists face is that research in "applied climatology" has become too diffuse. Many scientists who delve into applications of climate data are not "atmospheric scientists." For example, there are many physical geographers doing good work in applied climatology who never attend an AMS conference or publish in AMS journals. Geographers' annual conferences have many more papers on applied climatology than you can find at an AMS Conference. The same is true in agriculture and its many subdivisions, including horticulture, agronomy, and engineering. Then, there is hydrology and its stepchildren, hydrometeorology and hydroclimatology, with enormously successful applied climatological research largely done by civil engineers.

Applied climatology is threaded through every weather-sensitive field and has been so for many decades. Indeed, the field as such has become a part of many scientific and engineering disciplines. When engineers were designing the railroad bridges and the dams built in the 19th Century, applied climatology was at work. Our agriculturally-dependent nation of the 19th Century, through its land grant universities, launched the applied climatology research in the 1890s that has undergirded our nation's most successful economic story, agricultural production. Indeed, the two sister conferences here, one on forest and agricultural meteorology, and the other on hydrometeorology, are "applied climatology."

If all this is true, if success and high credibility is our heritage, what is left for applied climatologists to do? Plenty! Should there be "applied climatologists?" Yes! Is the field healthy? I don't think so.

Much needs to be done to deal with the enormous and inherent diversity of modern day applied climatology. We need to ensure that new forms of climatic data, current analytical techniques, and updated atmospheric knowledge are transferred and assimilated by the many related disciplines who are doing much of the applied research.

Some major questions can be raised.

- Where are the opportunities for study and funding in applied climatology?
- Is the training and education in applied climatology adequate?
- Are our allied disciplines teaching their scientists and engineers with the latest most relevant knowledge about atmospheric processes, latest climate analytical techniques, and using the best data available?
- Can we perform adequate climate impact analysis?
- Can we address adequately the national concern over the potential impacts of a changed future climate?

4. RECOMMENDED ACTIONS

Many problems and opportunities exist. Following is my list of "needs."

1. We need to develop better methods of analyzing climate impacts, particularly through models, and to explore more adequately the socioeconomic and policy impacts.
2. We must explore, in much more definitive terms, how non-extreme variations in climate affect physical systems.
3. We need to move intelligently into the labyrinth of the climate change research world to help study its potential effects. Whether a change occurs or not, we know there will be large future climate fluctuations to deal with due to natural causes, and we can utilize this current interest to pursue research to gain information that will allow society to better manage around climate variability.
4. The discipline of "applied climatology" needs greater identity and visibility within the atmospheric sciences and with the allied disciplines that utilize climatology. An in-depth study of the current scope of the field including the adequacy of education is needed.
5. The direction and support of applied research needs assessment. Too much federal support is mission-oriented and/or problem/project oriented. There are too

few sources of funds for more fundamental applied climatological research needed, for example, to develop new analytical methods, and to attract and educate new scientists in the field.

I call for a national assessment of the field of applied climatology. We need to assess the status of the field, the dimensions of the funding, the expertise that exists, and university-level training. Congress authorized NOAA to do this in 1990, but without providing funds. I urge the American Meteorological Society or interested federal agencies to support a National Academy of Sciences assessment so that we can scope the field and identify the needs to everyone's satisfaction. This would provide the foundation for enhancing the field and correcting the ills.