FINAL REPORT
ON
A STUDY OF THE 1976-1980 NORTH DAKOTA RAINFALL ENHANCEMENT PROJECT

By

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ABSTRACT

Evidence continues to increase supporting the conclusion that cloud seeding in North Dakota produces an increase in growing season rainfall which is significant both statistically and economically. State average rainfall volume increases of about 15% during the critical period from June 6 - July 11 are found. This is produced by an increase in the number of stations reporting rain in and downwind from the seeded areas, combined with an increase in the average rain which falls in each gage. No significant changes in the rainfall characteristics are found beyond 12 hours downwind of the seeding. Economic benefits for the state agricultural industry are of the order of tens of millions of dollars annually.

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A. INTRODUCTION

The purpose of this report is to present an on-going evaluation of the capability of the North Dakota Weather Modification Board (NDWMB) cloud seeding activities to increase rainfall where and when it is needed across the State.

Previous work done for the NDWMB by the author and his colleagues considered the period up to 1976 and compared the climatology of rainfall before seeding began (circa 1950) to that which was reported after seeding of one sort or another was undertaken somewhere in the State. The post 1950 rainfall enhancement was assessed rather crudely using: a) some 59 National Weather Service (NWS) daily cooperative observer reports, b) documentation as regards which counties were "in" and "out" of the seeding activities each year, and c) the mid-tropospheric wind reported at Bismarck each day to define downwind progression of a "seeding plume". A significant rainfall increase associated with this "seeding" was found over most of the State and the results are reported in detail by Eddy and Cooter (1979) and Eddy, Cooter, and Cooter (1979).

Beginning in 1979, we used refined observation networks and trajectory calculations to define:

a) exactly where, when, and how much seeding was released into the atmosphere,

b) a special 500-600 gage network of rainfall observations, and

c) a more sophisticated computer algorithm which makes use of all upper air data in and around the State to calculate the

> downstream trajectories of the seeding material (Heffter and Taylor, 1975). These latter trajectory calculations are performed by Dr. E. R. Reinelt of the University of Alberta in Edmonton. This work is reported in detail by Eddy (1980).

During the past year we have concentrated on the 5-year period from 1976 to 1980. The present report describes our results concerning: a) rainfall increases (and decreases) in and downstream from seeded areas, b) changes found in the characteristics of this rainfall, c) the statistical significance of these changes, d) variations in the thermodynamic and kinematic structure of the atmosphere associated with these changes, e) hypotheses of expected changes found using a simple cloud physics "cloud seeding" model, f) economic impacts of the observed changes (rainfall increases), and g) a background study of drought frequency and intensity across the State of North Dakota, done to begin an assessment of the rainfall enhancement possibilities during such anomalous weather regimes.

Figure 1 shows the long term ($\overset{8}{2}$0 years) average annual rainfall pattern for North Dakota. This is based on the NWS COOP data set which ranges from a few stations in the early years to well over 200 in more recent times. Figure 2 shows the special rain gage network distribution by county for one of our 5-year study years and Figure 3 shows the special network distribution for another year in some detail. These stations move to a certain extent from year to year; however, the basic station density remains the same. Figures 4 and 5 show the counties which have contracted for cloud seeding in each of these 5 years. These latter two figures show the position of our upper air observing station at BIS (Bismarck).

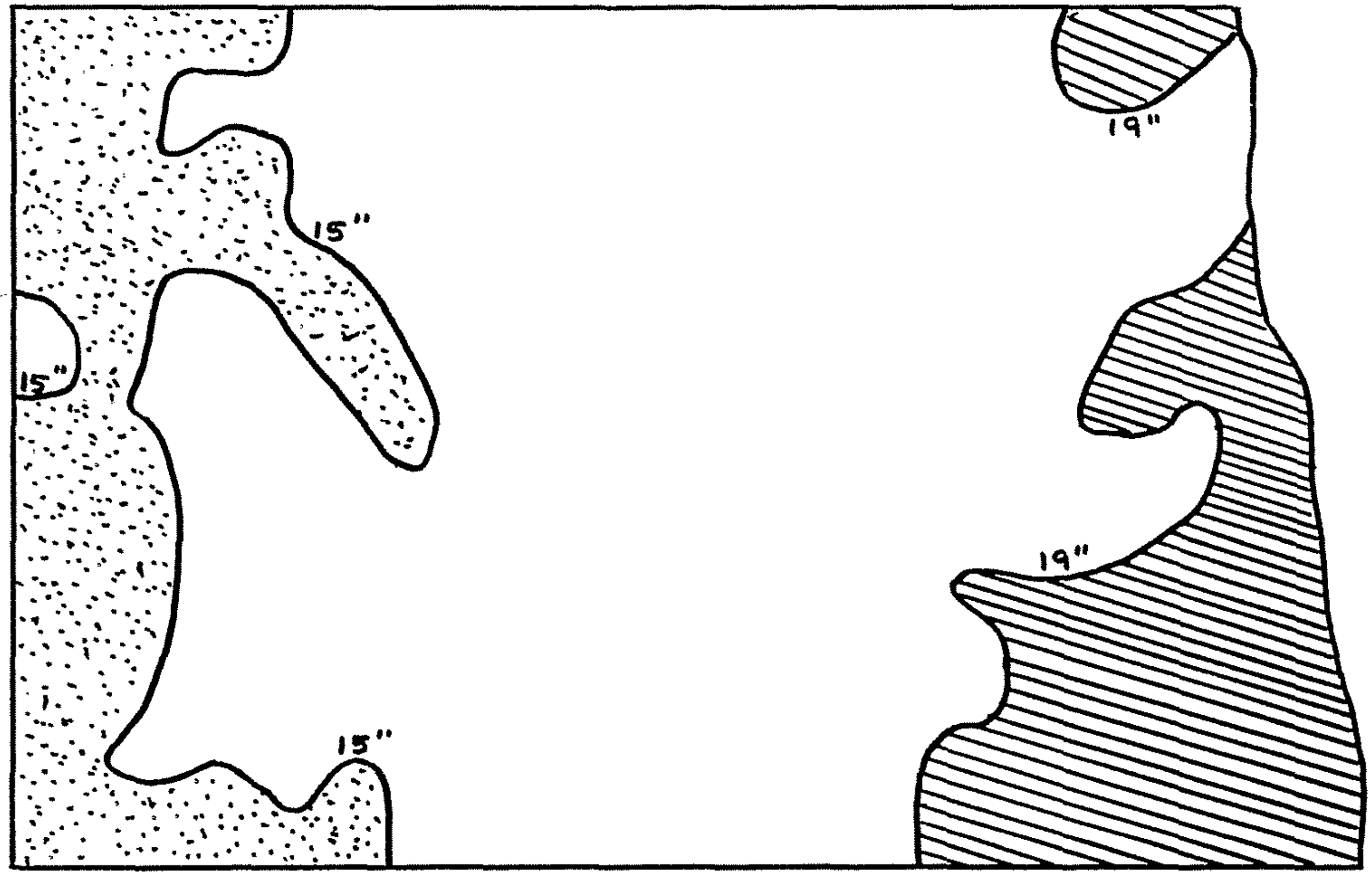
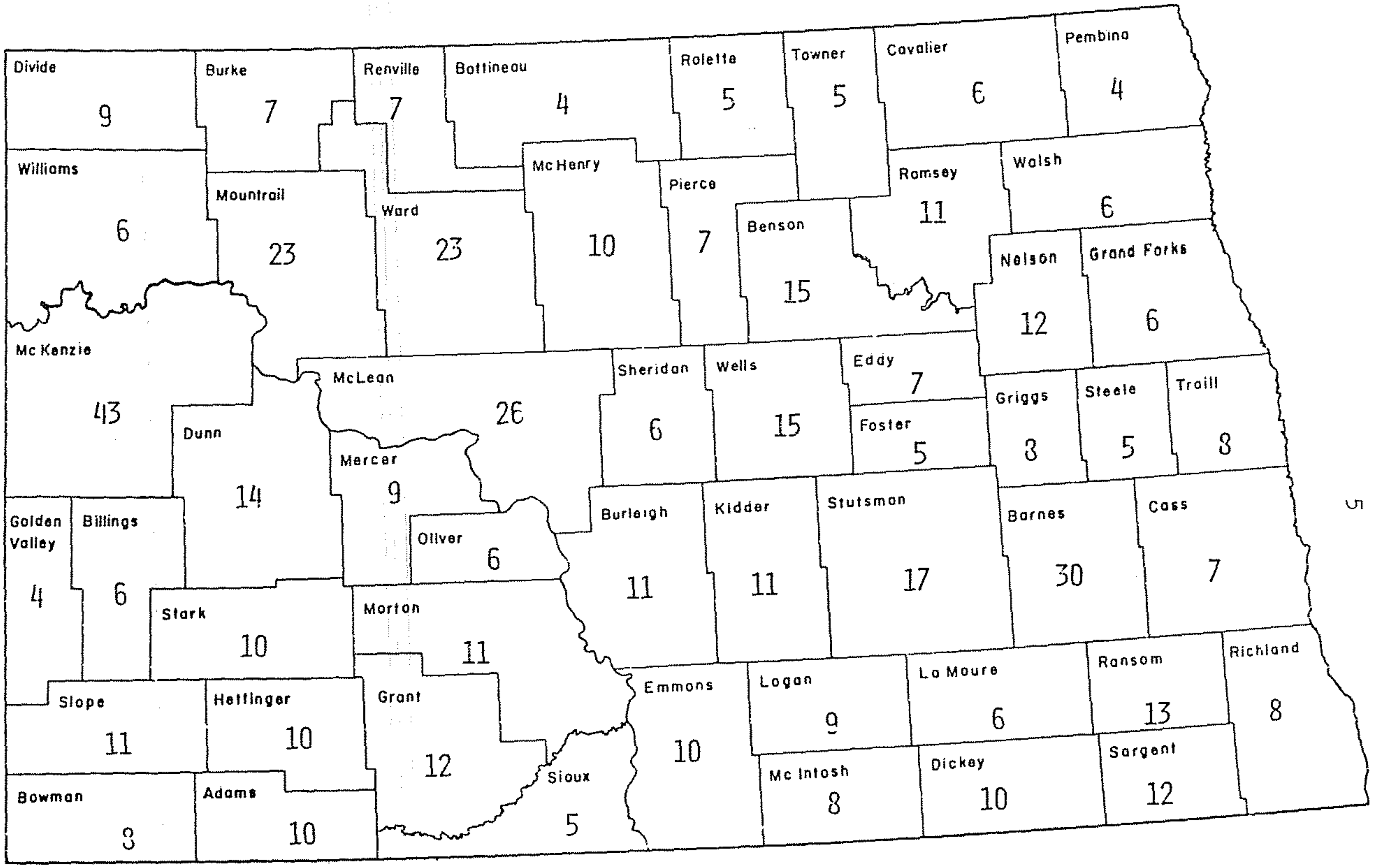


Figure 1: Long-term annual precipitation over North Dakota. Mean = 16.8", spatial standard deviation of station long-term means = 2.04". Approximately 16% of the state receives over 19" (hatched area) and 16% of the state receives under 15" (stipled area) during the "average" year.



1978 RAIN GAUGE NETWORK DISTRIBUTION BY COUNTY
(APRIL 1 - SEPT. 30)

FIGURE 2

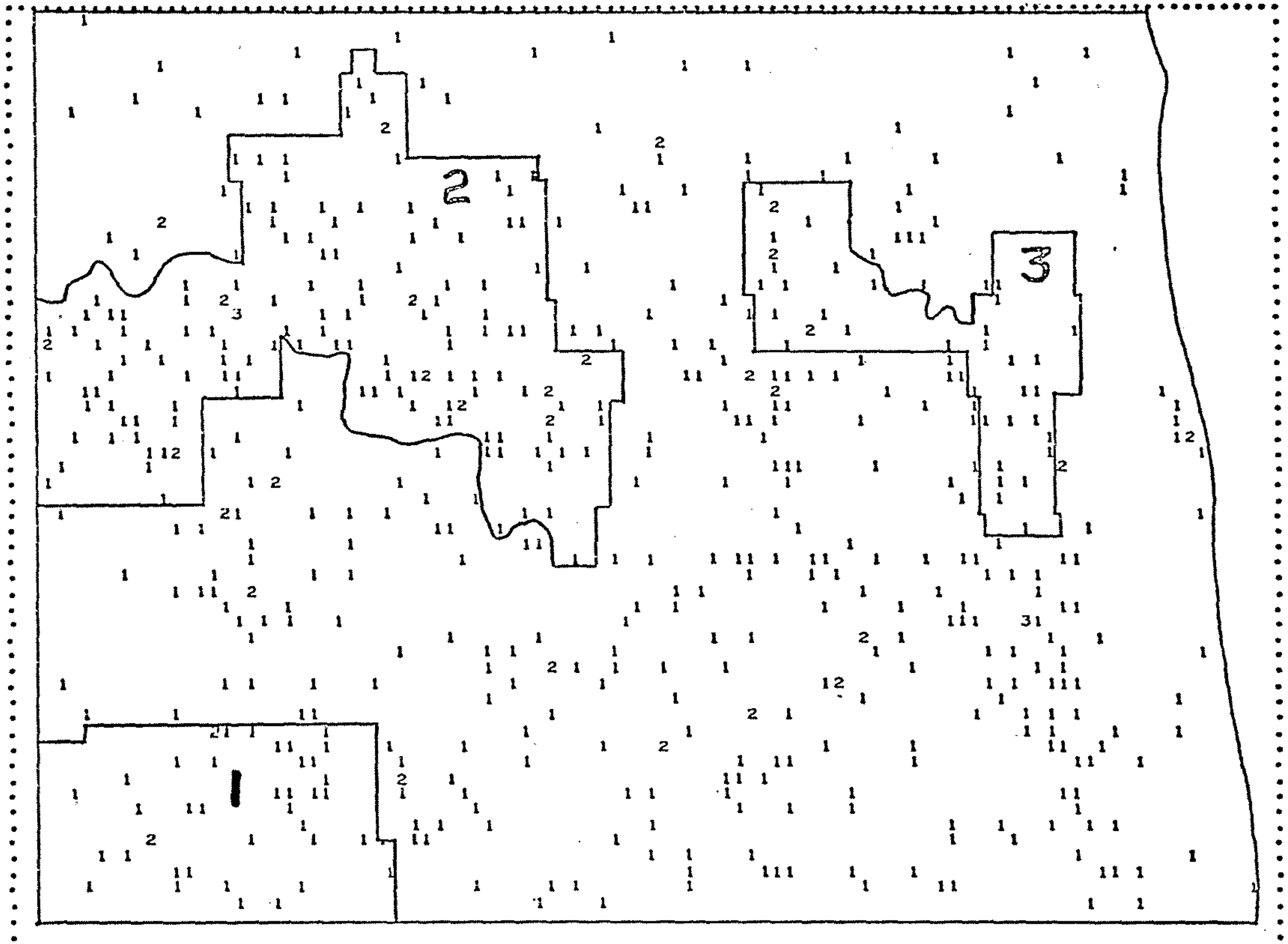


Fig. 3. The 1977 North Dakota daily rainfall observing network (coop net not included). Project areas shown

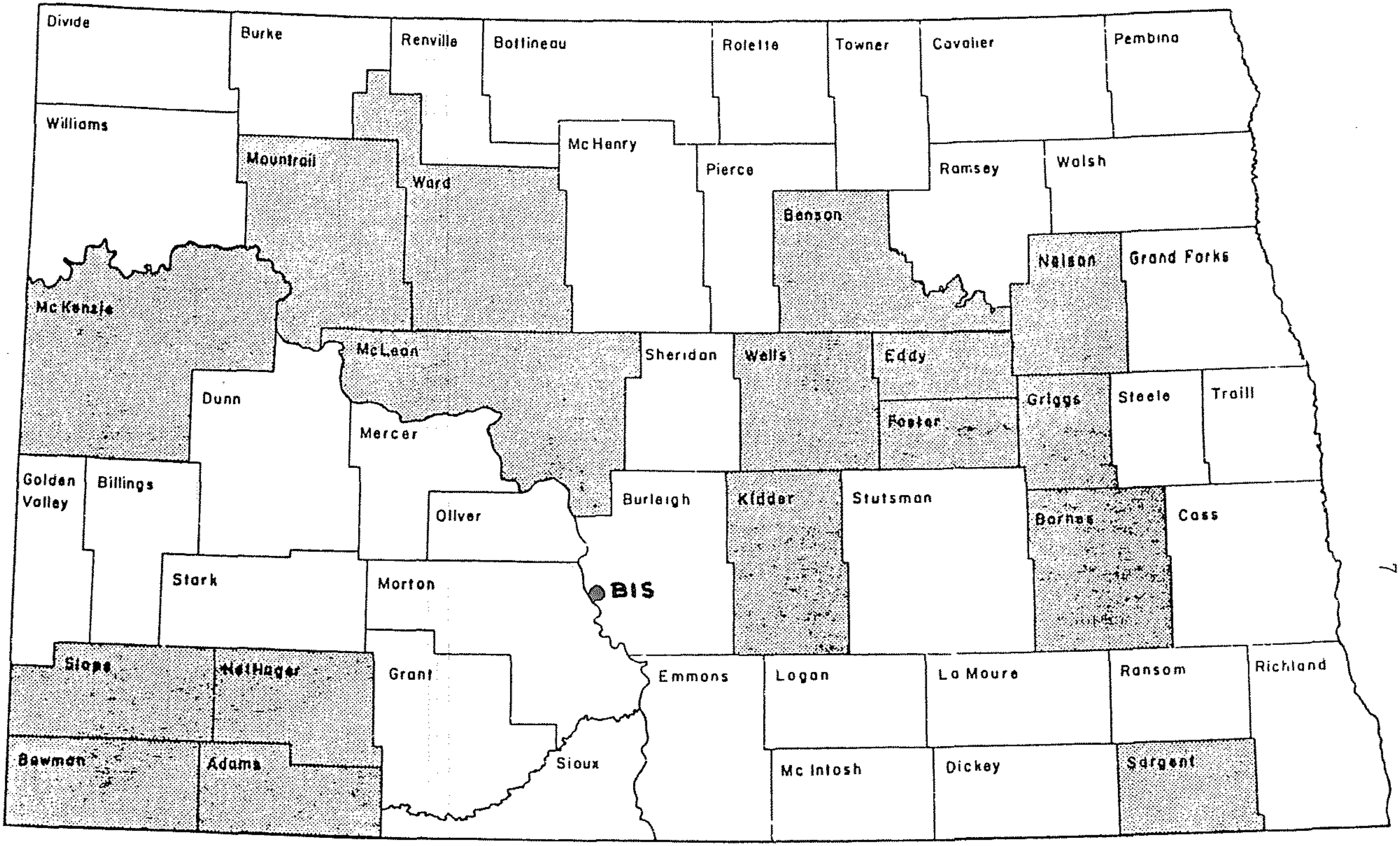


Figure 4: 1976 seeding project area. The location of the rawinsonde station (R/S) is at Bismarck (BIS).

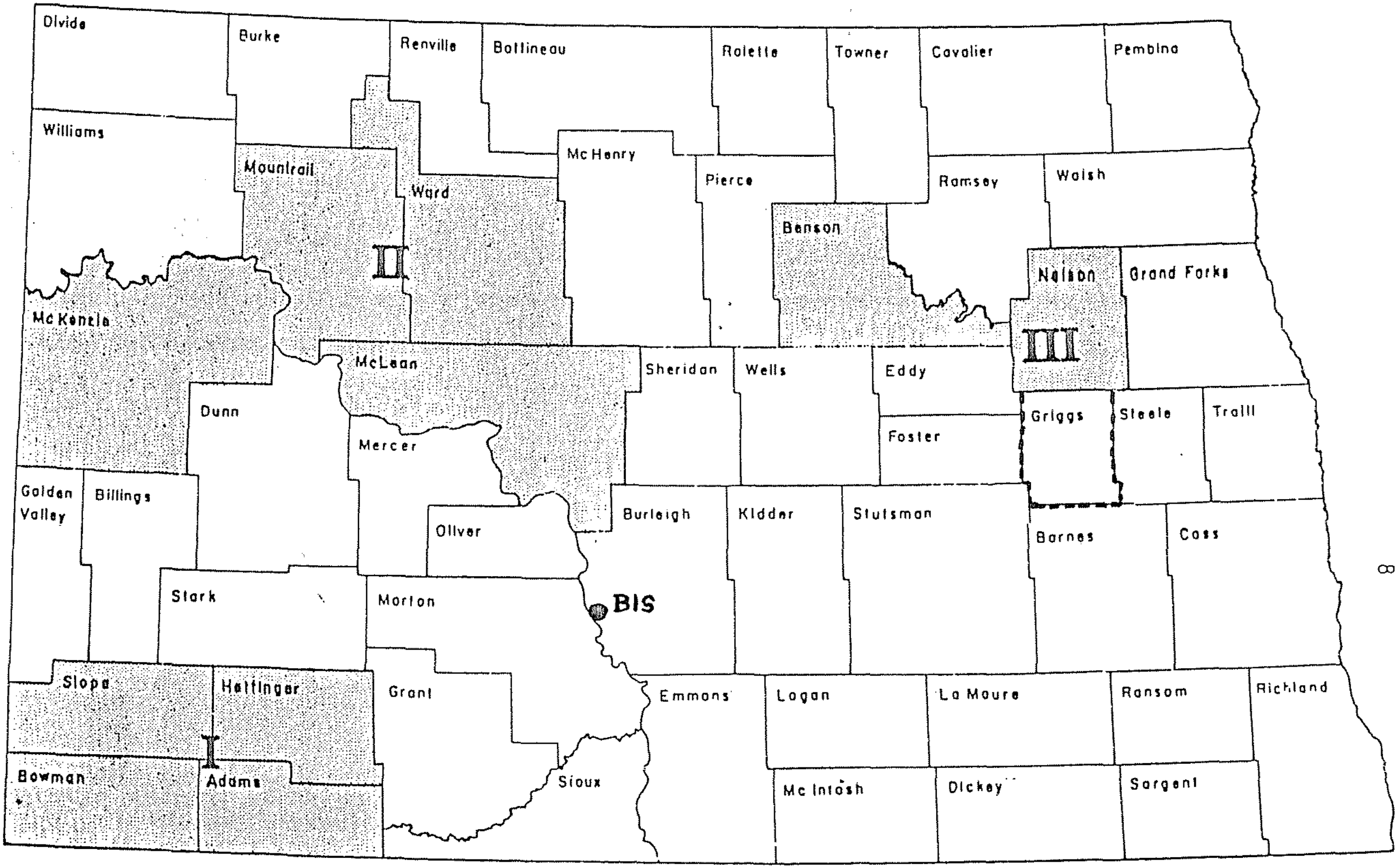


Figure 5: Seeding project areas 1977, 1978, 1979, 1980 shown shaded. During 1977 only, GRIGGS county was also in project area III. The location of the rawinsonde (R/S) station is at Bismarck (BIS).

B. ANALYSIS AND EVALUATION: THE PROBLEM

There have been two major thrusts to this problem:

i) to what extent have the rainfall patterns been changed by the cloud seeding?

and, ii) what is the probability that these analyzed changes are real and not simply "produced" by the techniques of analysis?

In this section we present the methodologies we have used to provide answers to each of these questions.

1. The Natural Variability

In order to test the significance of the difference between seeded and non-seeded rainfall in the most effective manner, it is helpful to remove natural sources of variability from the data sets. Two principal sources of such variability derive from, a) the tendency of rainfall to come from clouds associated with different types of synoptic-weather systems, and b) within each of these types: for there to be more or less atmospheric moisture available, more or less lifting of the air to condense such moisture, and other continuously varying properties of a similar nature. This section describes our search for ways to discover these two sources of variability in an objective manner. The first source ((a) above) we call clusters, stratifications, treatments or non-homogeneities. The second source we refer to as covariates. Figure 6 shows some features of the long term rainfall variability in the statewide average (non-zero) rainfall. Stations reporting zero rainfall were excluded in this case. The widths of the distributions shown are very roughly proportioned

Years	1951 To 1976	1951 To 1976	1913 To 1976	1951 To 1976	1913 To 1948	1951 To 1976	1951 To 1976	1951 To 1976
Wind Dir.	NW,W SW	All Winds	All Winds	NW,W SW	All Winds	SW	SW	SW
Seeding Area	No Seed	All Areas	All Areas	Seed	All Areas	All Areas	No Seed	Seed
N =	26809	96692	161215	20204	58274	20624	5732	7574

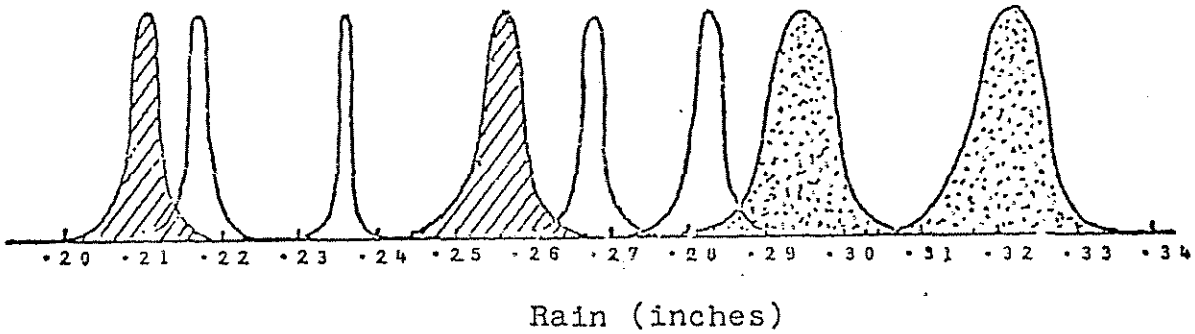


Figure 6. Some North Dakota climatology: mean rain on a rainy day. Reports of zero rainfall at a station not included. 59 cooperative network stations used.

to their expected variability. Notice that the mean value for the 96,692 non-zero rain reports found before 1951 is significantly greater than that obtained from the 58,274 non-zero reports taken after 1951. Since cloud seeding began about mid-century in North Dakota, one might conclude that it had decreased the rainfall. Such, of course, was not the case and such a conclusion represents one of many ways in which one can misinterpret rainfall analyses. In fact, the frequency of non-zero rain reports is much greater after 1951 than before and the net annual rainfall turns out to be about the same in both eras. What one might profitably consider based on this simple analysis is the possibility of a time change in the manner in which the atmosphere delivers its rain to the state. Long-term natural variability is suggested.

Significant irregularly occurring natural variability is suggested in Figure 35. Although this figure shows a soil moisture budget which also incorporates temperature affects, it shows that one should expect, AT IRREGULAR INTERVALS, persistent weather systems which deliver less than average or greater than average rainfall. These intervals can range from a few months to several years. Of course, on top of this variability we have the REGULAR annual cycles such as are shown in Figure 32. Figure 6 also suggests that wind direction is an indicator of expected rainfall amount. Figure 7 bears this out and adds the information that this directional effect is a function of season of the year. Does wind direction change imply a continuous variation in rainfall within a synoptic type and consequently be considered a covariate? Or, does a southwest wind imply one

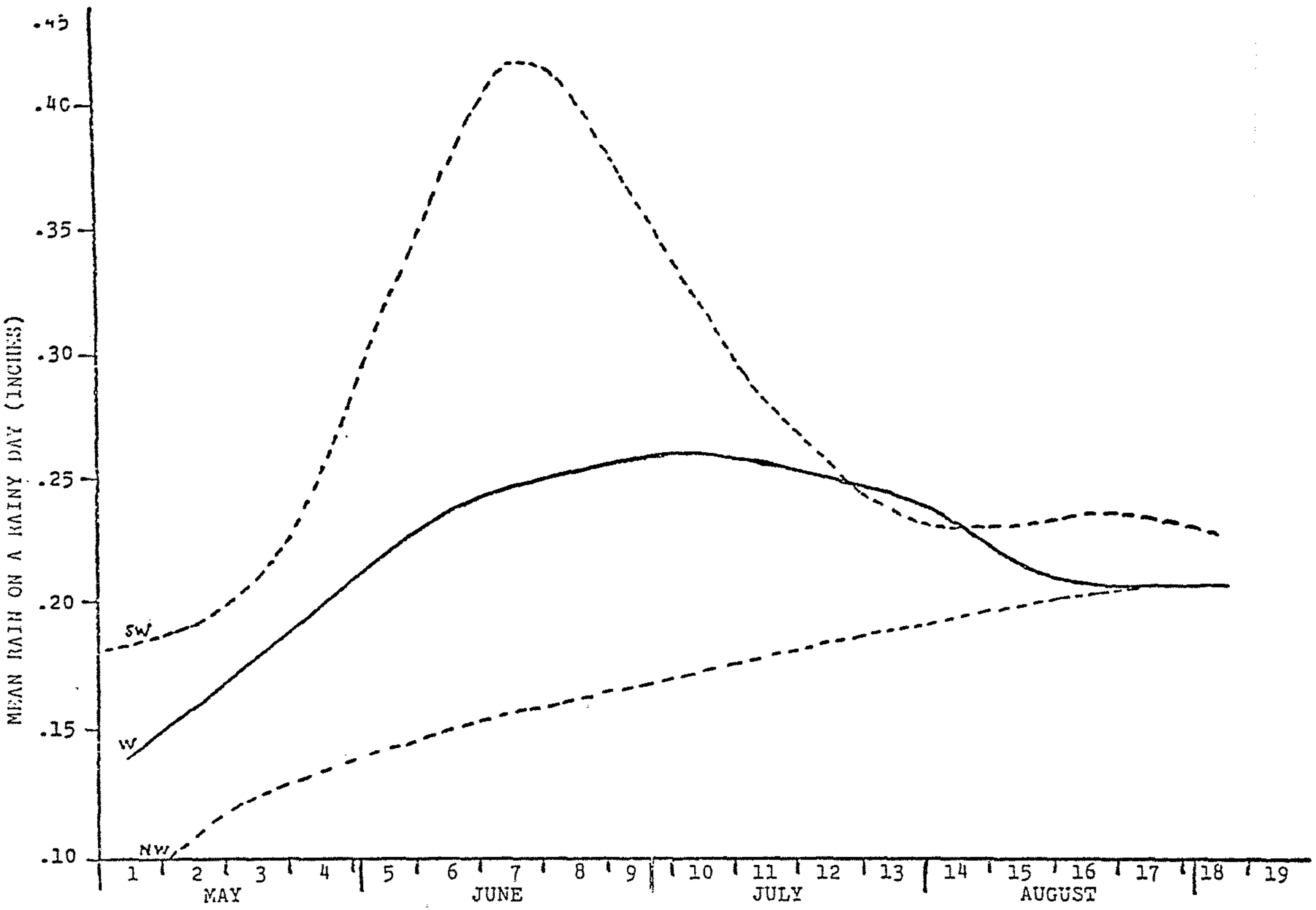


Figure 7. North Dakota mean rain on a rainy day as a function of wind direction and month.

weather type and a north wind another; consequently, should we account for discontinuous changes in the mean (expected value) in our analyses based on wind direction? More information is needed!

Figure 1 showed a northwest-southeast gradient from dry to wet in the annual precipitation averages across the state. Figure 8 shows about the same pattern for a time interval during the year which includes the cloud seeding season. However, when we check Figure 9 we find that the rainfall which occurs during the critical June growing period imposes a much more chaotic or random pattern on the general NW-SE trend. In fact, when Figure 9 is compared to Figures 4 or 5, one sees that the natural long-term variability in space in the target areas and during the critical few weeks of seeding activity is large enough to be of some concern in our evaluation problem. It was for this reason that we conducted our earlier analysis STATION by STATION to obtain results such as those shown in Figure 10. In this case we subtracted from each rainfall report (both seeded and non-seeded) the long-term average value for the station at the given time of year and for the given wind direction (COVARIATES), in order to obtain DETRENDED rainfall values. We averaged the detrended seeded rainfall values and from this we subtracted the average of the detrended non-seeded rainfall values to obtain the results shown. Another presentation of this same type of analysis is given in Figure 11. This shows another type of variability which permitted us to find a positive seeding effect only in the June and early July period.

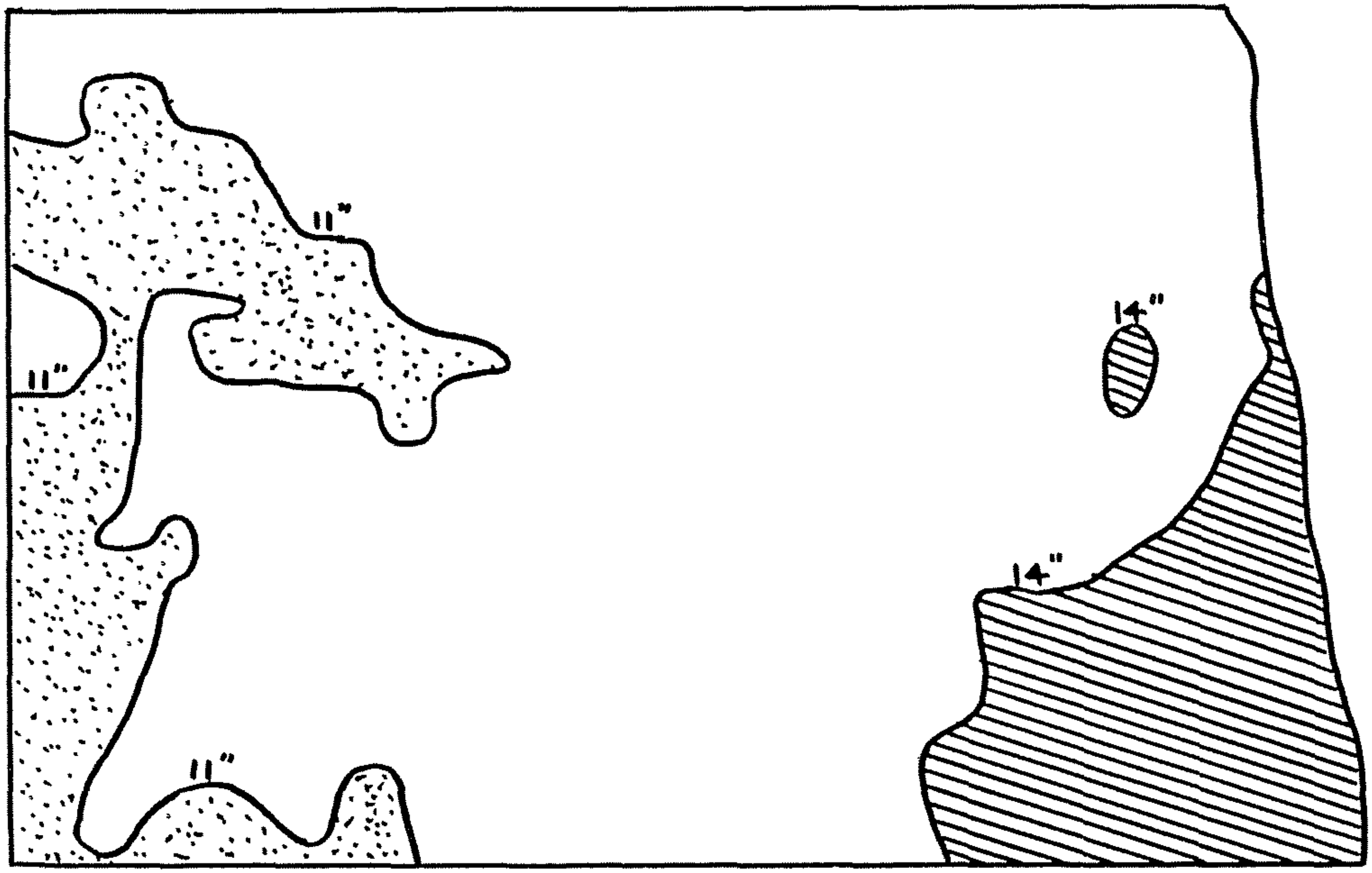


Figure 8: Long-term mean precipitation over North Dakota for period April 1 - September 15. Mean = 12.3", spatial standard deviation of station long-term means = 1.47". Approximately 16% of the state receives over 14" (hatched area) and 16% of the state receives under 11" (stipled area) during this 24-week period on the average.

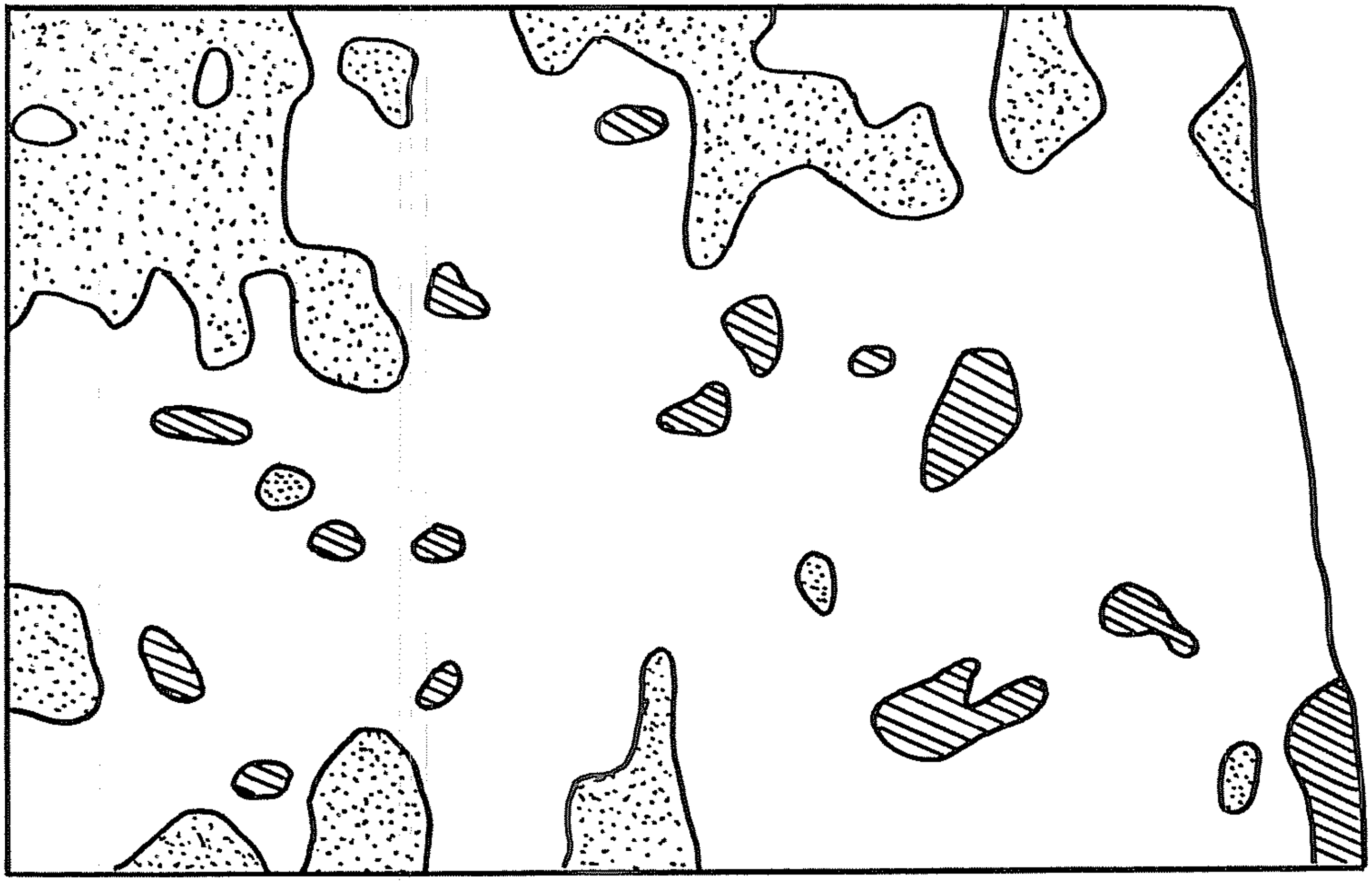


Figure 9: Long-term mean precipitation over North Dakota for period June 6 - July 11. Mean = 3.88". The stipled areas receive less than 3.5" and the hatched areas more than 4.5" during this 6-week period on the average.

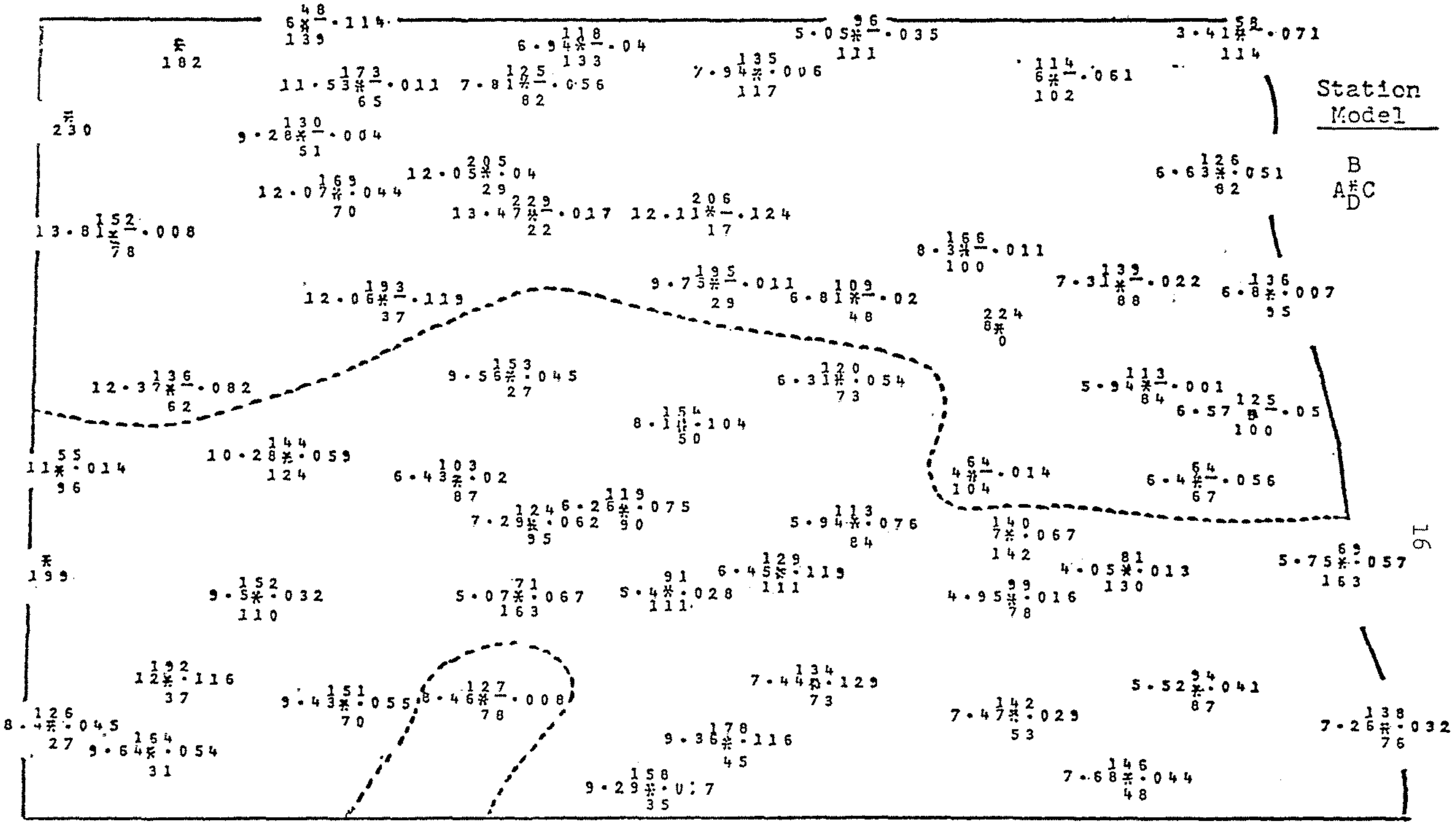


Figure 10. North Dakota seeding statistics 1951-1976. Station model:
A = mean number seeded rainy days per season (June 6-July 11)
B = Total number in seeded sample
C = (seeded - non-seeded) mean rain on a rainy day (inches)
D = total number in non-seeded sample.

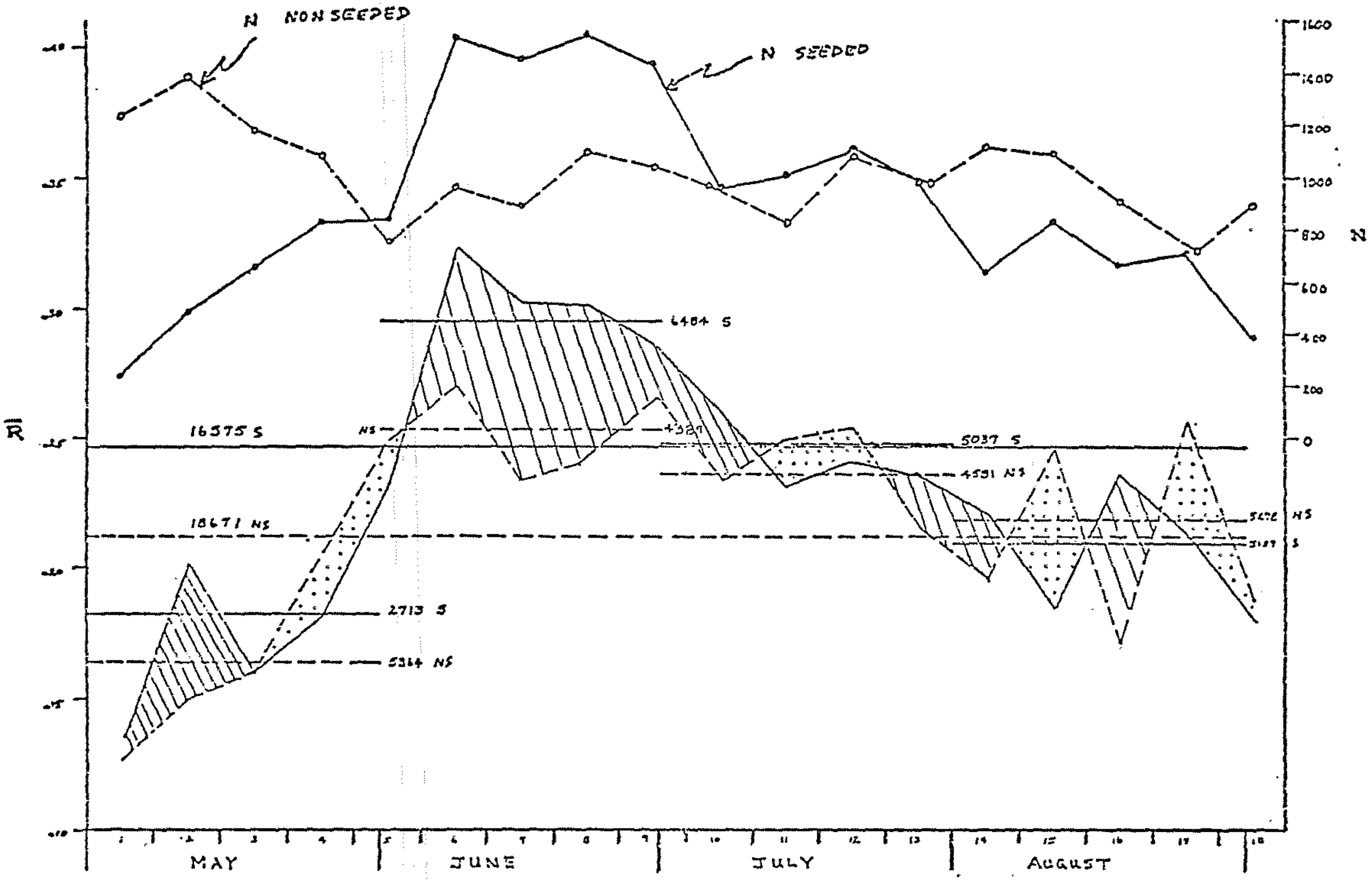


Figure 11. North Dakota daily rainfall coop reports from 1951 to 1976. $\bar{R}$ = mean rain on a rainy day in inches. N = number non zero reports. Solid line = seeded; dashed = non-seeded.

2. A Statistical Model Of Rainfall

The rainfall observations on which we base our analysis and evaluation are made once per day at 0700 in the morning local time. Thus, our basic experimental time unit is one day. The distribution across the state of our gage network makes our basic experimental space unit about 100 mi^2. Since a considerable amount of the rainfall in the state comes from cloud systems which are smaller than this space-time mesh size we will have to rely more heavily on the statistics of many cases than would be necessary if we could analyze the rain producers cloud by cloud.

Furthermore, since we are assessing a non-randomized operational program we must rely on the NATURAL RANDOMIZATION produced by variations in seeding location and wind direction to produce our seeded and non-seeded samples. This means that we must wait longer to obtain our adequate sample than would be the case had randomized cloud seeding been used. The sample size required to make a definitive evaluation is implied by Figure 12.

We want to group into clusters the observations made for each separate population, or synoptic weather type. Then we need enough observations of covariates and rainfall within each weather type to enable us to reduce the natural variability and average out the noise to the point where the expected difference between seeded rainfall and non-seeded rainfall stands out clearly. Since these expected differences can themselves vary from one weather situation to another, we need the assistance of quantitative cloud physicists to help stratify our data sets.

A RAINFALL MODEL

$$[R - \mu_R] \quad = \quad A\tau \quad + \quad (X - \mu_X) \quad + \quad \varepsilon$$

RESPONSE VARIABLES	TREATMENTS	COVARIATES	NOISE
RAINFALL	SEPARATE POPULATIONS	COMMON INFLUENCES	
RADAR REFLECTIVITIES	NON HOMOGENEITIES	WITHIN-POPULATION VARIABILITY	
CTT	DIFFERENT SEEDING TREATMENTS	CBT	
		AMBIENT STABILITY	
	DIFFERENT CLOUD TYPES	WIND DIRECTION	
	SYNOPTIC WEATHER TYPES		
	STATION LOCATION		

FIGURE 12

Once we find the needed TREATMENTS and COVARIATES, we proceed as follows. From each rainfall observation (both seeded and non-seeded) we subtract the <u>treatment effect</u> and the <u>covariate</u> effect. This leaves us with two sets of noisy residuals: one set for the seeded rainfall and one for the non-seeded rainfall. If we have done our job right, the noise should be random and tend to be averaged out as our sample size increases. If the seeding effect is systematic and NOT random it will show up as a progressively more distinct difference between the averages of the seeded and the non-seeded samples the more reports we obtain. The next section will show the progress we have made in this direction over the past year.

C. ANALYSES AND EVALUATIONS: THE RESULTS

As discussed in section A, our principal work over the past year has centered around the comparison of seeded with non-seeded rainfall on a day by day basis for the five years from 1976 to 1980 inclusive. The following section will present the results from analyses using three data sets:

i) the 500-600 special rain gage network across North Dakota (e.g. Figure 3),

ii) the seeding information provided by the logs of the pilots,

iii) air trajectory information from the rawinsonde network in and around the state.

The succeeding section illustrates our approach in searching for weather types and covariates. It uses output from the first section plus:

1) One-dimensional cloud model output statistics on the atmospheric thermodynamic and kinematic structure over North Dakota inferred from the BISMARCK, North Dakota rawinsonde observations. This (GPCM) cloud physics algorithm also estimates changes in the convective activity which should result from cloud seeding based on an objective (but simplistic) hypothesis.

1. "One Day - All Stations" Analyses And Evaluation Methodologies

Figure 13 has been abstracted from a computer printout showing seeding locations and air trajectories for one day in the North Dakota data set. The details of this procedure are described extensively in Eddy (1980). Briefly, the aircraft used on this day injected silver iodide in two main geographical-time clusters

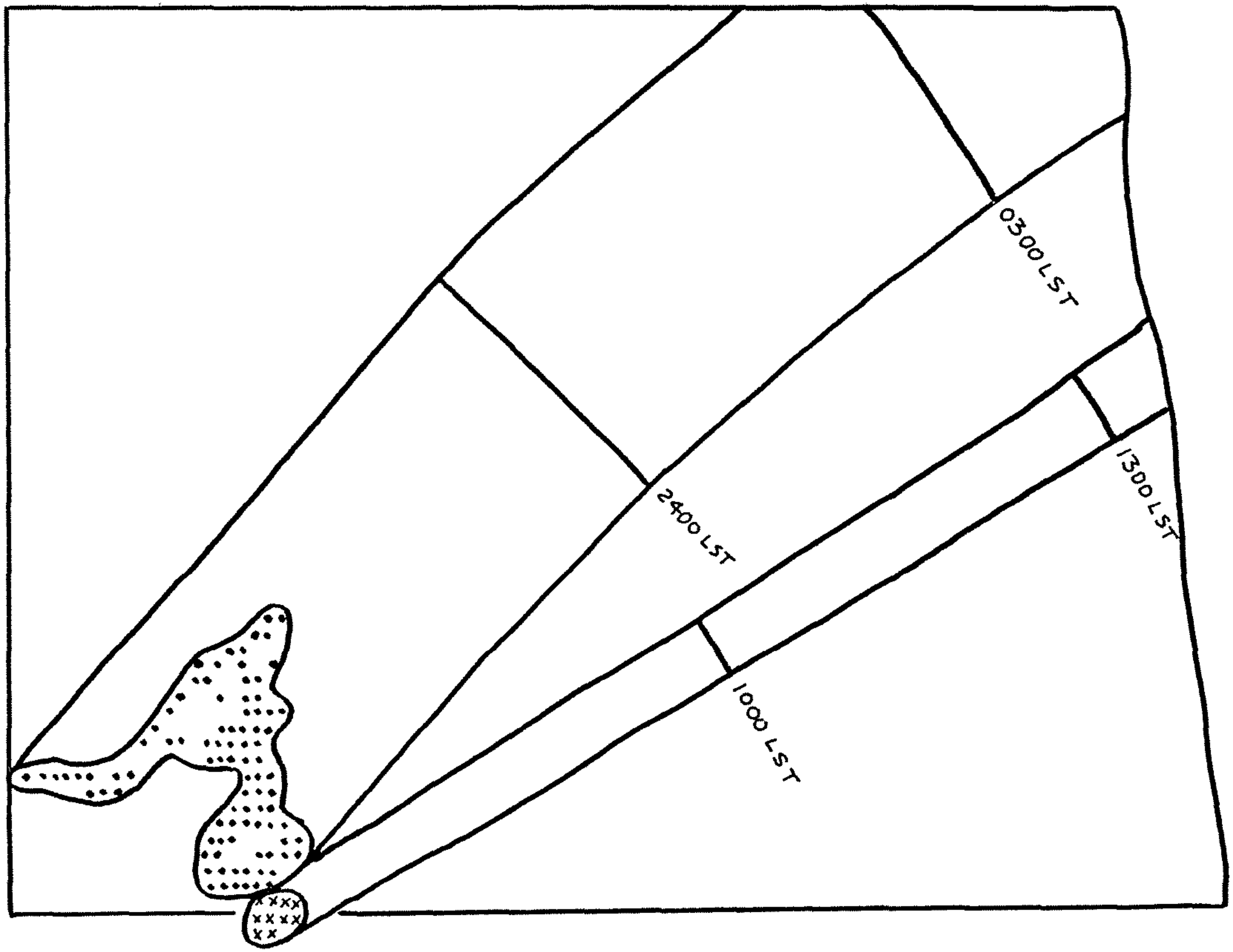


Figure 13: Two seeding areas and downwind plumes found for one 24-hour period (0700 LST-0700 LST) over North Dakota. The centroid of the larger area was found at 5,000 ft. and 2100 LST. The centroid of the smaller area was at 6,000 ft. and 0700 LST. Rain gage reports for the same 24-hour period will be flagged to show the sector in which they are located.

and we hypothesize that the wind bore this seeding material and the cloud systems toward the northeast as shown. Rain gage reports under the target areas were coded for the day as being in sector 1. The gages in the areas downwind from these target areas as far as the three-hour lines of demarcation (marked 2400 LST for the northern track and 1000 LST for the southern) were coded as being in sector 2. Gages in sectors 3 and 4 were similarly flagged. All gages lying outside any seeded sector were flagged with a zero. Mean daily rainfalls and intensity distributions were then calculated for each sector as well as for the combination of all seeded sectors and finally for all gages combined. We are now able to compare the seeded and non-seeded rainfall averages as well as the distributions of intensities for the day.

At this juncture we are making the tacit assumptions that (FOR THIS DAY) the entire state is in the same weather regime (synoptic situation) and that the covariate values are the same for the seeded as for the non-seeded rainfall. These assumptions are the counterparts in this all-space-at-one-time analysis, of the trend removal assumptions described above (Figure 10) in our previous all-time-at-one-point analysis. The main confounding influence on each day in our present analysis is the natural variability across the state. This must be reduced by combining many days with different wind directions and seeding areas. Before bringing about this combination we concern ourselves with the possibility that the "seeding effect" itself may be greater on days showing large statewide average rainfall than it is for days with small statewide average rainfall. Because of this possibility we transform the difference (d) between the seeded rainfall, $\overline{R}_s$ and the non-seeded rainfall $\overline{R}_{ns}$ according to the following formula:

$$d = (\overline{R}_s - \overline{R}_{ns})/\sigma_{(\overline{R}_s - \overline{R}_{ns})}$$

The precise formula for doing this is given on page 48. It is these "d" values which we combine to assess the significance of the seeding effect; whereas, it is the combined daily increase (or decrease) which we use to assess the economic impacts.

2. Results

Table 1 shows the general overall statewide results for the 5-year period under study. This table implies the same kind of results as were shown in Figure 11: the most effective rainfall enhancement derived from seeding in North Dakota is to be found during the six-week period from June 6-July 11. Table 2, however, implies further that rainfall increases of lesser statistical significance can be produced outside this period.

Another facet of the problem studied concerned daily rainfall intensity distributions in the non-seeded and seeded areas. As can be seen in Figure 14, the gages in the seeded areas tended to have higher daily rainfall values than did the gages in the non-seeded areas. This could have occurred by there being more rain per storm cell OR by there being more cells per day in the seeded areas than outside these areas. The latter possibility seems to be indicated by Table 3 which showed a higher proportion of the gages reporting non-zero rainfall in the seeded areas than was found in the non-seeded areas.

TABLE 1

STATEWIDE ANNUAL AVERAGE VALUES (5-YEAR MEANS (1976-1980))		
All Seeded Days During Season	Total	= 6.66"
Portion Attributed To Seeding During Season		= .89"
Mean Percent Increase (Using All Seeded Days)		= 15.4%
Mean Total Rain June 6-July 11		= 4.02"
Portion From Seeding June 6-July 11		= .50"
Mean Percent Increase June 6-July 11		= 14.2%

NOTE: In the above the 6.66" considers <u>seeded days only</u>; whereas the 4.02" is <u>all rain</u> during the period of major impact on spring wheat. Thus, the percent increase on <u>seeded days only</u> during the June 6-July 11 period will be somewhat greater than 14.2%.

TABLE 2

	June 6 - July 11		For All Seeded Days in Year		
	Actual Rain	ΔR	Actual Rain	ΔR	NUM Seed Days
1976	3.67	.80	5.86	1.34	70
1977	5.08	.67	7.20	.89	53
1978	5.59	.18	6.66	.51	47
1979	2.96	.29	6.12	.79	63
1980	2.79	.57	7.47	.94	63
Mean	4.02	.50	6.66	.89	60
	14.2% Increase		15.4% Increase		
	For All 36 Days		For Seeded Days Only		

SUMMARY OF NORTH DAKOTA 5-YEAR RAINFALL MODIFICATION ACTIVITIES

NON-SEED MEAN RAIN = .09"

WIND →	TARGET	0-3 Hrs.	3-6 Hrs.	6-9 Hrs.	9-12 Hrs.
SEED RAIN	.25"	.18"	.19"	.12"	.10"
SEED RAINY STNS	62%	53%	46%	36%	34%

NON-SEED RAINY STATIONS = 27%

Figure 14: Downwind Seeding Effect in North Dakota.

5-Year Average (1976-1980).

217 Seeding Days.

34,912 Seeded Reports.

115,323 Non-Seeded Reports on seeded days only.

All Wind Directions (The Figure Above Is Schematic).

Rainy Stns = the % of the observations which showed non-zero rainfall in each sector.

TABLE 3

RATIOS OF NON ZERO RAIN COUNTS TO TOTAL COUNTS
(ON SEEDED DAYS ONLY)

	All Rain	Non Seed Rain	Seed Rain	Target	0-3 hrs	3-6 hrs	6-9 hrs	9-12 hrs	12-15 hrs
1976	.28	.23	.41	.52	.42	.32	.27	.41	.22
1977	.38	.31	.56	.67	.58	.54	.38	.32	.32
1978	.35	.28	.57	.75	.59	.47	.23	.34	.27
1979	.28	.24	.44	.58	.48	.41	.39	.27	.16
1980	.35	.30	.55	.60	.56	.55	.51	.37	.18
Mean	.328	.272	.506	.624	.526	.458	.356	.342	.230

Lastly, the downwind effect was, in general, positive (increased rainfall), with no seeding influence detected more than 12 hours downstream from the target areas.

The year to year breakdown of the composite results shown in Figure 14 are given in Table 4.

Another important piece of evidence to support a seeding effect concerns changes in the rainfall intensities shown by gage observations. Table 3 implied such a shift toward higher 24-hour rainfall amounts falling in seeded gages than in non-seeded gages. Table 5 gives supporting evidence. Figure 15 shows this effect graphically for the 5-year period.

It is important to realize that seeded days tend to produce more rainfall naturally than do non-seeded days, and, in fact the distribution of rainfall on non-seeded days is different from that of non-seeded rainfall on seeded days. Table 6 shows this result.

Why are non-seeded days different from seeded days? Is the synoptic weather situation basically different? Many of our non-seeded days occur in April and May before the field programs begin; consequently, it is logical to suppose that the spring rain producers differ from those of summer. It is also the case that in spring the clouds are colder and the moisture supply less (two reasonable covariates).

We have discovered that these differences in rainfall intensity distributions produced by seeding tend to disappear as the systems move downwind, and in fact disappear after about 12 hours. Figures 17-21 show this result.

TABLE 4

STATE MEAN DAILY RAIN IN INCHES
(SEEDED DAYS ONLY)

	All Rain	Non Seed Rain	Seeded Rain	Mean d Value	N_d	S.D.(d)
1976	.08	.06	.13	1.18	50	.14
1977	.13	.10	.23	.87	42	.15
1978	.14	.10	.24	1.13	36	.17
1979	.09	.08	.16	1.14	40	.16
1980	.11	.09	.22	.95	42	.15
Mean	.110	.086	.196	1.05	210	.07
N_{TOT}	150235	115323	34912			

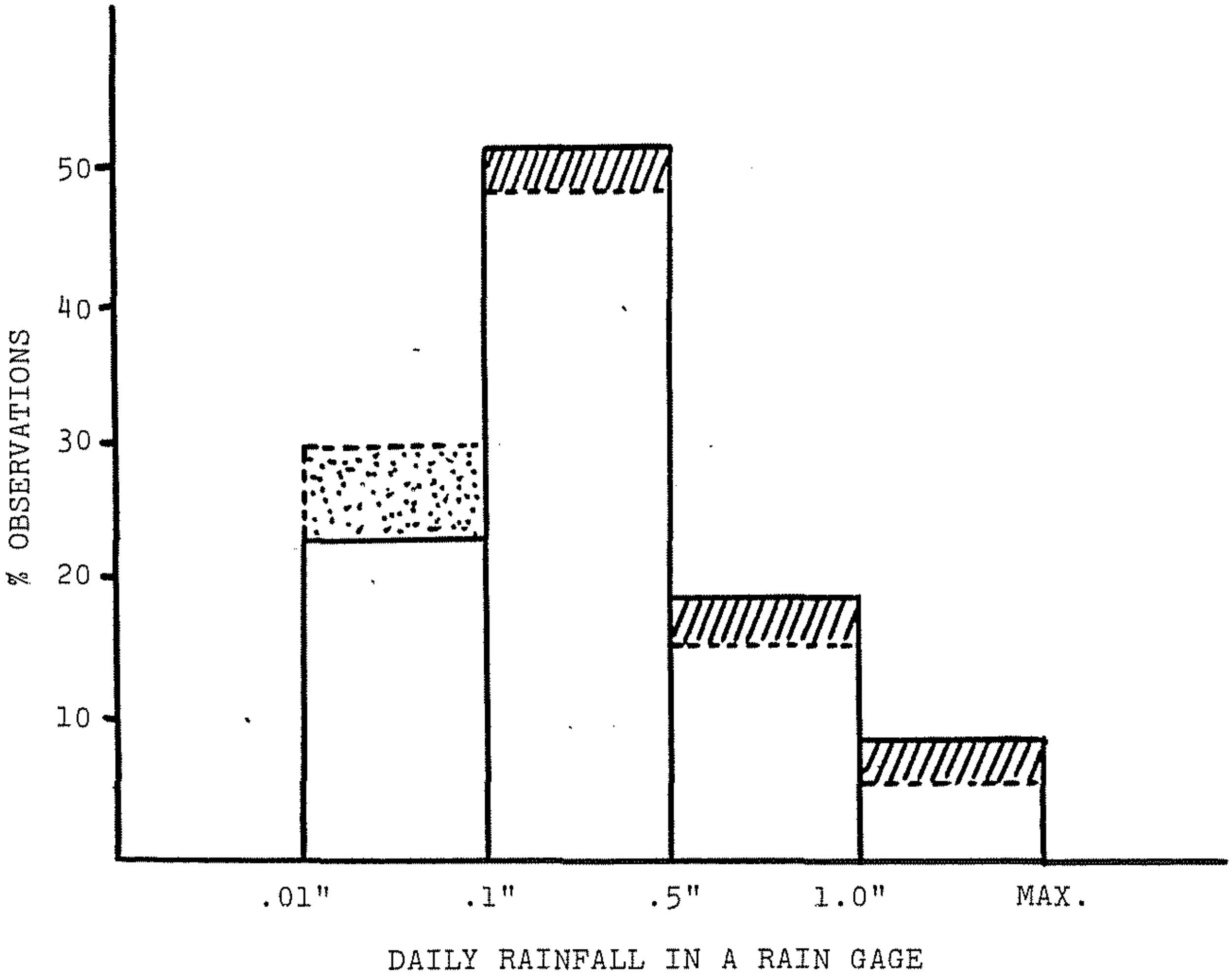
	Target	0-3 hrs	3-6 hrs	6-9 hrs	9-12 hrs	12-15 hrs
1976	.20	.10	.09	.08	.13	.04
1977	.25	.22	.28	.12	.09	.06
1978	.35	.23	.21	.11	.12	.02
1979	.24	.16	.14	.13	.06	.06
1980	.21	.21	.25	.18	.08	.07
Mean	.25	.18	.19	.12	.10	.05
N_{TOT}	8271	13470	8334	3174	1139	318

	.01 - .1	.1 - .5	.5 - 1.0	1.0 - MAX	N
1976	30.0	48.6	15.3	5.9	4,589
1977	18.2	53.1	19.8	8.7	4,055
1978	14.6	52.9	22.1	10.2	2,894
1979	26.1	50.7	13.7	9.3	2,302
1980	22.2	50.3	18.6	8.8	3,781
Weighted Mean	22.6	51.1	18.0	8.1	17,621

Table 5a: Percent frequency of seeded rainfall - all sectors - by year and intensity class.

	.01 - .1	.1 - .5	.5 - 1.0	1.0 - MAX	N
1976	35.96	46.20	14.05	3.79	6,682
1977	25.33	52.65	16.65	5.37	6,384
1978	28.12	44.38	17.79	9.72	4,261
1979	31.83	46.94	13.08	8.14	5,466
1980	27.91	51.53	14.97	5.59	8,388
Weighted Mean	30.00	49.00	15.00	6.00	31,181

Table 5b: Percent frequency of non-seeded rainfall on seeded days by year and intensity class.



Percent frequencies in 4 rainfall intensity categories.

SOLID = seeded rainfall

DASHED = non-seeded rainfall

HATCHED areas show higher frequencies in seeded areas

STIPLED area shows lower frequency in seeded areas

Figure 15: All 5 years. All seeded sectors; non-seeded rainfall on seeded days only.

TABLE 6
RAINFALL FREQUENCIES FOR ALL DAYS
APRIL 15 - SEPTEMBER 30, 1976 - 1980

Daily Rain Intensity (inches)	All Non-Seeded Rain	Seeded Rain	Non-Seeded Rain on Seeded Days
$0<R<.1$	.325	.226	.30
$.1\leq R<.5$	.500	.511	.49
$.5\leq R<1.0$	.131	.180	.15
$1.0<R$	.044	.081	.06
N	74977	17621	31181

The seeded rain is also broken down as a function of downwind sector.

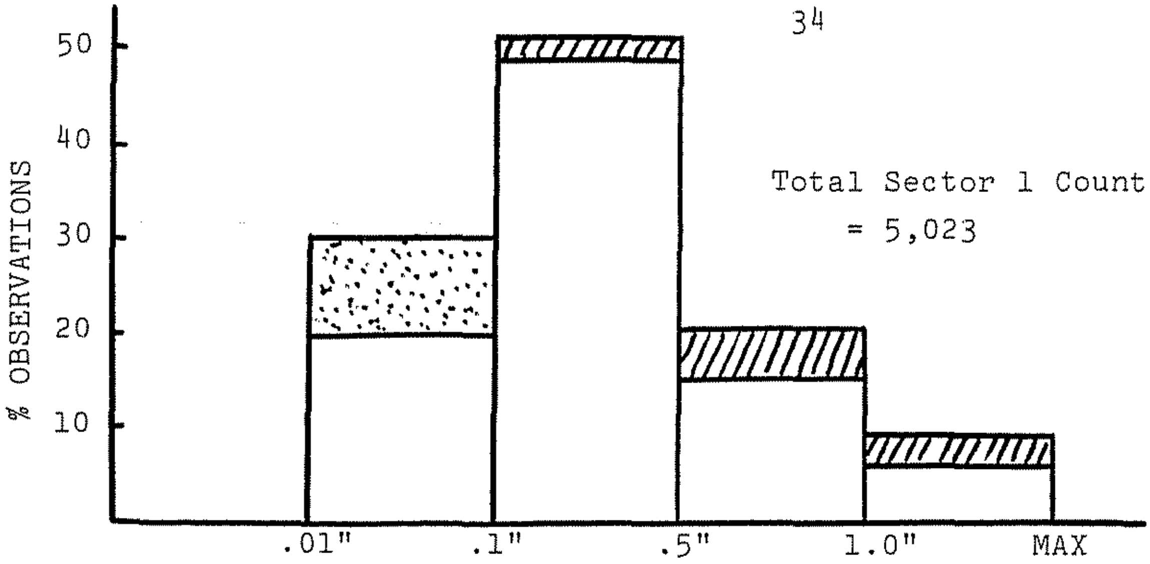


Figure 16: All 5 years. Target area.

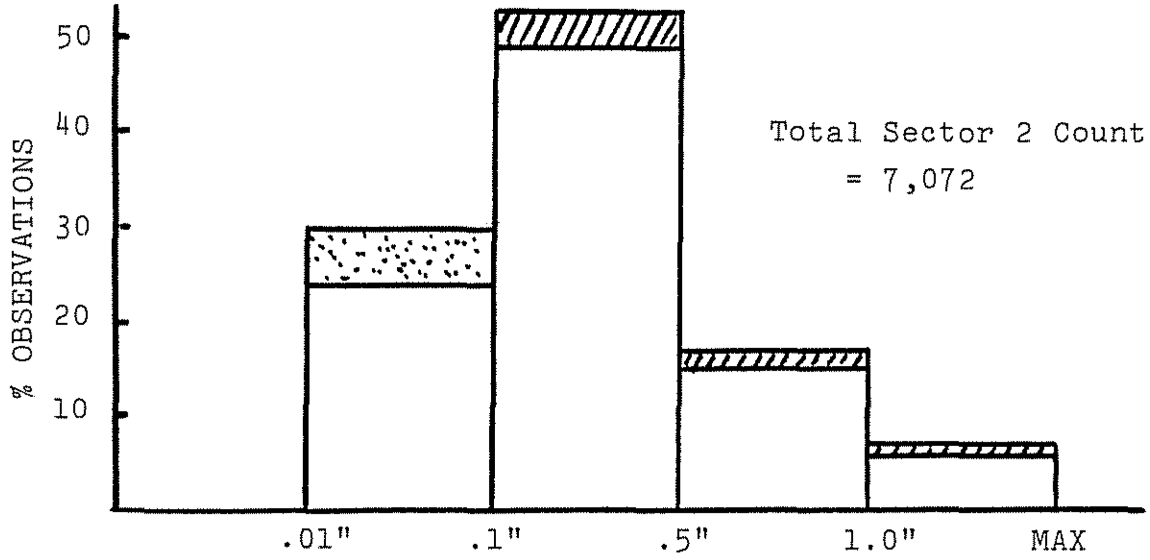


Figure 17: All 5 years. 0-3 Hours.

Percent frequencies in 4 rainfall intensity categories.

Hatched areas show higher frequencies in seeded areas.

Stipled area shows lower frequency in seeded areas.

Note: Non-seeded rain on seeded days only.

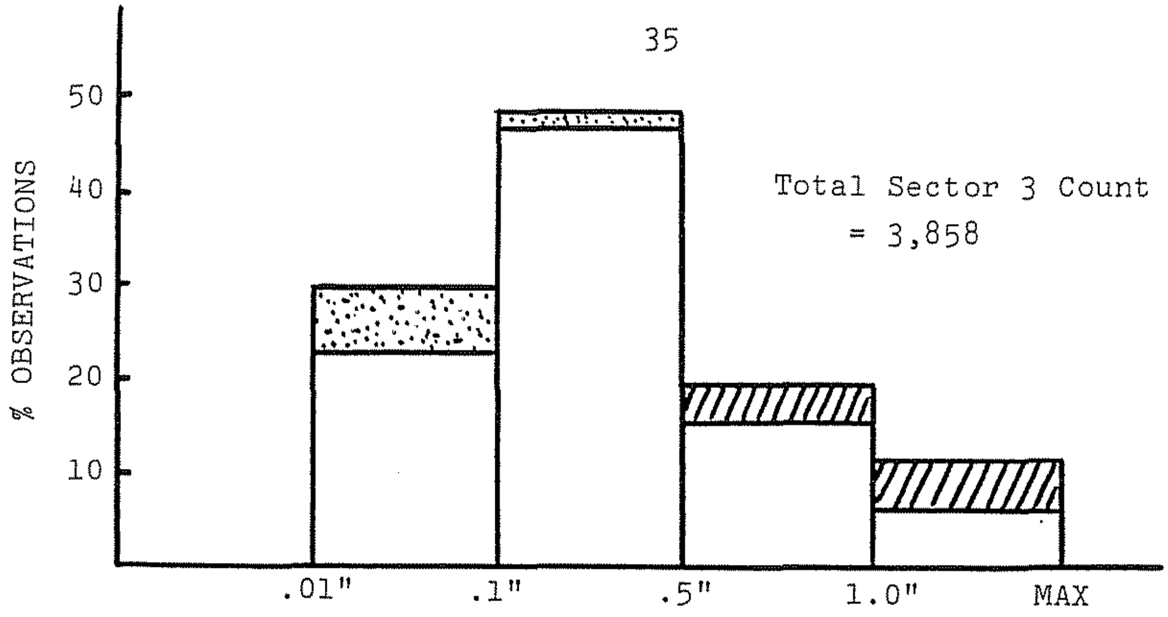


Figure 18: All 5 years. 3-6 Hours.

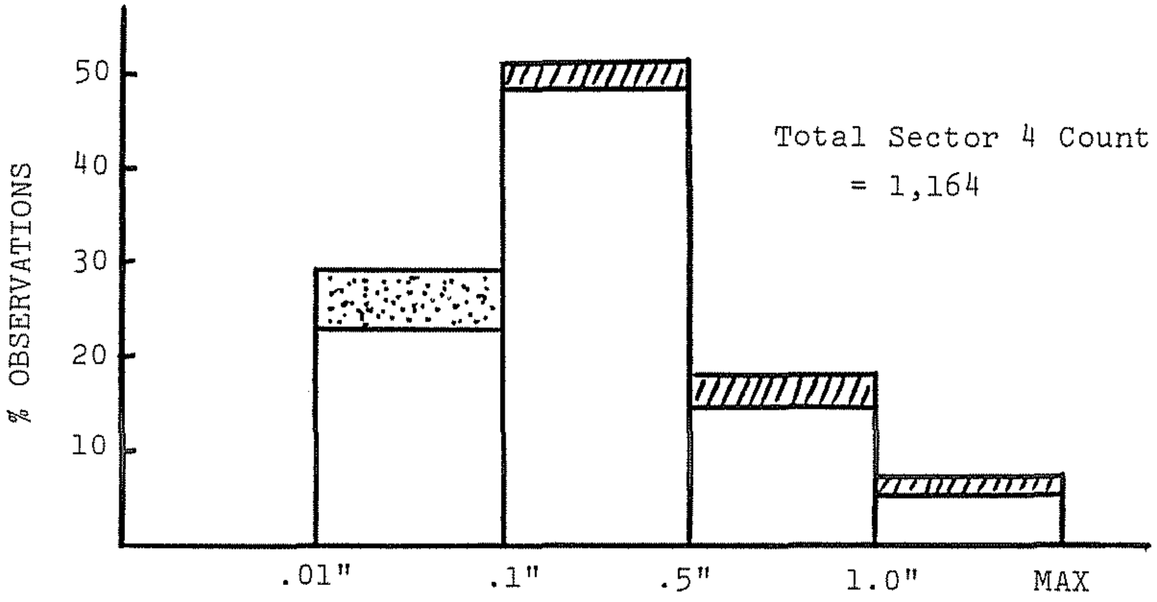


Figure 19: All 5 years. 6-9 Hours.

Percent frequencies in 4 rainfall intensity categories.

Hatched areas show higher frequencies in seeded areas.

Stipled area shows lower frequency in seeded areas.

Note: Non-seeded rain on seeded days only.

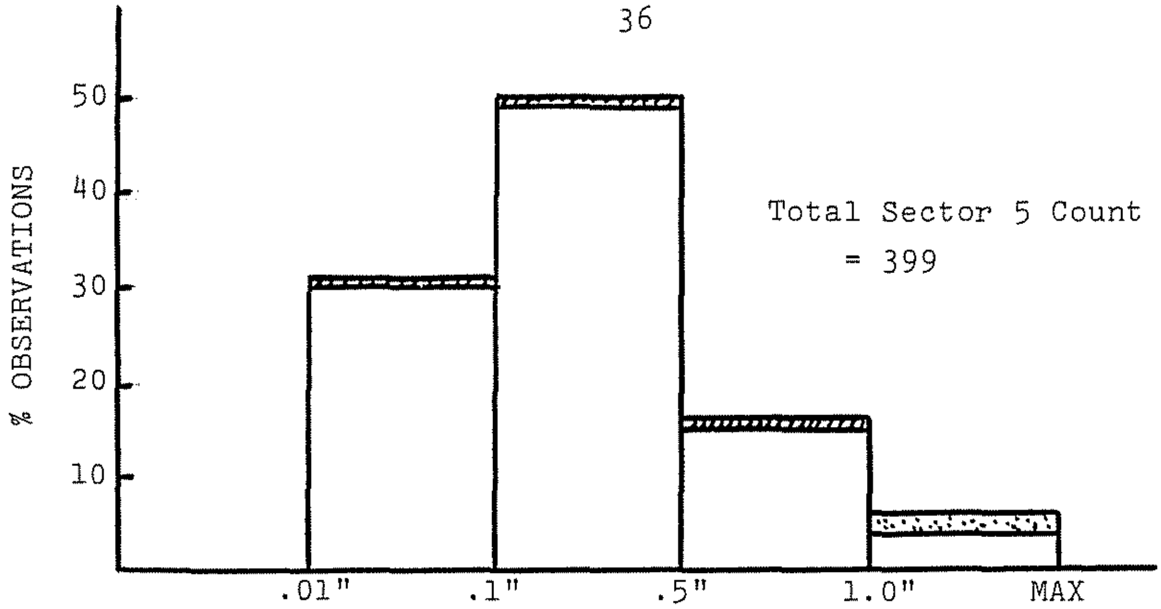


Figure 20: All 5 years. 9-12 hours.

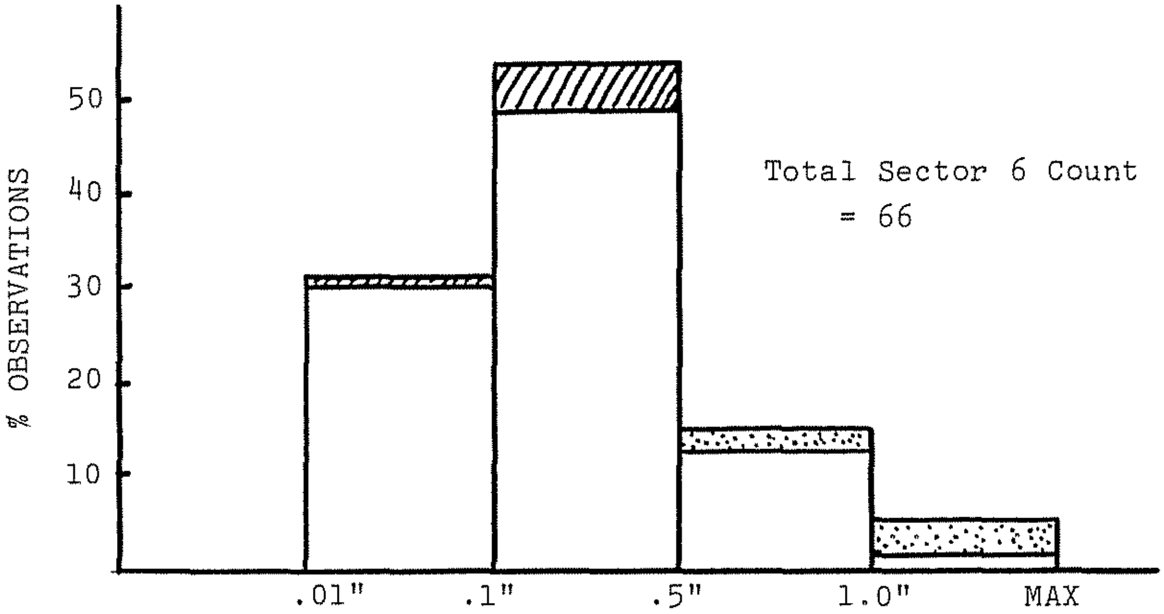


Figure 21: All 5 years. 12-15 Hours.

Percent frequencies in 4 rainfall intensity categories.

Hatched areas show higher frequencies in seeded areas.

Stipled area shows lower frequency in seeded areas.

Note: Non-seeded rain on seeded days only.

3. The Evaluation

During the 1976-1980 five-year period we studied 217 seeding days to assess the effect of the cloud seeding activities undertaken by the North Dakota Weather Modification Board on the rainfall distribution across the state. Although there were a few more seeded days, they had sample sizes in either the seeded or the non-seeded sectors which were too small to permit significant conclusions to be drawn.

As discussed above, each day was considered separately before it was added to the composite results. Since the averate rainfall on one day comes from a weather system which could produce more natural rainfall than would be produced on another day, we removed this effect (for purposes of significance testing) to a certain extent by normalizing the difference between average seeded and average non-seeded rainfall each day. Thus, IN THE LONG RUN if one averaged these normalized daily differences (1 value/day) he would expect to find a mean value of 0 and a standard deviation of 1 IF THERE WERE NO SEEDING EFFECT. We found a significant positive seeding effect for each of the five years studied.

Table 7 summarized our findings. It is clear that our factor "d" has the form of a student "t" statistic. One of the main points of concern in assigning confidence limits to the seeding effects shown in this table centers around the number of "degrees of freedom" or the independence of the data in the sample. We reported in Eddy, Cooter and Cooter (1979) the results of a study of the space autocorrelation in the rain gage observations.

TABLE 7

STATISTICS FROM DAILY VALUES COMPARING SEEDED RAINFALL STATEWIDE AVERAGE TO NON-SEEDED RAINFALL STATEWIDE AVERAGE

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8
1976	70	54	1.10	.14	6	7	.65	.43
1977	53	43	.85	.15	9	9	.50	.33
1978	47	36	1.13	.17	8	5	.67	.44
1979	63	42	1.09	.15	8	6	.64	.42
1980	63	42	.95	.15	12	7	.56	.37
5-YEARS	296	217	1.02	.07	43	34	.60	.39

X_1 = Total number seeded days.

X_2 = Number seeded days with over 7 non-zero rain reports in each of seeded and non-seeded areas.

$X_3 = \bar{d} = (\bar{R}_s - \bar{R}_{ns})/\sigma(\bar{R}_s - \bar{R}_{ns})$.

X_4 = Standard deviation of $\bar{d} = 1/(X_2)^{1/2}$.

X_5 = Number of negative d values "observed".

X_6 = Number negative d values "expected" if $d \sim N(0,1)$.

$X_7 = \bar{d}/1.69$ (adjusted for space autocorrelation).

$X_8 = X_7/1.52$ (adjusted now for both time and space autocorrelation).

These showed that the calculated variance of the difference could be too small by a factor of 2.85. This means that our "d" values should be adjusted downward by a factor of 1.69. Table 7 shows that the differences between (statewide) seeded and non-seeded rainfall are still significant for each of the five years. In fact, if one assumes a time autocorrelation from one day to the next of as much as $\rho = .4$, and further that these space and time autocorrelations are independent (a very severe assumption), then we are still left with far less than one chance in twenty that our seeding increase result was a fluke. We are forced to conclude that the rainfall in and downwind from our seeded areas was significantly greater (averaged over the state) than it was in the non-seeded areas over the 5-year period from 1976 to 1980.

4. The Search For Treatments And Covariates

As was discussed in section B above, this is a problem which looks to several meteorological subdisciplines for a solution. We have looked at time trends in the climate and space trends across the state in the daily weather. These were discussed by Eddy, Cooter and Cooter (1979). The differences in the cloud physics of the rain processes among air mass thunderstorms, squall lines, warm frontal rain and cold lows still need to be quantified. Although this should also be done from a synoptic climatology point of view, the method we have chosen to use is an analysis of the thermodynamic and kinematic structure of the ambient atmosphere over North Dakota during a particular day, performed on the Bismarck rawinsonde (R/S). We use a set of computer algorithms developed by Hirsch (1971) of the South Dakota School of Mines and Technology and expanded by Dave Matthews of the Bureau of Reclamation. The Great Plains Cloud Model (GPCM) is a 1-dimensional algorithm which estimates convective clouds which should develop in a given environment (R/S) provided a trigger mechanism is available. The surface temperature rise required to set off the instability is estimated and the consequent natural cloud growth is "predicted". Further: a modified cloud growth is also "predicted" assuming the introduction of a specified amount of silver iodide in a specified manner with a postulated cloud physics process.

It is the use of sets of GPCM output for purposes of stratifying our seeded rainfall increases (or decreases) and for purposes of looking for covariates upon which we report here. Tables 8-11 show the selection of variables from which we can choose for our purpose.

Table 12 lists a small sample of eleven ways in which we have classified each of our 5 years (1976-1980) of data. Firstly we will define the terms found in that table.

CTT = natural cloud top temperature (Table 10).

CBT = cloud base temperature (Table 8).

TIME = the time it would take a parcel of air to rise from the base to the top of a natural cloud. This has been estimated using the cloud thickness, the maximum vertical velocity given by the GPCM model and a parabolic shape to the vertical velocity profile (Table 10).

$\overline{R}_{ns}$ = mean rain over all gages lying in the non-seeded areas of the state on a given day (from NDWMB 500-600 gage special network).

$\overline{R}_{s}$ = mean rain over all gages in a target area or anywhere downwind on a given day (from NDWMB 500-600 gage special network).

d = a normalized value of $(\overline{R}_s - \overline{R}_{ns})$ (Equation 1, p. 48).

H = the increase in cloud depth because of silver iodide seeding as predicted by the GPCM (Table 10).

W_{max} = the maximum updraft speed predicted for the natural cloud (Table 10).

DIR_{500} = 500 mb wind direction (Table 11).

$\overline{R}_{all}$ = State mean rainfall for a day (from the NDWMB 500-600 gage special network).

The mixing depth used in computing the convective condensation level (CCL) in mb

Cloud base height (km)

Cloud base temperature (°C)

Surface convective temperature (°C)

Surface temperature rise required to reach convective temperature (°C)

Sub-cloud mixing ratio (g/kg)

Environmental mixing ratio; SFC-200 mb (g/kg)

Height of lowest inversion (m)

Mean lapse rate (°C/100 meters)
0-50, 0-100, 100-150, 150-200, 400-500,
500-600 millibars above surface

Mean mixing ratio (g/kg); same levels as for XLAPS

Numeric code to indicate if cloud growth

If IABORT = 0	growth was possible
If IABORT = 1	excessive heating was required to reach convective temperature and growth was deemed impossible.
If IABORT = 2	the rawinsonde data did not extend to the 200 mb level and the model was unable to determine growth.
If IABORT = 999	the sounding data were not available.

Table 8: GPCM Output Variables.

THE WIND SHEARS BELOW ARE FOR NINE ATMOSPHERIC SLABS: 0-50, 0-100, 100-150, 150-200, 400-500, 500-600, 300-500, 300-700 AND 300-800 MB ABOVE GROUND LEVEL

U Component shear (meters per second)

V Component shear (meters per second)

Directional shear (degrees)

U Component shear (per second)

V Component shear (per second)

T Component shear (per second)

Table 9: GPCM (Analyzer) Output Variables.

THE NEXT SIX TAPE RECORDS CONTAIN DATA FOR NATURAL AND MODIFIED CLOUDS WITH VARIOUS UPDRAFT RADII

RADIUS(1) = 0.5 km
RADIUS(2) = 1.0 km
RADIUS(3) = 1.5 km
RADIUS(4) = 2.0 km
RADIUS(5) = 3.0 km
RADIUS(6) = 10.0 km

Model cloud radius (km)

Cloud top height (km)
Note: For these and the following variables,
J = 1 indicates the natural cloud,
J = 2 indicates the modified cloud.

Speed of maximum cloud updraft (m/sec)

Height of maximum updraft (km)

Temperature at the maximum updraft height (°C)

Maximum reflectivity (dB)

Height of the maximum reflectivity (km)

Efficiency of precipitation (%)

Efficiency of condensation (%)

Predicted rainfall (inches)

Natural cloud depth (km)

Modified cloud depth (km)

Cloud top temperature (°C)

Total QC COLD (g/kg)

Total QH COLD (g/kg)

Table 10: GPCM Output Variables.

THE NEXT SIX RECORDS CONTAIN DATA FOR THE
VARIOUS MANDATORY PRESSURE LEVELS:
200, 300, 400, 500, 700 AND 850 MB
LEVELS, IN THAT ORDER

Pressure in millibars
Height of pressure surface in meters
Temperature at the pressure level (°C)
Dew point depression (°C)
Relative humidity (%)
Potential temperature (K)
Equivalent potential temperature (K)
Wet-bulb temperature (K)
Saturation wet-bulb temperature (K)
Wind direction (degrees)
Wind speed (meters per second)
Saturation deficit (grams per cubic meter)

Precipitable water SFC - 850 mb
Precipitable water SFC - 700 mb
Precipitable water SFC - 500 mb
Total precipitable water
Height of the 0°C isotherm (meters)
Height of the -5°C isotherm (meters)
Height of the -10°C isotherm (meters)
Height of the -15°C isotherm (meters)
Mean mixing ratio of the lowest 100 mb (g/kg)
Lifted index - 100 mb adiabatic
Lifted index - 50 mb layer mean values
Total totals index
George's K-index
Severe weather threat (SWEAT) index

Table 11: GPCM (Analyzer) Output Variables.

TABLE 12

STRATIFICATIONS RUN FOR 5-YEARS

Cloud Radius = 3 KM
GPCM Output for Natural Clouds (Except H)

CODE	VARIABLES			NUMBER IN SAMPLE					
	ROW	COL	STRAT	TOTAL	1976	1977	1978	1979	1980
1	CTT	CBT	Time = 8	717	130	148	150	151	138
2	$\bar{R}_{ns}$	$\bar{R}_{s}$	d = 0	362	84	68	62	73	75
3	d	CBT	CTT = -20	247	62	43	40	53	49
4	d	H	Time = 8	247	62	43	40	53	49
5	Ratio	H	d = 0	247	62	43	40	53	49
6	d	Time	CTT = -20	247	62	43	40	53	49
7	d	W_{max}	CTT = -20	247	62	43	40	53	49
8	d	W_{max}	CTT = -35	247	62	43	40	53	49
9	d	DIR_{500}	CTT = -20	247	62	43	40	53	49
10	$\bar{R}_{all}$	DIR_{500}	CTT = -20	247	62	43	40	53	49
11	d	$\bar{R}_{all}$	CTT = -20	247	62	43	40	53	49

Note: Ratio = $(\text{non zero/total})_s / (\text{non zero/total})_{ns}$; Time = K * time to cloud top
H = GPCM predicted increase cloud depth

Next we turn our attention to Table 12, codes 3, 7, and 11. The 5-year composite results of these tabulations are shown in Tables 13, 14, and 15. These tables all make use of the GPCM analyses of 5 years of daily 1200z R/S data at Bismarck during the seeding period each year. (We use April 1-Sept. 30); however, when $\overline{R}_s$ is used then only seeded days are considered.

We will describe our system by using code 3 (Table 13) as an example. The page contains two main tables and the numbers within each are counts of days in that particular "slot". The total count in Table 13 = 247 (152 + 95); this means that our data set consisted of 247 days when we found values for $\overline{R}_s$, $\overline{R}_{ns}$, CBT and CTT during the 5-year period. These 247 days are split into 152 days when the (GPCM predicted natural) CTT was less than -20°C and 95 days when the (GPCM predicted natural) CTT was warmer than or equal to -20°C (see Table 12, column 4, row (code) 3.

In each of the two tables the days are split (columns) into five CBT categories as shown. Also in each of the two tables the columns are split (rows) into five normalized-rainfall-increments $(\overline{R}_s - \overline{R}_{ns}/\sigma(\overline{R}_s - \overline{R}_{ns}))$. The sixth column and the sixth row are sums of the tabular row values and column values respectively. Estimated conditional and simple probabilities are also shown.

$$d = \frac{\bar{R}_S - \bar{R}_{NS}}{\left(N_S S_S^2 + N_{NS} S_{NS}^2\right)^{1/2}} \bullet \left(\frac{N_S N_{NS}(N_S + N_{NS} - 2)}{N_S + N_{NS}}\right)^{1/2}$$

WHERE $S^2 = \frac{1}{N} \sum_{I=1}^{N} (R_I - \bar{R})^2$

R_{SI} = A RAIN REPORT IN A SEEDED SECTOR

R_{NSI} = A RAIN REPORT IN THE NON-SEEDED AREA

AND A RAIN REPORT = THE 24-HOUR RAINFALL BETWEEN 0700 LST AND 0700 LST

EQUATION 1

CODE 3

CLOUD BASE TEMPERATURE °C

			-7.5	-2.5	+ 2.5	+7.5		P(d)
		0	0	0	3	3	6	.04
	-1.5	0	0	0	2	6	8	.05
d	-.5	1	1	7	19	37	65	.43
	+.5	0	0	4	12	27	43	.28
	+1.5	0	0	3	12	15	30	.20
		1	1	14	48	88	152	
P(d>+.5 | CBT)		0	0	.50	.50	.48	.48	On Seed Days
P(CBT)		.01	.01	.09	.32	.58		On Seed Days
P(CBT)								On Non Seed Days

P(CTT < -20°C) = .62

CLOUD BASE TEMPERATURE °C

			-7.5	-2.5	+2.5	+7.5		P(d)
		0	0	0	1	5	6	.06
	-1.5	0	0	0	0	3	3	.03
d	-.5	0	1	3	17	17	38	.40
	+.5	0	0	3	5	12	20	.21
	+1.5	0	1	2	13	12	28	.29
		0	2	8	36	49	95	
P(d>+.5 | CBT)		-	.50	.63	.50	.49	.51	On Seed Days
P(CBT)		0	.02	.08	.38	.52		On Seed Days
P(CBT)								On Non Seed Days

P(CTT > -20) = .38

TABLE 13

CODE 7

MAX VERT MOTION IN M/S

		3	7	11	15			P(d)
	-1.5	0	0	1	1	4	6	.04
	-.5	0	0	0	0	8	8	.05
d	+.5	0	1	4	10	50	65	.43
	+1.5	0	0	1	4	38	43	.28
		0	0	1	6	23	30	.20
		0	1	7	21	123	152	
$P(d>+.5 \mid W_{max})$		–	0	.29	.48	.50	.48	On Seed Days
$P(W_{max})$		0	.01	.05	.14	.81		On Seed Days
$P(W_{max})$								On Non Seed Days

$P(CTT < -20°C) = .62$

MAX VERT MOTION IN M/S

		3	7	11	15			P(d)
	-1.5	3	3	0	0	0	6	.06
	-.5	1	1	1	0	0	3	.03
d	+.5	7	16	10	2	3	38	.40
	+1.5	3	4	6	6	1	20	.21
		7	12	7	2	0	28	.29
		21	36	24	10	4	95	
$P(d>+.5 \mid W_m)$		.48	.44	.54	.8	.25	.51	On Seed Days
$P(W_{max})$		.22	.38	.25	.11	.04		On Seed Days
$P(W_{max})$								On Non Seed Days

$P(CTT > -20°C) = .38$

TABLE 14

CODE 11

TOTAL RAIN (STATE MEAN FOR DAY) IN INCHES

		.01	.11	.21	.31			P(d)
	-1.5	0	3	1	0	2	6	.04
	-.5	0	5	2	0	1	8	.05
d	+.5	24	25	7	3	6	65	.43
	+1.5	1	26	8	2	6	43	.28
		7	16	5	1	1	30	.20
		32	75	23	6	16	152	
P(d>+.5|R)		.25	.56	.57	.50	.44	.48	On Seed Days
P(R)		.21	.49	.15	.04	.11		On Seed Days
P(R)		.54	.38	.08	.01	0		On Non Seed Days

P(CTT < -20°C) = .62

TOTAL RAIN IN INCHES

		.01	.11	.21	.31			P(d)
	-1.5	0	2	1	2	1	6	.06
	-.5	0	1	1	1	0	3	.03
d	+.5	15	12	5	3	3	38	.40
	+1.5	1	9	6	2	2	20	.21
		3	17	3	1	4	28	.29
		19	41	16	9	10	95	
P(d>.5|R)		.21	.63	.56	.33	.60	.51	On Seed Days
P(R)		.20	.43	.17	.09	.11		On Seed Days
P(R)		.48	.34	.10	.02	.04		On Non Seed Days

P(CTT > -20°C) = .38

TABLE 15

Tentative inferences

Table 13: d, CBT, CTT:

1) rainfall increases associated with seeding predominate rainfall decreases no matter what the cloud top temperature and no matter what the cloud base temperature,

2) there are twice as many cold cloud tops as warm cloud tops in this data set,

and

3) by far the most clouds in this North Dakota data set have base temperatures warmer than +2.5°C.

Table 14: d, W_{max}, CTT; additional inferences:

1) warm cloud tops are associated with slow maximum vertical motions and cold cloud tops with fast vertical motions,

and

2) in the case of the warm cloud tops, the positive d values (Eqn. 1) seem not to be associated with any particular vertical motion, although there is a tendency to peak around 11-12 m/s; while in the case of the cold cloud tops, the positive d values (seeding rainfall increase) tend to cluster around the fast updrafts. COULD THE SEEDING OF LARGE (TALL=COLD TOP) CLOUDS TO REDUCE HAIL, ALSO BE INCREASING RAIN?

Table 15: d, $\overline{R}_{all}$, CTT; additional inferences:

a) most of the daily mean rainfall for this North Dakota data set is less than 1/4 inch with the peak (mode) around 1/10 inch. This seems to be independent of the CTT,

and

b) with warm cloud tops, the seeding is more likely to produce rainfall increases in synoptic situations delivering less than .2 inches (statewide average); whereas, for cold cloud tops, the rainfall increases are likely to occur with a slightly higher statewide average rainfall.

In the above analyses, the R/S observation used was 1200z on the same date as the rain report. This means that the upper air sounding was timed to occur at the end of the 24-hour on which the rain fell, as indeed was the rain measurement itself. The following tables present the analysis results for 1980 code 7 (d, W_{max}, CTT) to provide a comparison between the 1200z R/S as used and the sounding 12 hours earlier at 0000z. This earlier sounding would have been taken near suppertime during the time of the maximum (on the average) convective activities which produced the measured rainfall.

Although the sample size in Table 16 is small, the conclusions drawn as regards the seeding rainfall increases as a function of maximum (natural) vertical motion and (natural) cloud top temperature remain unchanged. The main consequence of this change in R/S timing is to lose part of our data set if we choose the afternoon sounding.

The above is only a sample of the planned analyses. Future stratifications will be guided to a major extent by the Todd-Howell hypotheses concerning the cloud physics of precipitation enhancement.

One very important aspect of the above results must be underscored: the GPCM itself acts as a stratifier of weather types. There is a considerable amount of rainfall which is not of the convective type and which would show up in the model output as IABORT = 0 or 1. Thus the day involved would not show

R/S at 0000 GMT 1980

W_{max} M/S

d

		3	7	11	15
	0	0	0	0	1
-1.5	0	0	0	0	1
-.5	0	0	1	3	2
+.5	0	0	1	0	4
+1.5	0	0	0	0	2

CTT L.T. -20°C

W_{max} M/S

d

		3	7	11	15
	0	0	0	0	0
-1.5	0	0	0	0	0
-.5	0	2	3	0	0
+.5	2	0	0	0	0
+1.5	1	4	0	0	0

CTT G.E. -20°C

R/S at 1200 GMT 1980

W_{max} M/S

d

		3	7	11	15
	0	0	0	1	1
-1.5	0	0	0	0	1
-.5	0	0	1	3	12
+.5	0	0	0	0	9
+1.5	0	0	1	1	3

CTT L.T. -20°C

W_{max} M/S

d

		3	7	11	15
	2	0	0	0	0
-1.5	1	0	0	0	0
-.5	2	3	2	0	1
+.5	0	0	0	1	0
+1.5	2	2	0	0	0

CTT G.E. -20°C

Table 16: Code 7 (d, W_{max}, CTT).

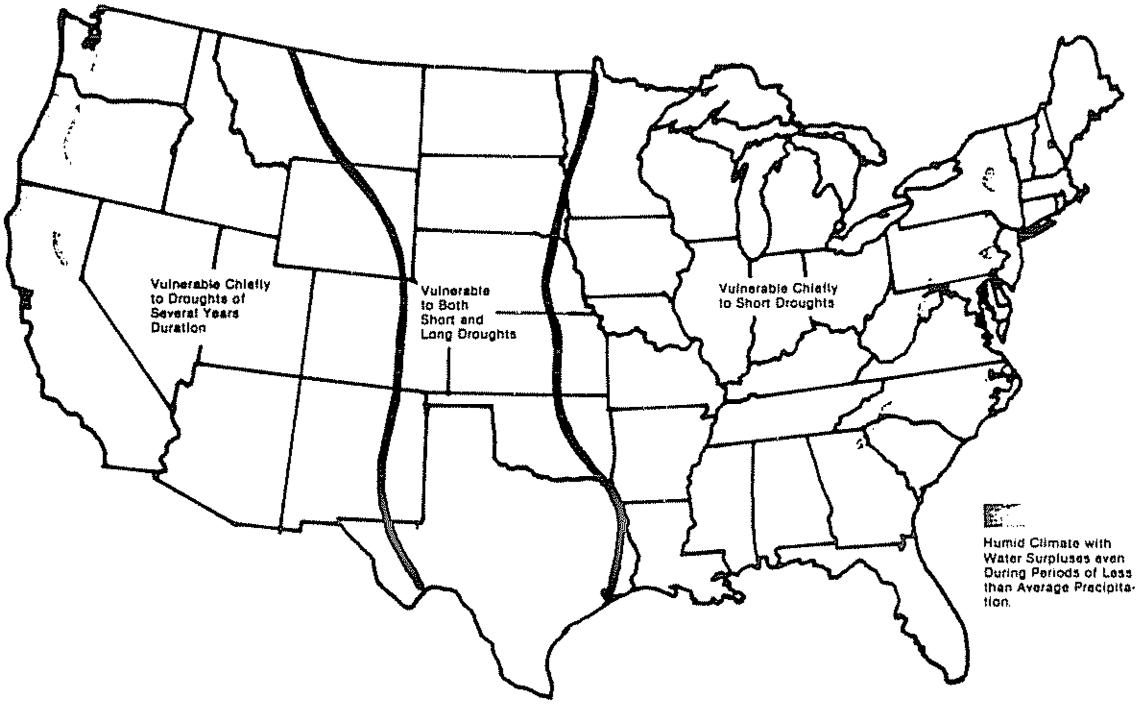
up in the above analysis. This "stratification by default" must be done in a more positive sense------possibly by using variables such as positive vorticity advection.

Although there is still a good way to go before the *clusters* and *covariates* can be specified objectively, the job can be done and the results will be valuable.

D. IMPACT

This section of our report is presented in two segments. Segment 1 discusses an approach to the analysis of agricultural drought in North Dakota which was developed by the author and Ellen Cooter in 1978 and the relevant portions of that report are presented in the following pages. We have considered spring wheat for illustrative purposes and both precipitation and temperature effects are integrated through the use of a simple hydrologic accounting system. The purpose is to illustrate the manner in which the agricultral community across the state can expect those climate parameters which most affect their industry to vary naturally over many years. Figure 22 shows that the state is vulnerable to both short-term and long-term drought and it is for this reason that we have begun to define those climate variables responsible in order eventually to assess the value of weather modification in reducing the impact of these naturally occurring disasters.

Segment 2 deals with the economic impact on the state of rainfall enhancement over the 1976-1980 period. Dr. Cooter has used 14 crops for his analysis and drawn on several sources of expertise in the State of North Dakota for his information on local agricultural economics.



Areas vulnerable to drought

SOURCE: United States Department of the Interior, Geological Survey, 1970
The National atlas of the United States of America.

FIGURE 22

1. Drought In North Dakota

Time series of daily values of precipitation, maximum temperature and minimum temperature were obtained from the National Climate Center for 55 National Weather Service stations across North Dakota. Data from all stations in each of the nine Climate Divisions were averaged over a week in the case of temperatures, and daily averages were summed for a week in the case of precipitation. Figures 23 and 24 give examples of short portions of these weekly by CD average values for mean temperature and for precipitation taken from CD9. Drought characteristics must be deduced from some combination of pairs of such superficially incredibly dissimilar series.

As another drought indicator, we obtained Hard Red Spring (HRS) yield data for each year between 1929 and 1975 for each of our 9 Climate Divisions in North Dakota.

The decision was made to investigate three methods of combining the temperature and precipitation data for the purpose of assessing drought conditions. All three have been developed by W. C. Palmer and were reported by him in 1965 and 1968.

Soil moisture (SM) and evapotranspiration (ET) come from using Palmer's 1965 system for integrating the basic variables on a weekly basis instead of the monthly interval he chose for his own studies. The crop moisture index (CMI) basically follows the procedure used currently to produce the charts published by the USDA/NOAA weekly Crop and Weather Bulletin.

Figure 23: Weekly North Dakota CD 9 (SE) Temperature Detail (1934-1942). Tick Marks Begin Year.

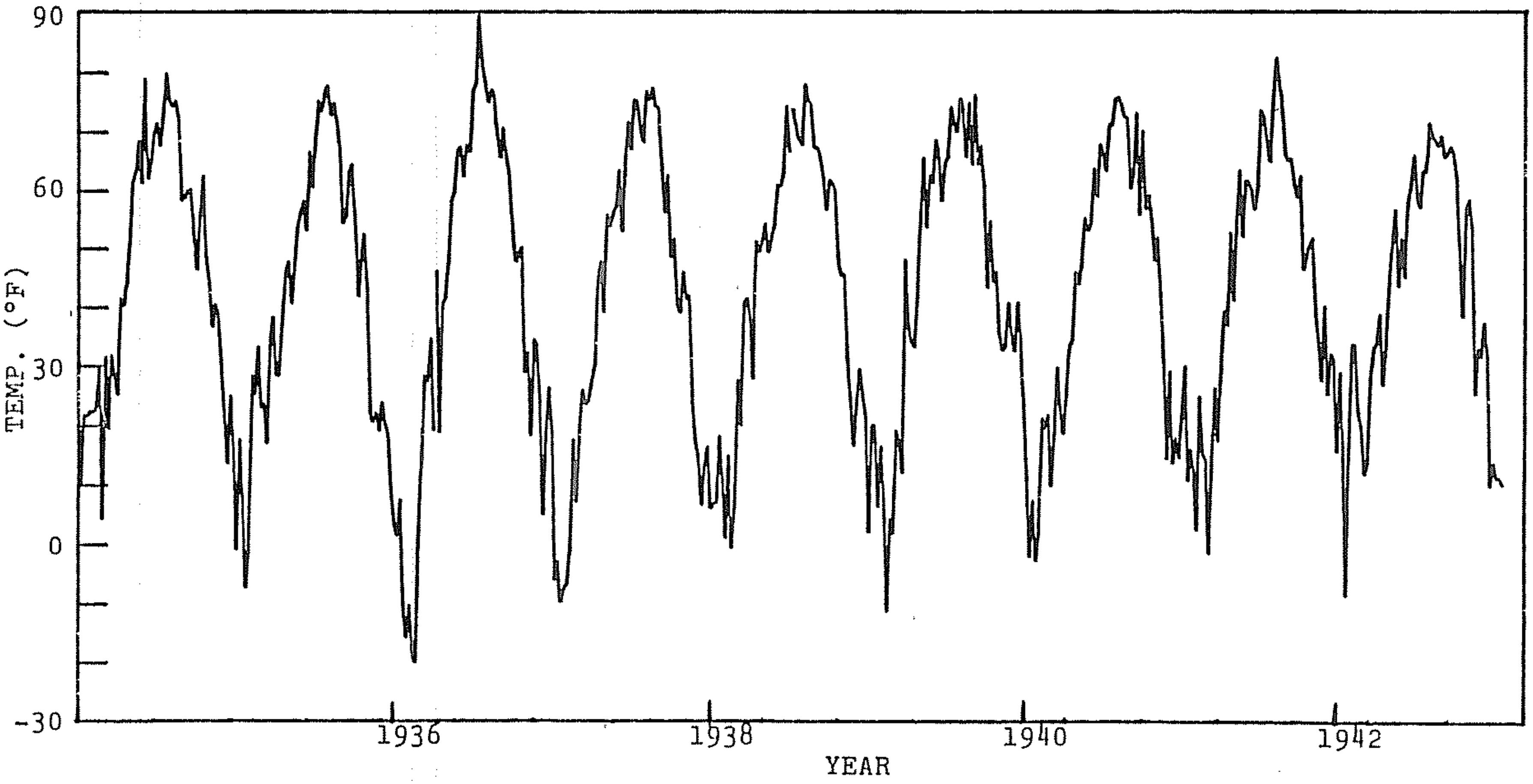
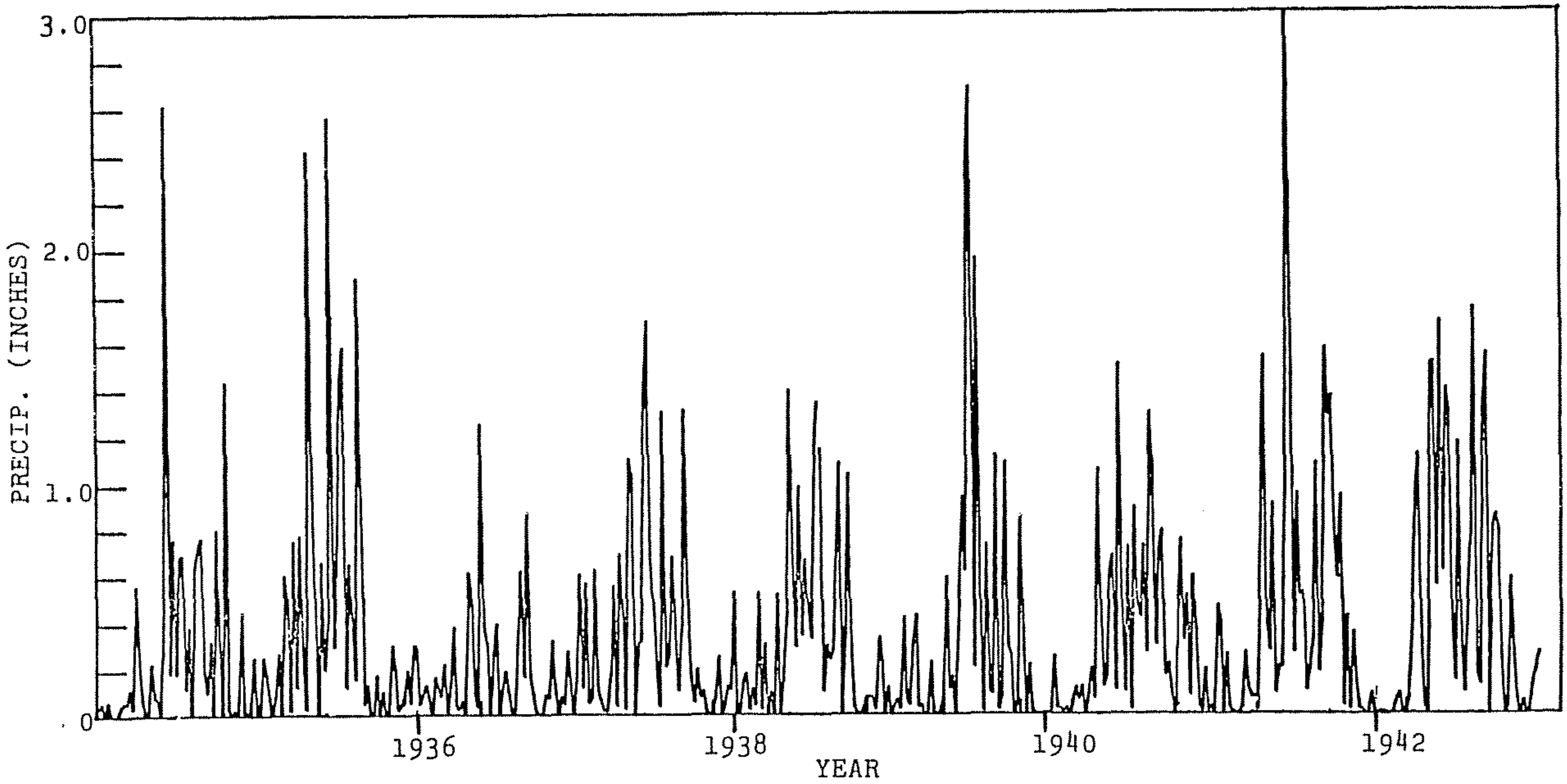


Figure 24: Weekly North Dakota CD 9 (SE) Precipitation Detail (1934-1942).
Tick Marks Begin Year.



a. Soil Moisture

Soil moisture (SM) for this study was calculated using a hydrologic accounting system similar to the one reported by Palmer (1965). Soil moisture is previous storage plus precipitation (P) minus evapotranspiration (ET) up to a set maximum (Table 17). Excess P is runoff. A surface layer can supply up to one inch to ET, but only a fraction of demand beyond that will be supplied by the underlying layer. Evapotranspiration is that part of a potential evapotranspiration (PET) which is satisfied. Thornthwaite (1968) gives:

$$PET_i = ((1.6(5.5556(T_i-32)/B)^A)HOURS/12)/2.54/(30/7)$$

where T_i = weekly/CD average temperature in °F. (PET=0 when $T < 32$),

$\overline{T}_i$ = long term weekly/CD average temperature °F,

HOURS = number of daylight hours,

7/30 = transformation from monthly values used by Thornthwaite to weekly values used in this study,

B = heat index computed from long term record

$$= (1/4) \sum_{i=1}^{52} ((\overline{T}_i-32)/5)^{1.514}$$ where $\overline{T}_i$ is set = 32 if it is climatologically < 32,

$$A = .49239 + .01792B - .0000771B^2 + .000000675B^3.$$

At this point it should be mentioned that our present use of soil moisture is as a predictor variable in a linear regression equation and hence it is the deviations of this variable about its linear trend (essentially its long-term mean) which is important. Thus, small differences between the calculated PET long-term mean and the "true" value of its long-term mean will make no significant difference to our end results. The main consequence of such a difference will show up as a small decrease in the time constant of soil water depletion, but will make very little difference in the ability of our procedure to detect major drought signatures.

The average soil available water capacity (AWC) of each crop district has been obtained by Palmer and is in current use by the National Weather Service. We obtained these values from Lyle Denny of the National Weather Service as tabulated below.

CRD	NORTH DAKOTA
1	6
2	7
3	7
4	8
5	8
6	8
7	8
8	8
9	8

Table 17: Available Water Capacity (AWC) Values In Inches.

During any given time period (1 week in our case) a plant uses: firstly, precipitation (and if this is all used), secondly, water from the surface layer at the potential rate (and if this is all used) finally, water from the underlying layer at a rate given by the following formula.

$$L_{\mu} = (PET - P - L_S)S'_{\mu}/AWC$$

where L_{μ} = water used from the underlying layer,

P = precipitation,

L_S = water used from the surface layer,

PET = water demand potential for the week,

S'_{μ} = moisture stored in the underlying layer at the beginning of the week.

Any precipitation not used by the plant is used firstly to refill the surface layer, next to fill the underlying layer (no time lag nor fractional filling is required), and lastly any remainder is considered to be runoff. An example of weekly soil moisture variations is shown in Figure 25.

b. Evapotranspiration

Evapotranspiration is calculated in the process of calculating soil moisture. If enough moisture is available firstly from the precipitation and secondly from the surface layer, then the ET is equal to the PET described above. If more water is demanded because of the temperature conditions (PET) then a fraction of this is obtained from the underlying layer as described above.

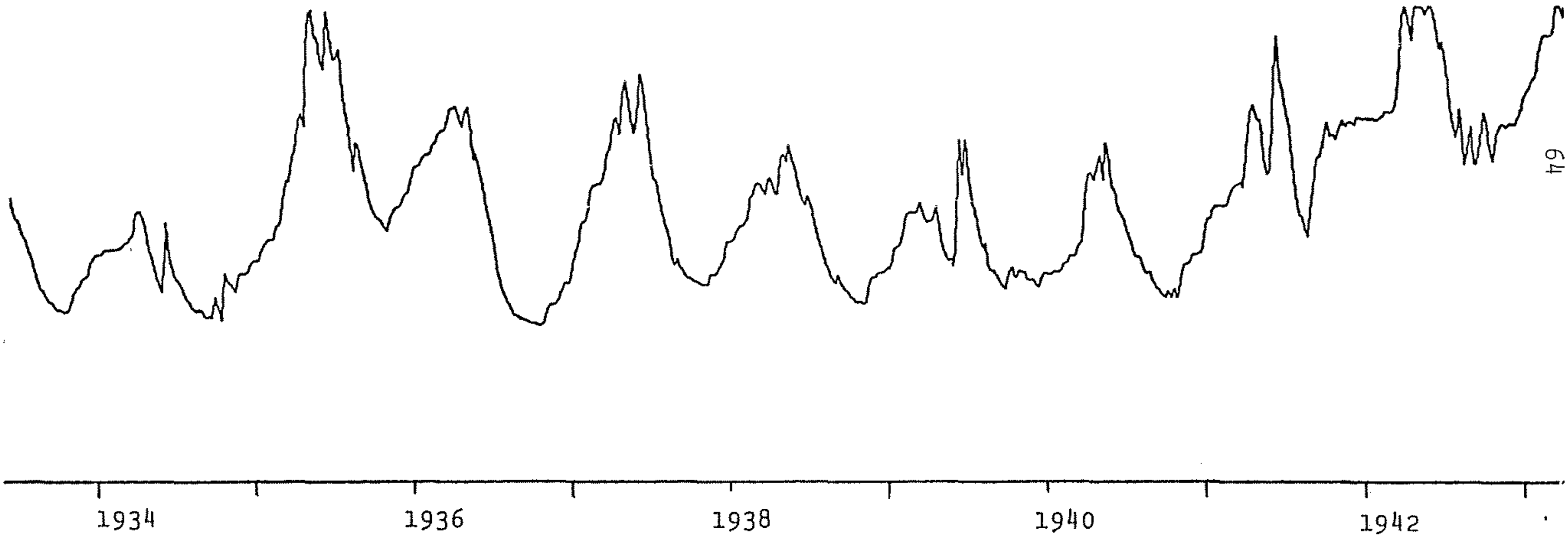


Figure 25: Weekly North Dakota CD 9 Raw Soil Moisture Detail. Tick Marks Begin Year.

It is clear that ET can vary directly with the precipitation (under fairly peculiar temperature fluctuations) while the SM remains constant. A nine-year portion taken from a typical weekly ET series is given in Figure 26.

c. Crop Moisture Index

The CMI reported by Palmer (1968) combines soil moisture, evapotranspiration, recharge and runoff. The algorithm we use follows: where i designates a given week:

$$\mathrm{CMI}_i = Y_i + G_i$$

$$= 0 \text{ if } \mathrm{SM} = 0$$

+where $$Y_i = .67\, Y_{i-1} + 1.8[\mathrm{ET}_i - \mathrm{PET}_i * \alpha_i{}^{1/2}]$$

$$= -1 \quad \text{when } i=1$$

and $$G_i = G_{i-1} + H_{i-1} + [(\mathrm{SM}_{i-1} + \mathrm{SM}_i)/2 * \mathrm{AWC}] + \mathrm{R} + \mathrm{RO}$$

$$= 0 \quad \text{when } i=1$$

and $$H = G_{i-1} \quad \text{if} \quad 0 \leq G_{i-1} < .5$$

$$= .5 \quad \text{if} \quad .5 \leq G_{i-1} < 1.0$$

$$= .5G_{i-1} \quad \text{if} \quad 1 \leq G_{i-1}$$

and $$\alpha_i = \overline{\mathrm{ET}_i}/\overline{\mathrm{PET}_i}$$

$$= 0 \quad \text{if} \quad \overline{\mathrm{PET}_i} = 0$$

$$\overline{\mathrm{ET}_i} = (1/N) \sum_{j=1}^{N} \mathrm{ET}_{ij}$$

+The formula advocated by Palmer accentuates ET slightly more; i.e., $Y_i = .67\, Y_{i-1} + 1.8[\mathrm{ET}_i\, \alpha^{-1/2} - \mathrm{PET}_i\, \alpha^{1/2}]$.

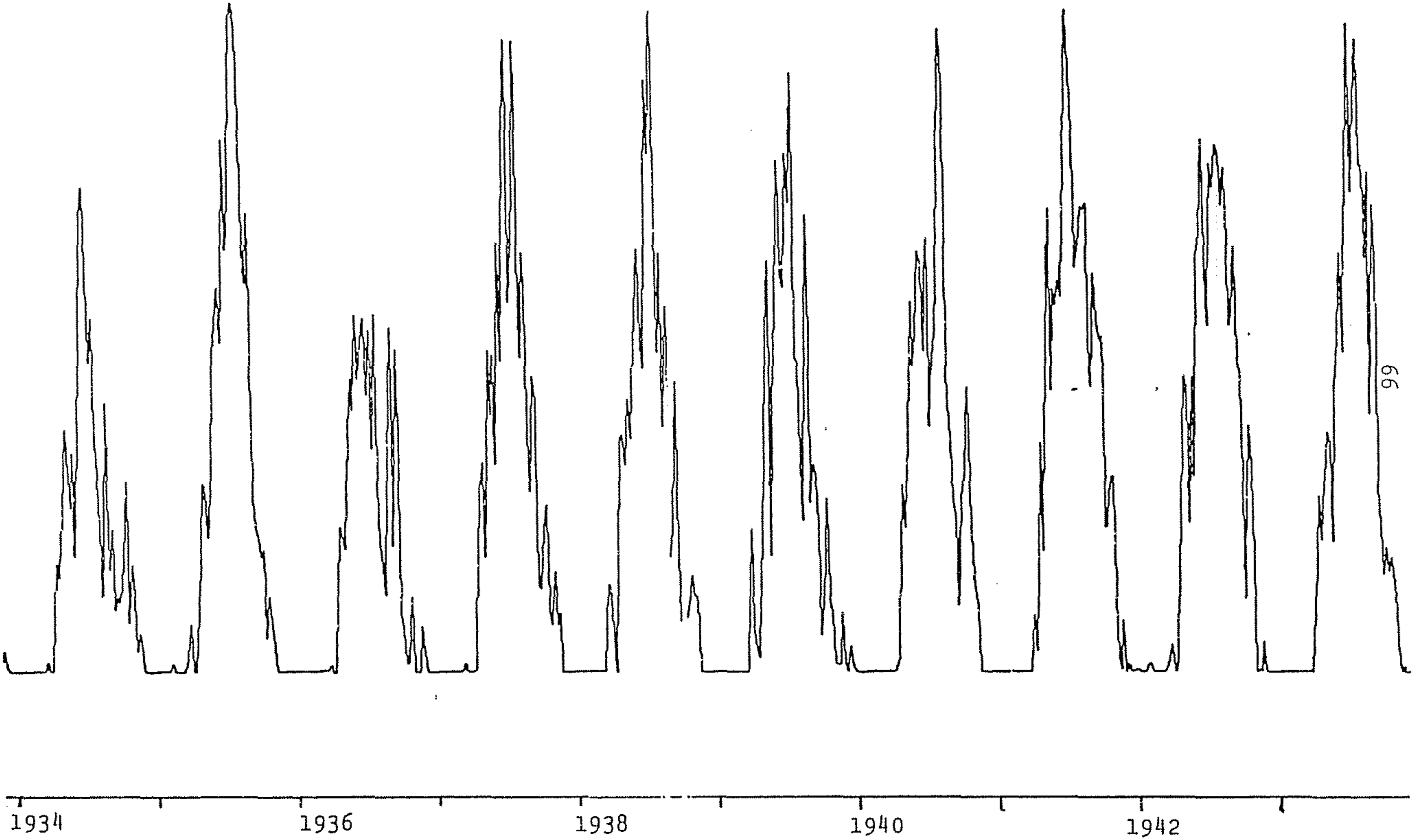


Figure 26: Weekly North Dakota CD 9 (SE) Evapotranspiration Detail (1934-1942), Tick Marks Begin Year.

$$\overline{PET}_i = (1/N) \sum_{j=1}^{N} PET_{ij}$$

N = number of years in data series

AWC = available water capacity (see Table 17).

Short examples of weekly CMI are given in Figures 27 and 28 to illustrate the contrast between the two methods of calculating crop moisture index. Our method accentuates dry periods slightly.

d. Growing Season Soil Moisture and Evapotranspiration

In order to obtain reasonable representative values for the total amount of SM and ET influencing the growing season, weekly values of these variables were summed each year for weeks 21-28 inclusive.

e. Modelling the Data

The object of modelling our derived variable series here is to find an attribute which can be depended upon to indicate the occurrence of drought as a sporadically recurring phenomenon. If we are planning to look for prolonged excursions of the data from its mean value, we must first be sure that the mean value is not changing significantly with time. We did not find statistically significant linear trends in soil moisture, evapotranspiration nor crop moisture index in the weekly value time series.

The next step was to examine the distribution of the weekly values about the 63-year mean for the series.

Figure 27: Weekly North Dakota CD 1 (NW) Crop Moisture Index Detail (1934-1942) (after Palmer). Tick marks begin year.

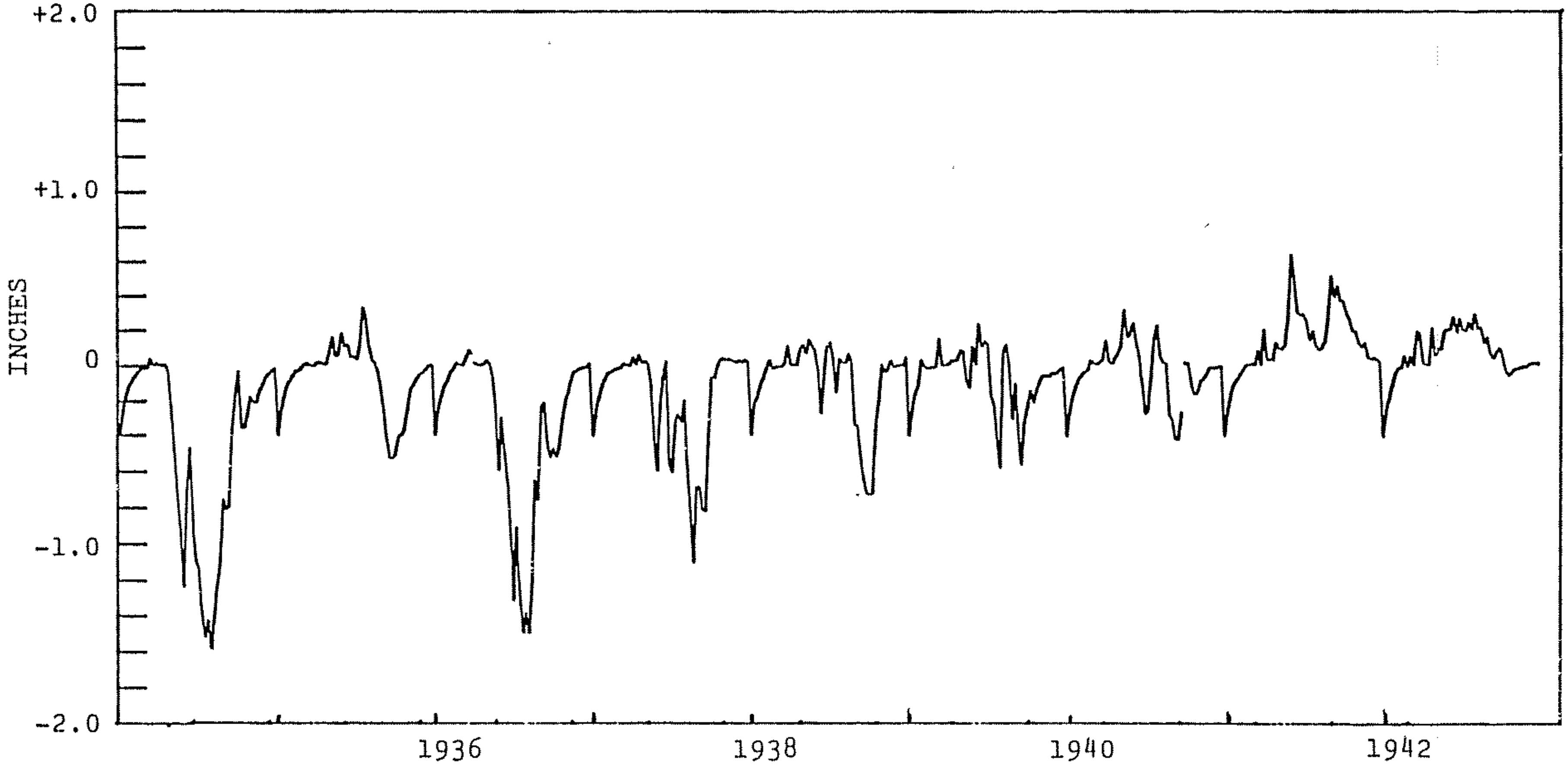
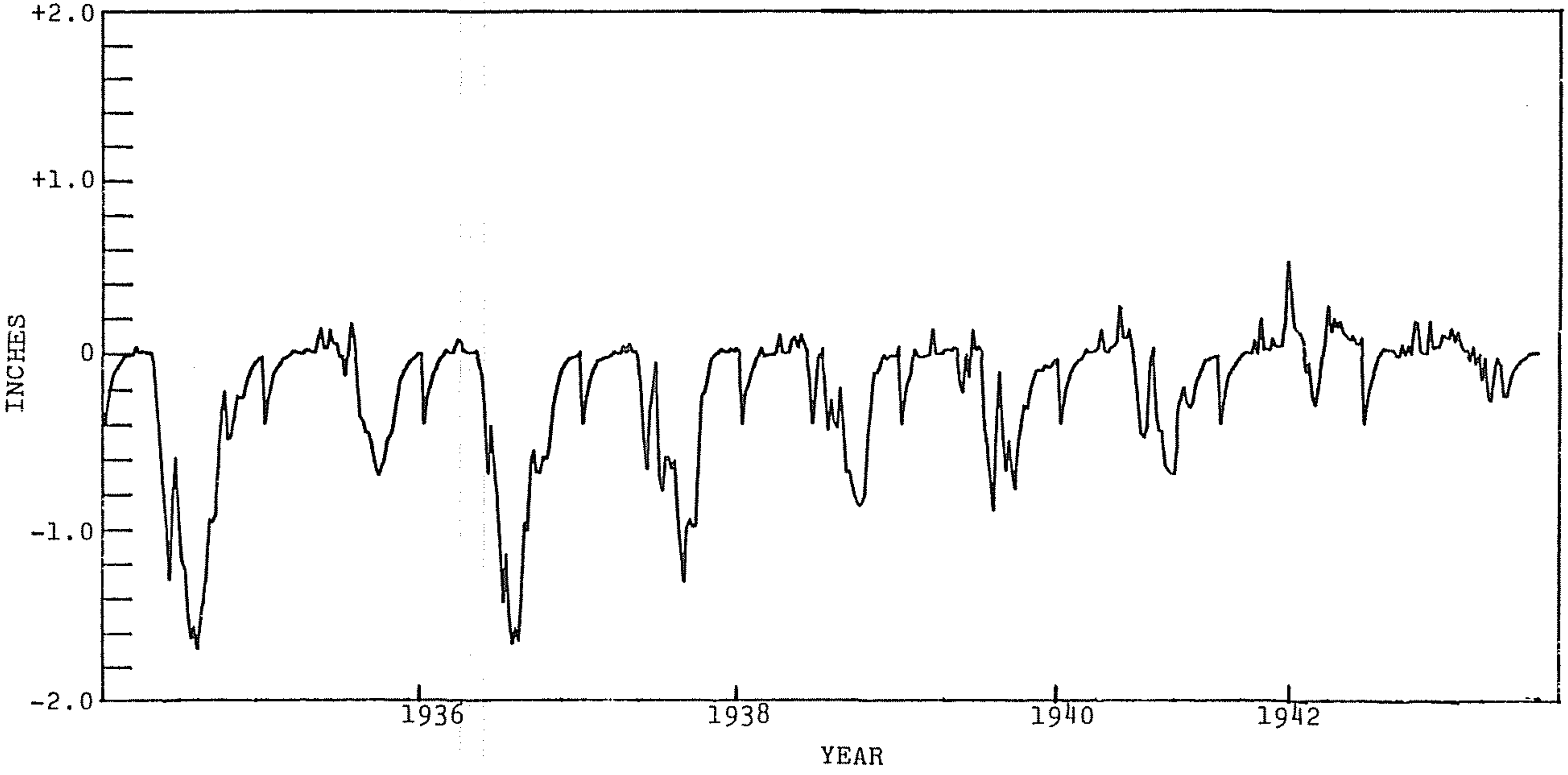


Figure 28: Weekly North Dakota CD 1 (NW) Crop Moisture Index Detail (1934-1942) (this study). Tick marks begin year.



The histograms shown in Figures 29, 30, and 31 contain a wealth of information about the character of the data. At this point, attention is drawn to the histogram in each figure marked RAW. The frequency count in each category has been standardized to 1000 and plotted as heavy dots against a background showing a Gaussian distribution. Both the mean value for the RAW data series is given and the RMS value about this mean. A measure of the variation of the actual observed data frequencies (O_i) about the appropriate non-standardized Gaussian value (E_i) is given labelled χ^2 , where:

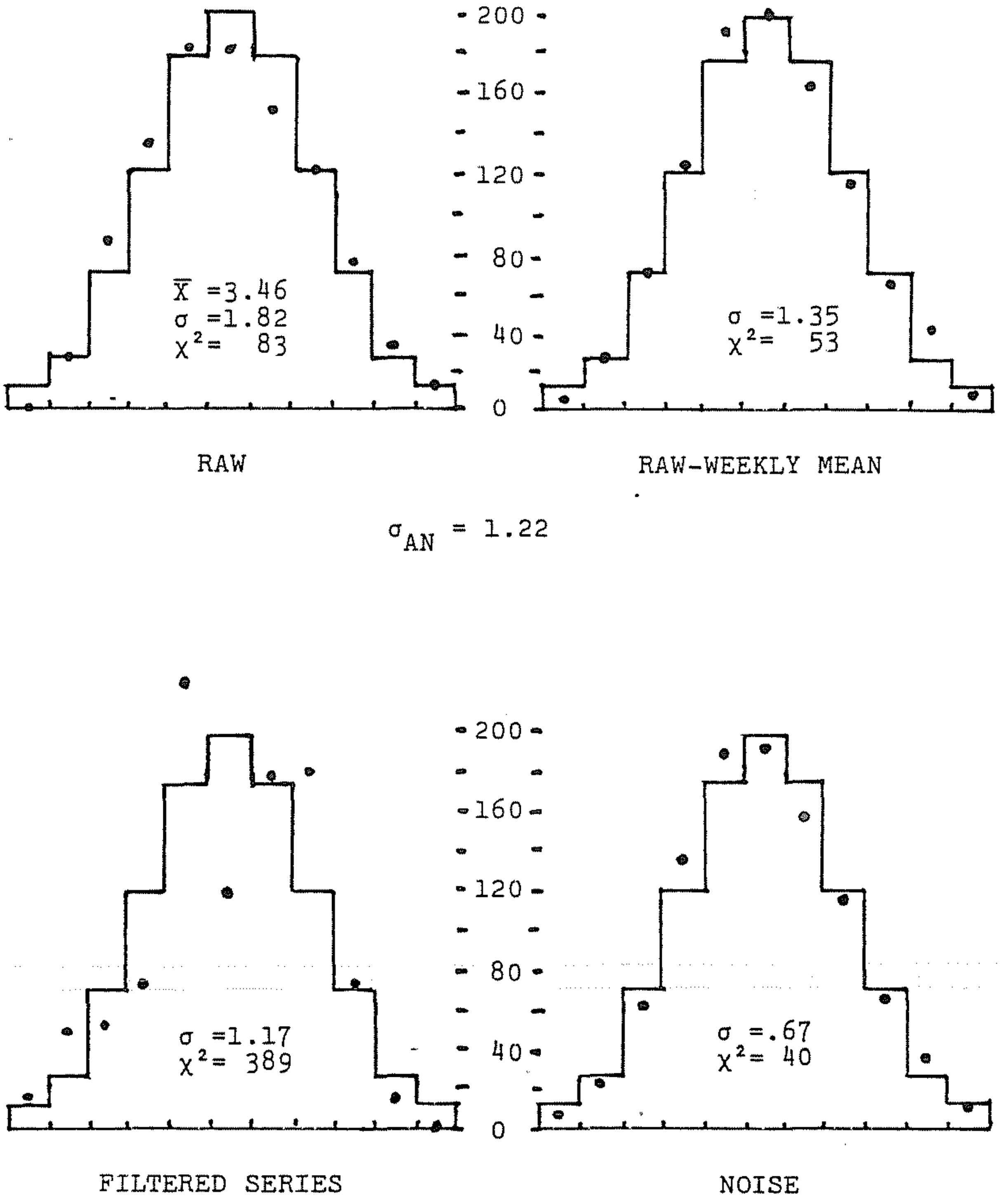
$$\chi^2 = \sum_{i=1}^{11} ((O_i - E_i)^2/E_i).$$

In some cases this value varies as CHISQUARE with 9 degrees of freedom ($\chi^2_{.01,9} \approx 22$).

Consider the soil moisture first. The plots for North Dakota show no terrible non-gaussian deformities, although the χ^2 values suggest that one may be present.

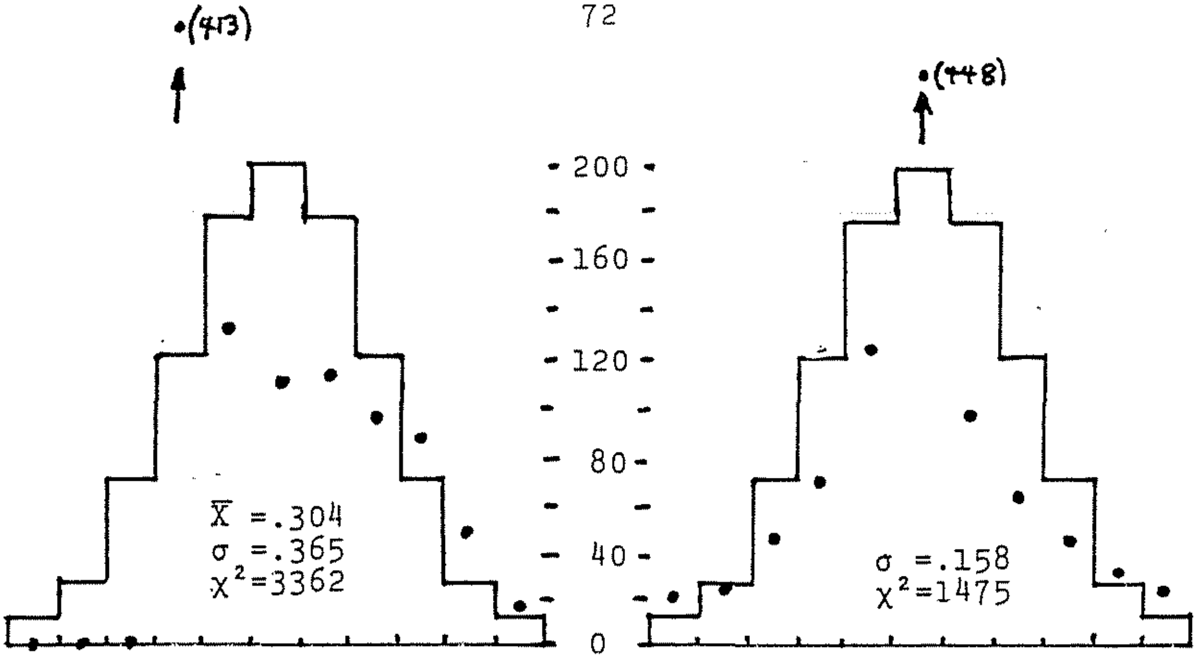
Next we examine the raw evapotranspiration. Figures 26 and 30 show immediately that we will have a problem. Not only do we have runs of zero values in the winter, but the wintertime variations are zero and so this type of derived variable is heteroscedastic or non-stationary with respect to the variance.

The crop moisture index (CMI) was investigated using the North Dakota data and the distribution function aspects of the results are shown in Figure 31.



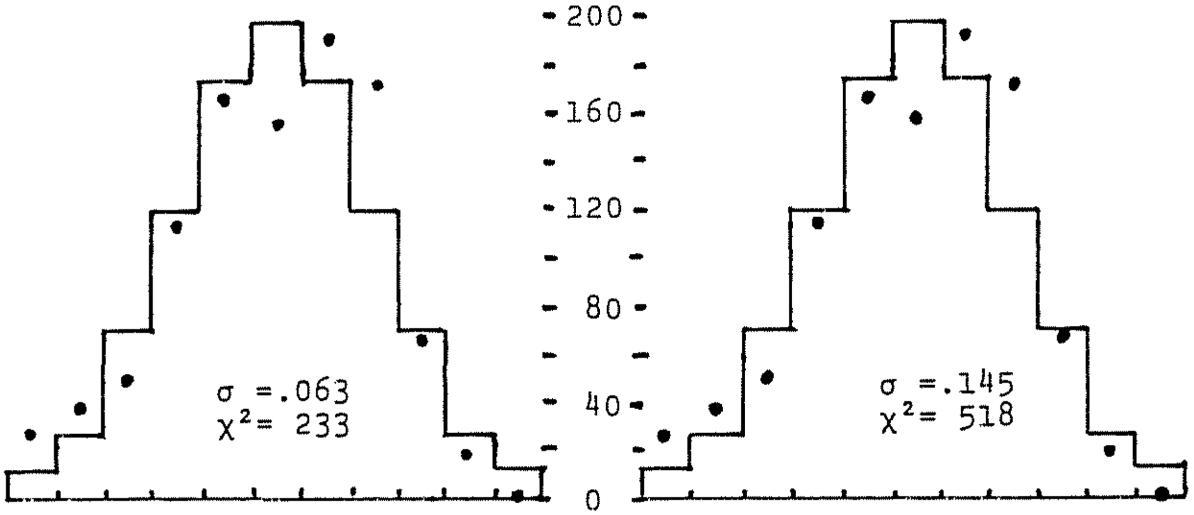
Classes = .5σ Wide; Total Count Standardized to 1000.

Figure 29: Histograms of weekly soil moisture series components: North Dakota State.



RAW RAW-WEEKLY MEAN

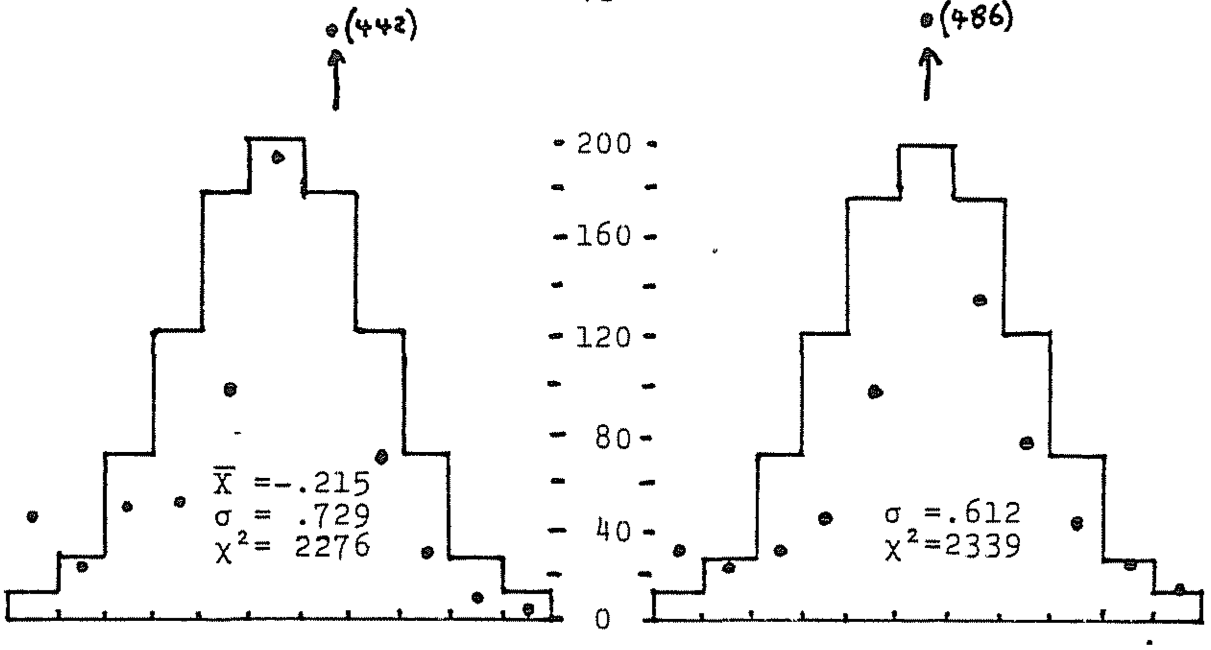
σ_{AN} = .358



FILTERED SERIES NOISE

Classes = .5σ Wide; Total Count Standardized to 1000.

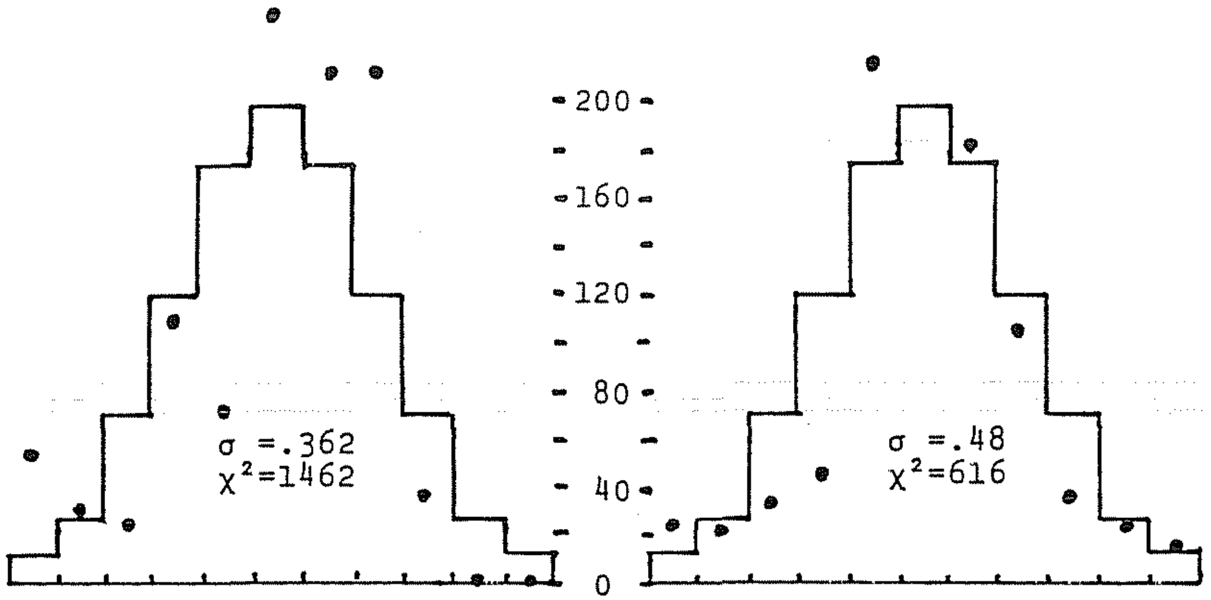
Figure 30: Histograms of weekly evapotranspiration series components: North Dakota State.



RAW

RAW-WEEKLY MEAN

σ_{AN} = .397



FILTERED SERIES

NOISE

Classes = .5σ Wide; Total Count Standardized to 1000.

Figure 31: Histograms of weekly crop moisture index series components: North Dakota State.

Although the statistically most satisfying series to work with would be the temperature, one of the least satisfying is the precipitation (see Figure 24, for example) and a drought deals with a lack of water. We must use some combination of supply (precipitation) and demand (temperature induced evapotranspiration).

Much of the above problem with skewness in our data series can be removed by removing an annual cycle of weekly averages.

We will consider this by analyzing the following model for the derived data series.

$$X = \mu + a + s + \varepsilon$$

where X = the "observed" data value (actually the average over a week and a CD)

μ = the mean

a = an annual cycle component

s = a component we shall call our signature series

ε = noise.

We shall perform our partitioning in such a way that,

$$\sigma_X^2 \simeq \mu^2 + \sigma_a^2 + \sigma_s^2 + \sigma_\varepsilon^2$$

The curves derived from the raw data to represent the term, a, are shown in Figures 32, and 33, for CMI, ET and SM. It is interesting that the soil moisture and evapotranspiration curves are about 3 months out of phase with one another. The 52

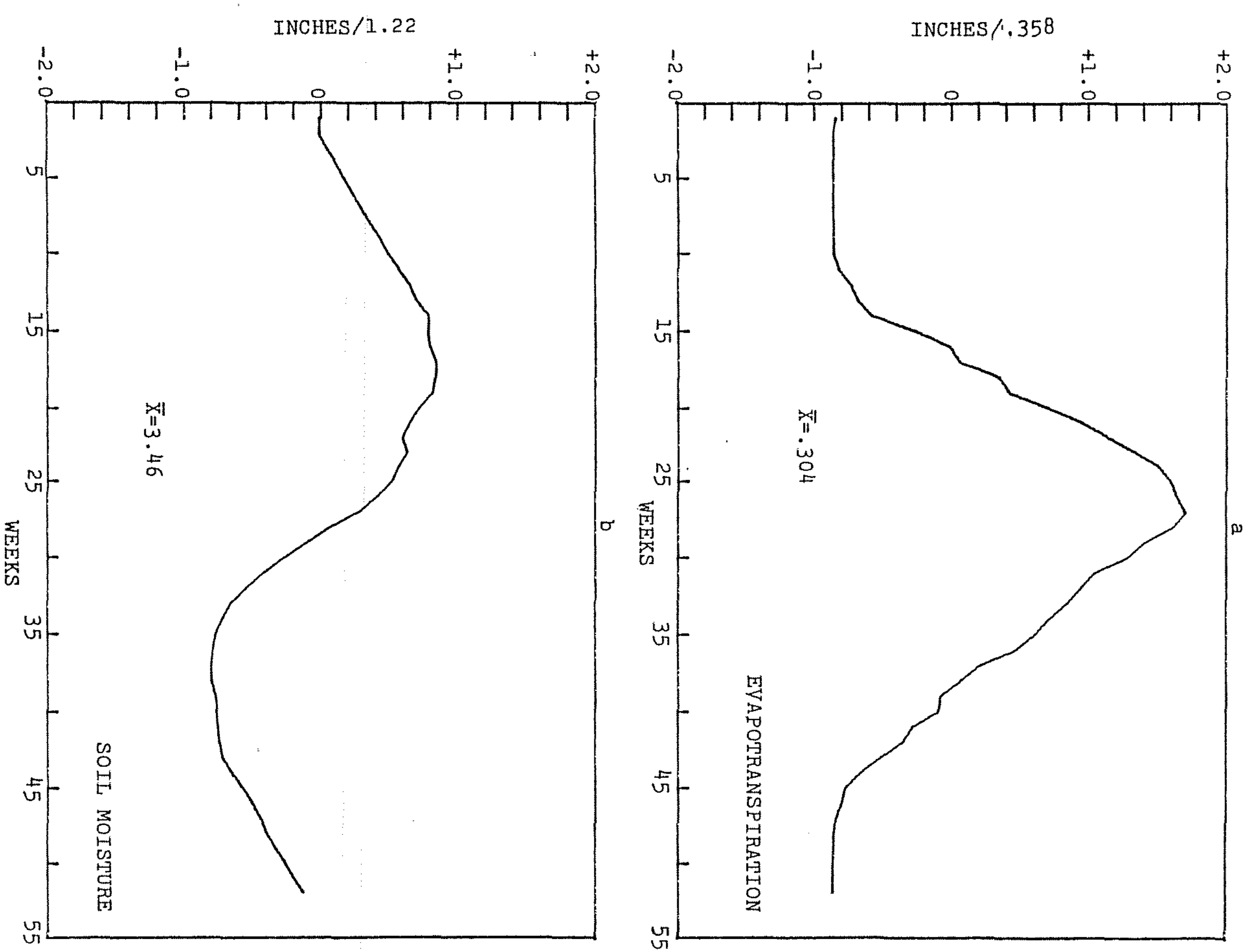


Figure 32: a) Annual cycle weekly mean evapotranspiration: North Dakota State (1913-1973).
b) Annual cycle weekly mean soil moisture: North Dakota State (1913-1973).

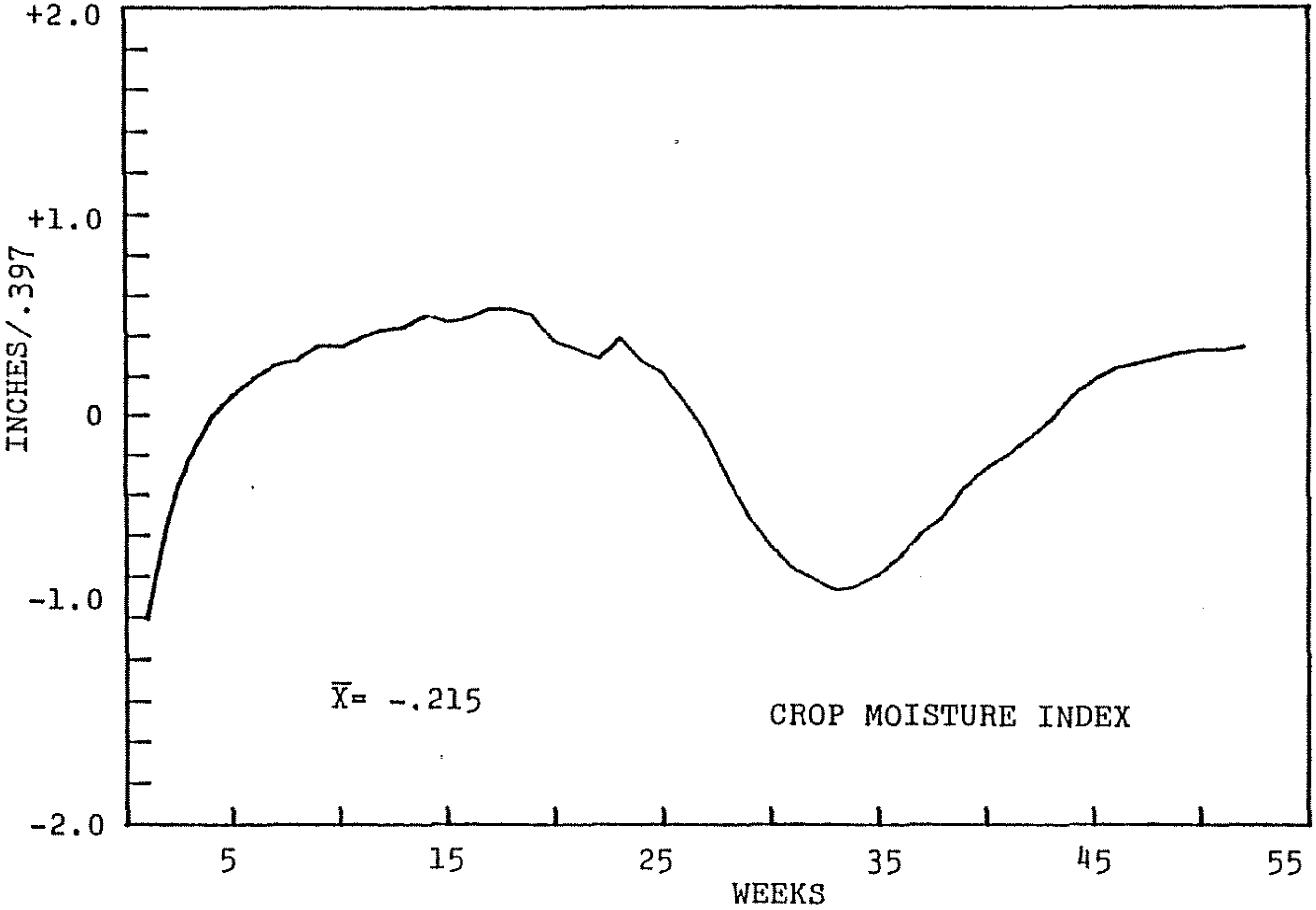


Figure 33: Annual cycle weekly mean crop moisture index: North Dakota State (1915-1971).

values for "a" on each of these curves are given by

$$a_j = \frac{1}{N} \sum_{i=1}^{N} Y_{ij}, \qquad j = 1, 2, \ldots 52$$

where N = number of years in the data set.

Note that these annual cycles were obtained from normalized data so the numbers along the ordinate must be multiplied by the standard deviation and then the result added to the mean to obtain the true scale in inches.

After removing the annual cycle of weekly mean values from each of the series we were left with data distributed as shown in the RAW-WEEKLY MEAN histograms shown in the upper right of Figures 29 - 31 inclusive. The skewness problem has been reduced, but not eliminated.

At this point we would like to filter our remaining data components to try to discover slowly varying deviations from the mean which could be indicators of phenomena such as droughts. Two low pass filters were tested for this purpose. Figure 34 shows their response functions. These filters were designed following the procedure of Lanczos (1956). The manner in which they operate on the time series is shown in Figures 34, 35, and 36.

We are now able to show the DROUGHT SIGNATURES which can be obtained using climatological time series of soil moisture, evapotranspiration and crop moisture index. Figures 35, 36, 37, 38 and 39 show that long lasting droughts are shown best using the 3-year filter and short intense droughts are highlighted by the 1-year filter.

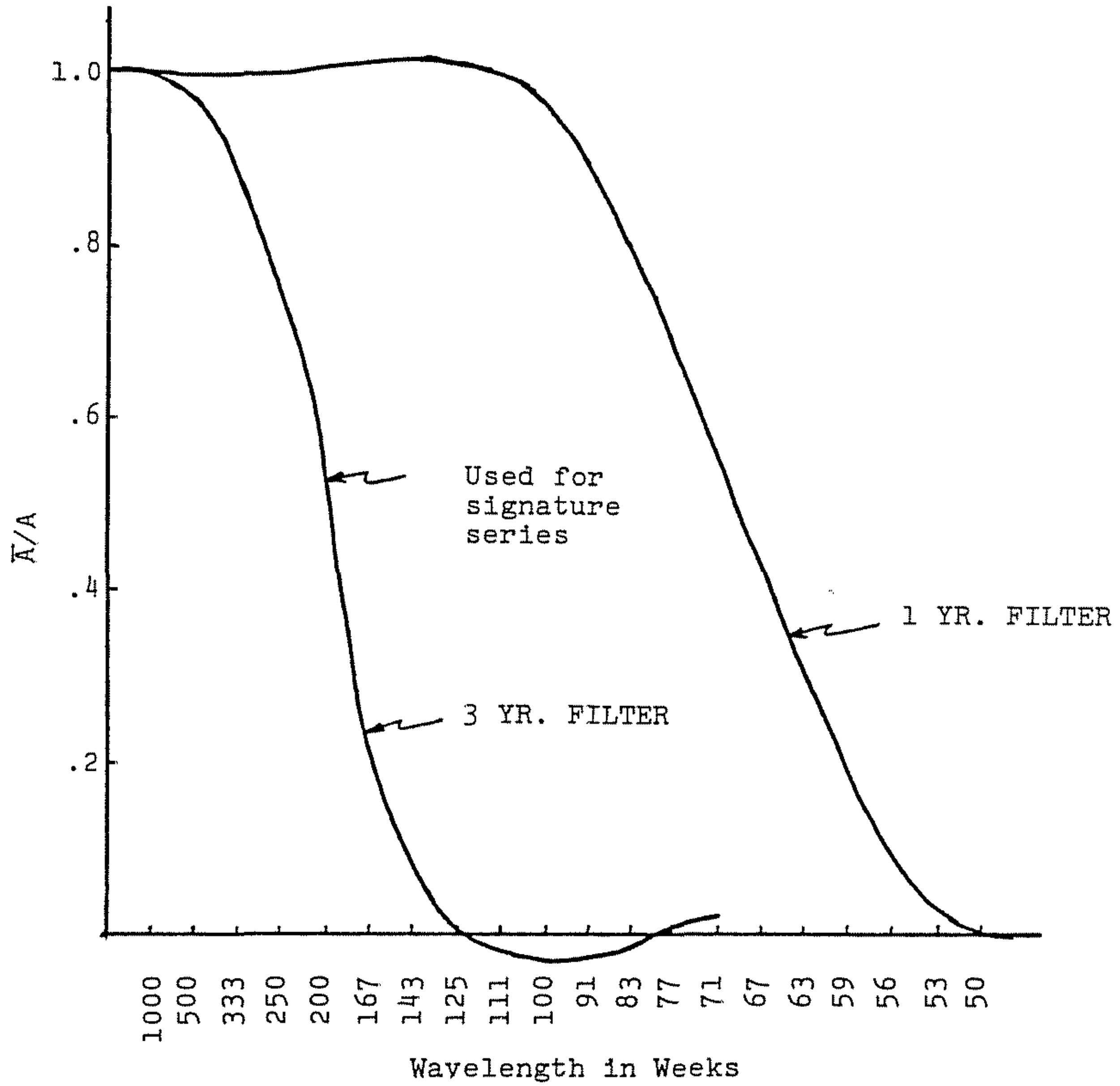


Figure 34: Ratios filtered amplitude to input.

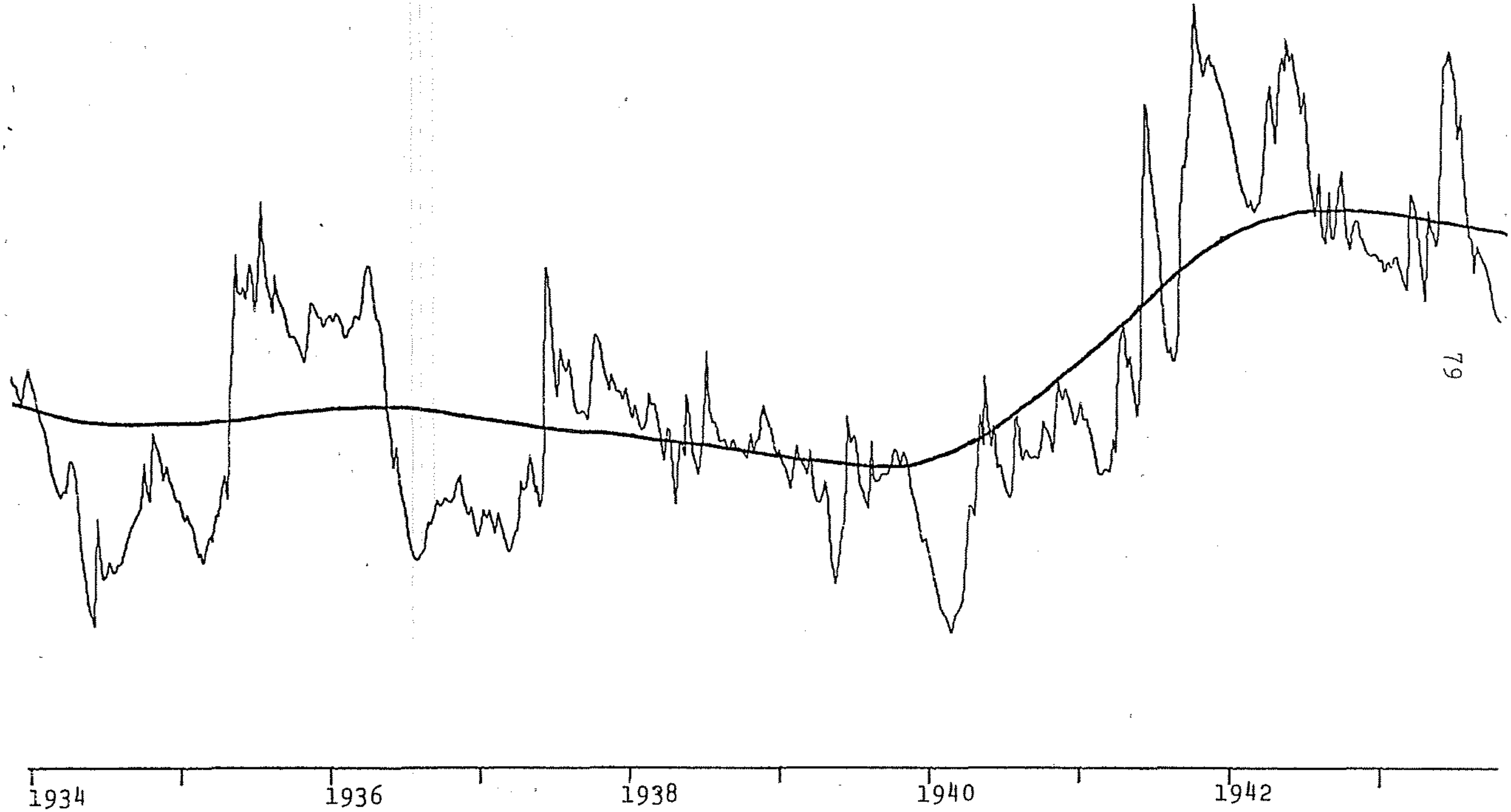


Figure 35: Weekly plus 3 year filtered N.D. State soil moisture (Raw-weekly) detail (1934-1942). Tick marks begin year.

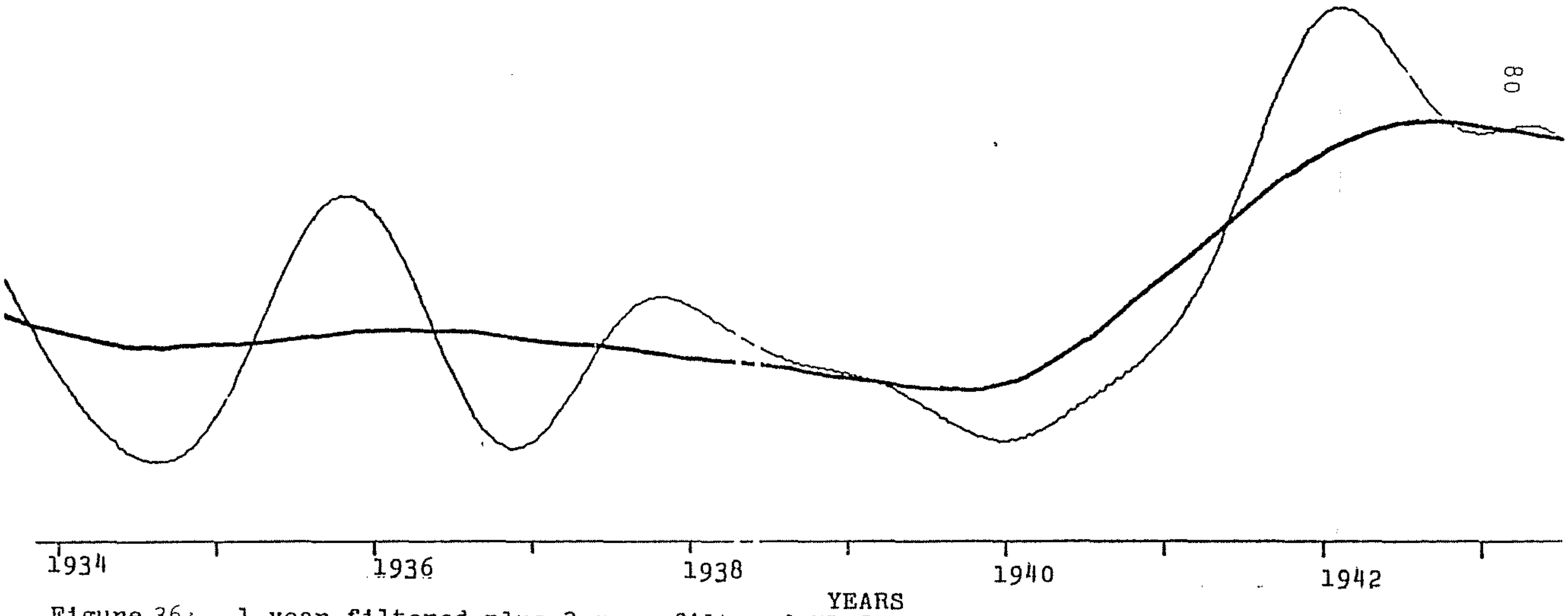


Figure 36: 1 year filtered plus 3 year filtered ND State soil moisture detail (1934-1942). Tick marks begin year.

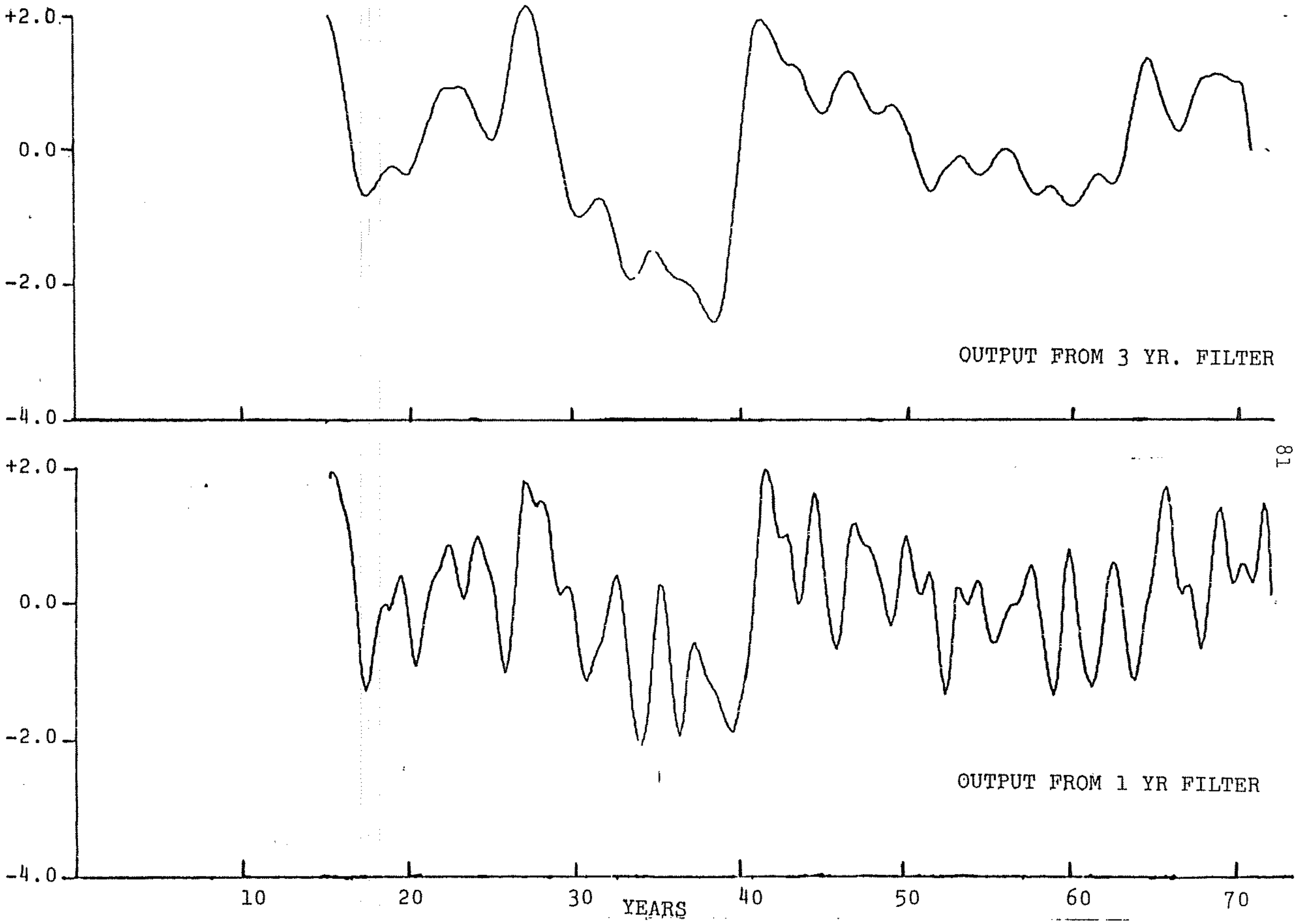


Figure 37: Filtered soil moisture: North Dakota State (1915-1971). Tick marks begin year.

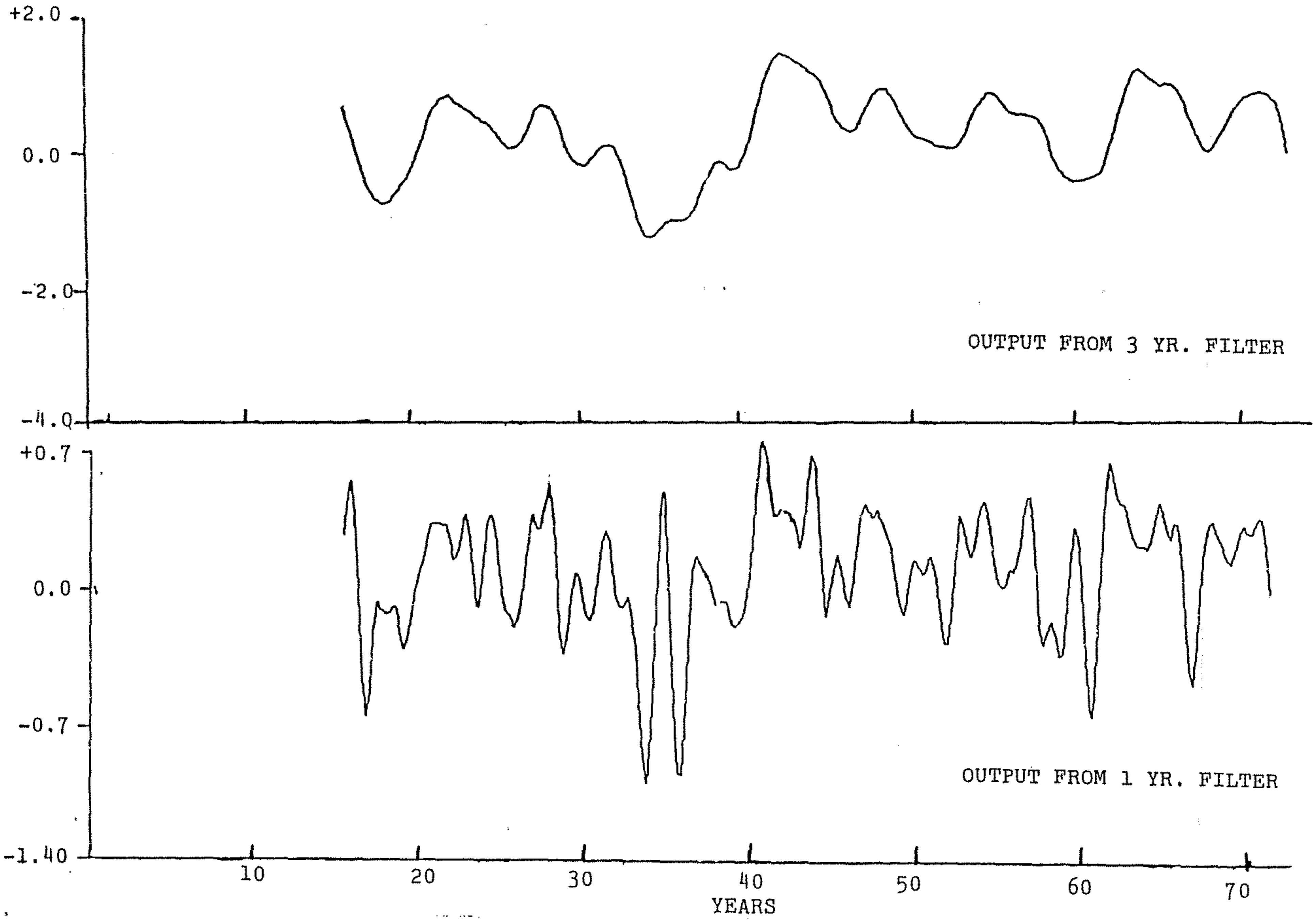


Figure 38: Filtered evapotranspiration: North Dakota State (1915-1971). Tick mark begins year.

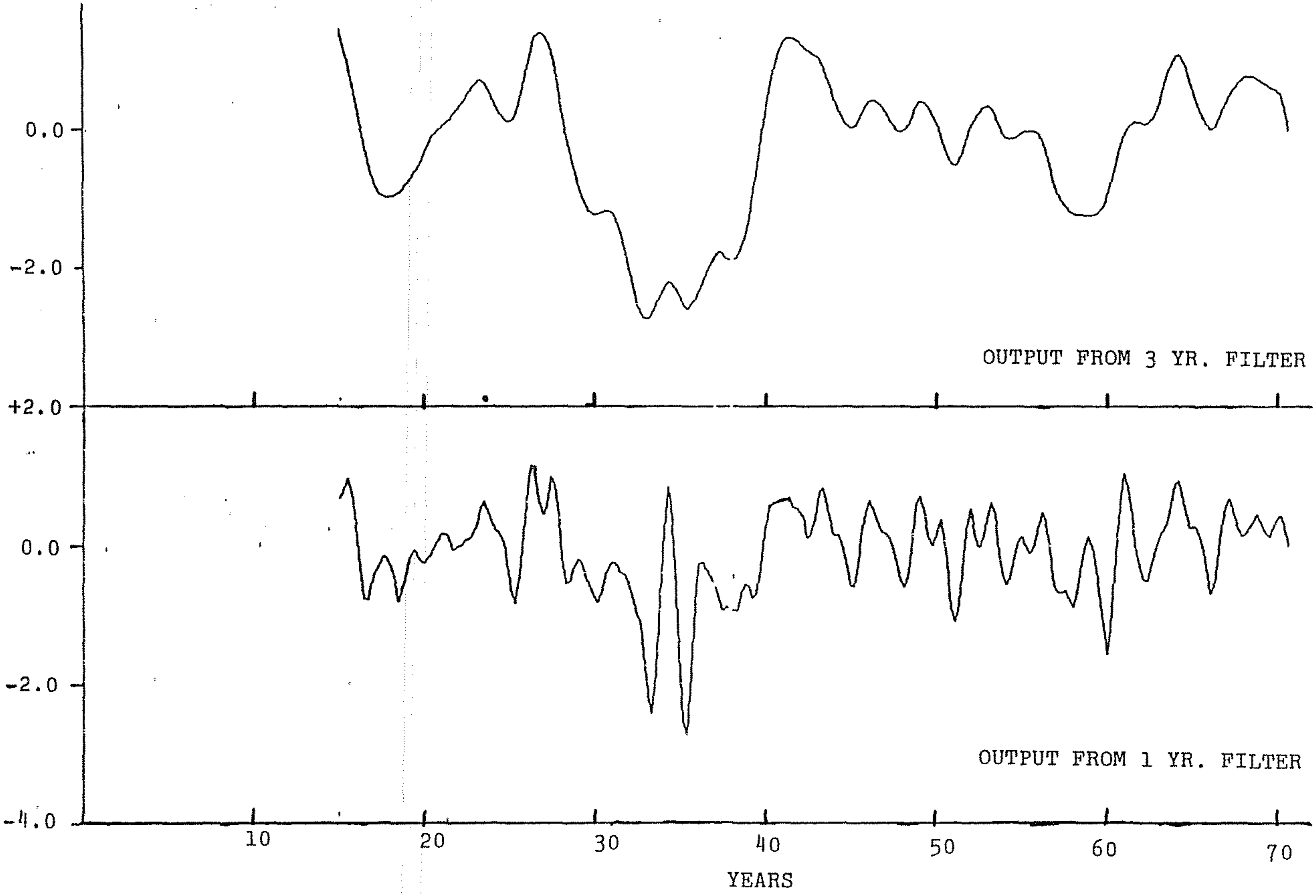


Figure 39: Filtered crop moisture index: North Dakota State (1915- 1971). Tick marks begin year

Soil Moisture

The longest, driest period found in the state average of any of the four areas occurred with a 97-week run ($SM < -2.5\sigma$) from early June 1938 to mid-April 1940 in North Dakota. In fact, the rarest event in the entire length of the soil moisture signature series was a run of 347 weeks with $SM < -1.5\sigma$ from mid-December 1933 to early August 1940 in this northern wheat growing state. Figure 40 shows that the consequence of this on H.R.S. wheat production was to cut the yield to half what could have been expected had "average" soil moisture conditions prevailed at the time.

Evapotranspiration

Here, the greatest departure below average was a run ($ET < -2.25\sigma$) of 78 weeks from early November 1933 to early May 1935. A run of 217 weeks with $ET < -1.5\sigma$ occurred between mid-April 1933 and early June 1937.

Crop Moisture Index

The driest period in the CMI signature series was a 50-week run below -2.25σ between early September 1933 and late August 1934. The rarest event of any series of any parameter occurred with a 357 week run ($CMI < -1.5\sigma$) from late December 1932 to late October 1939 in the North Dakota state average signature series of the crop moisture index.

In order to estimate the number of times in a given period (say 20 years, or 100 years) that the people of North Dakota could expect a drought of a given severity and duration to occur,

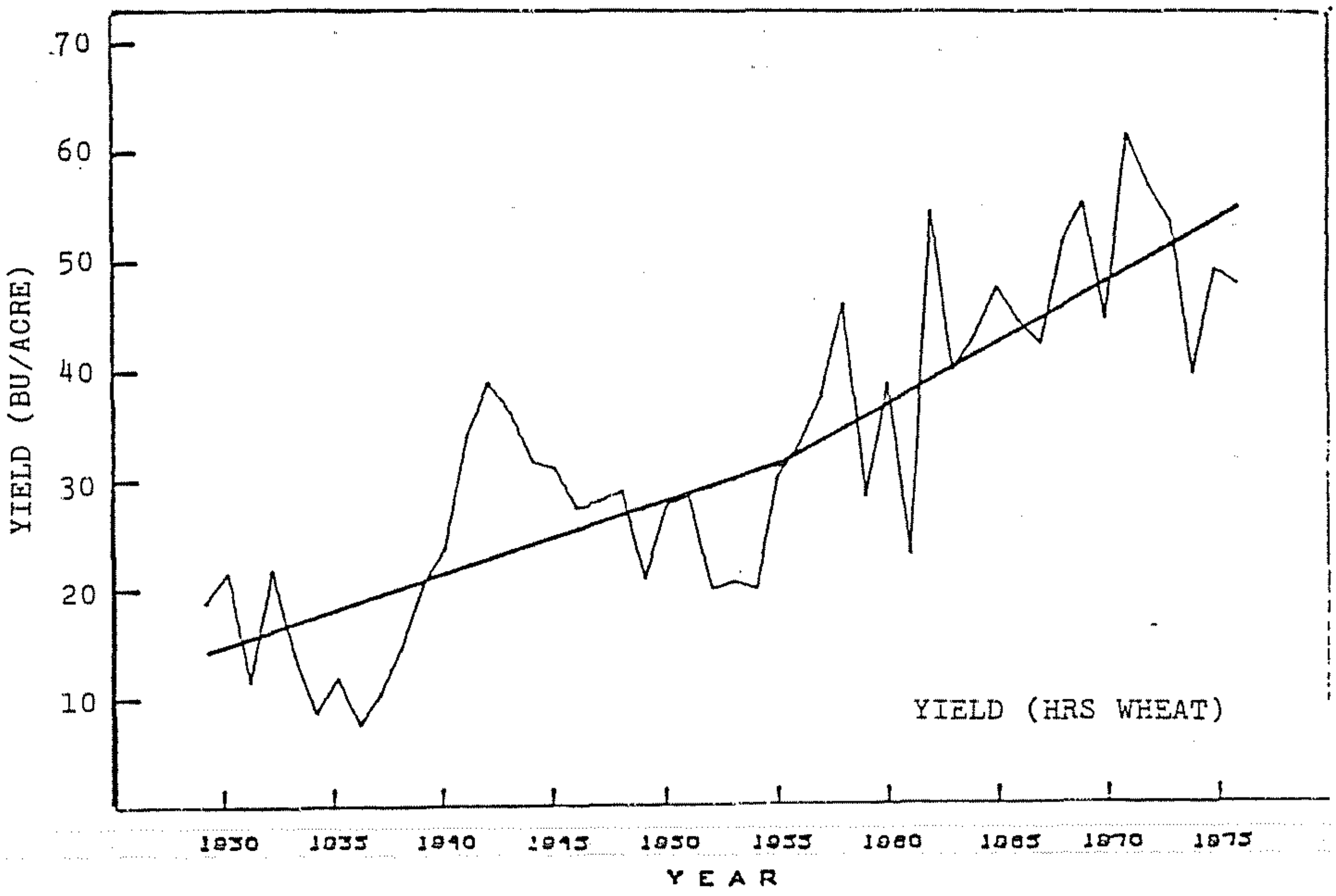


Figure 40: Spring Wheat Yield, North Dakota.

we simulated the "signature series" stochastic component using a red noise model. Since the properties of such a model are known, we were able to hypothesize drought recurrences based on these simulations.

The long drought of the 1930s showed up with the expected intensity and coherency. Such a run was found only two times in thirty simulated 60-year series. Thus the frequency with which North Dakota can expect to endure a drought like that of the 1930s is about twice in thirty 60-year time spans. This would also happen about once in thirty 30-year time spans. This comes to about once in 900 years [provided, of course, the underlying basic climatology doesn't change over such a period].

The analysis which we have shown here suggests that the value of rainfall enhancement with respect to preventing excessive soil moisture depletion should be assessed from two points of view: for

i) reducing the regular dry portion of the annual cycle,

and ii) reducing the irregular or stochastic runs of drought whose frequency of occurrence can be predicted even though the timing cannot.

2. Economic Impact: W.S. Cooter

Techniques analogous to those presented in Eddy, Cooter, and Cooter (1979) and Cooter (1980) will now be applied to the analysis of the economic impacts associated with operational weather modification activities in the state of North Dakota during the period 1976-1980. The discussion will provide an analysis geared to the impacts for each of the five years in question and a set of impacts representing average yearly conditions over the whole period. As in the previous studies, the first step is to take estimates of crop reporting district level precipitation changes attributed to weather modification over a critical period running from Julian Day 157-192 (June 6 to July 11 except in leap years) and then estimate yield and production responses for a set of crops. The dollar value of these production changes is then aggregated over the state. Using input-output techniques, sets of indirect economic responses are estimated. Finally, benefit-to-cost ratios are estimated both in terms of the direct impacts to agricultural production and in terms of the total direct and indirect impacts to the state economy.

A vital part of the analysis is the set of crop yield response models. Models developed earlier (see Cooter, 1980) for oats, barley, durum wheat, other spring wheat, and tame hay are used in the present study. In addition, models for the following crops were adapted from the ARE study (Added Rainfall Effects Study Team, 1974): soybeans, sugarbeets, potatoes, flaxseed, sunflowers, corn grain, wild hay, native pasture, and corn silage. The ARE models were developed for a set of 4 study areas. The yield response coefficients needed to be realigned to a crop reporting district (CRD) logic. To accomplish this, the coefficients for given ARE areas were distributed over all the counties within the areas. The counties were then regrouped by CRD's. To obtain CRD coefficients, the county coefficients were weighted according to the harvested or utilized acreages for the crops. Average acreage figures over the period 1973-1977 for all crops other than wild hay and native pasture were obtained from the North Dakota Crop and Livestock Reporting Service (1979). Figures for wild hay and native pasture were obtained from the _1974 Census of Agriculture_ (U.S. Bureau of the Census (1977)). The county yield response coefficients were then put in linear combinations, using factors of the form (county acreages/CRD acreages) as weights, to produce a set of CRD models. In Table 18 the yield response coefficients are summarized. In Table 19 the CRD harvested or utilized acreages are summarized.

Using information provided by Dr. J. Johnson, Department of Agricultural Economics, North Dakota State University, prices for the various crops were obtained. Average prices over the period 1976-1980 were used. Using information provided by the Cleveland County, Oklahoma office of the USDA Cooperative Extension Service, it was ascertained that corn silage has about 1/3 the feed value of tame hay. The unit price of corn silage was therefore estimated as 1/3 that of tame hay. These price data are summarized in Table 20.

Using techniques described elsewhere in the present report, a set of CRD precipitation change estimates for the 36-day critical period were obtained for each of the years 1976-1980. The increases or decreases were found statewide

		CROP REPORTING DISTRICTS								
Crop	Units	1	2	3	4	5	6	7	8	9
Oats	Bu/Ac/In	2.95			2.69	1.86		2.61	2.64	1.24
Barley	Bu/Ac/In	1.94			1.60	1.36		1.88	1.74	
Durum Wheat	Bu/Ac/In				1.05			1.23	1.35	
Other Spring Wheat	Bu/Ac/In	1.17			.88				.87	
Soybeans	Bu/Ac/In			1.50			1.50			1.50
Sugarbeets	Tons/Ac/In			1.00			14.00			
Potatoes	Cwt/Ac/In			14.00			14.00			
Flaxseed	Bu/Ac/In	1.56	1.90	1.45	1.26	1.69	1.49		1.78	1.75
Sunflowers	Tons/Ac/In		.02	.06		.06	.06			.06
Corn Grain	Bu/Ac/In		0.570	2.55		1.29	2.61			2.75
Tame Hay	Tons/Ac/In	.0441		.0355		.0460	.0362		.0696	.0347
Wild Hay	Tons/Ac/In	.0319	.0358	.0244	.0321	.0376	.0364	.0300	.0328	.0342
Native Pasture	Tons/Ac/In	.0533	.0609	.0351	.0526	.0629	.0435	.0500	.0542	.0556
Corn Silage	Tons/Ac/In	.7400	.5600	.5400	.5700	.5600	.3800	.5000	.7500	.4900

Table 18: Yield Regression Coefficients For 36 Day (June 6-July 11) Rainfall Total.

TABLE 19

ACRES OF CROP HARVESTED (1973-1977 AVERAGE)

	CROP REPORTING DISTRICTS									
CROP	1	2	3	4	5	6	7	8	9	STATE
Oats	148,300			136,000	172,900		133,400	174,800	272,600	1,038,000
Barley	122,200			54,800	178,600		87,800	67,700		511,100
Durum Wheat				216,200			90,700	600,000		906,900
Other Spring Wheat	717,700			542,700				566,600		1,827,000
Soybeans			6,700			97,800			73,300	177,800
Sugar Beets			71,300			50,600			26,400	148,300
Potatoes			124,700			6,400				131,100
Flaxseed	52,400	122,500	78,700	38,800	124,000	93,200		63,700	175,700	749,000
Sunflowers		89,600	234,700		264,900	386,600			282,200	1,258,000
Corn Grain		2,600	3,300		3,700	31,800			186,400	227,800
Tame Hay	298,500		196,300		513,500	137,500		574,300	525,600	2,245,700
Wild Hay	109,000	198,000	74,000	96,000	183,000	33,000	48,000	162,000	178,000	1,081,000
Native Pasture	224,000	258,000	115,000	238,000	299,000	120,000	266,000	347,000	376,000	2,243,000
Corn Silage	4,500	12,900	14,600	41,500	40,400	22,900	30,700	70,900	82,600	321,000
TOTAL	1,676,600	683,600	919,300	1,364,000	1,780,000	979,800	656,600	2,627,000	2,178,800	12,865,700

70,000 mi^2 = 44,800,000 acres

TABLE 20

CROP	PRICE	STATE DOLLAR IMPACTS*
Oats ($/Bu)	1.50	1,202,885
Barley ($/Bu)	2.20	714,445
Durum Wheat ($/Bu)	3.60	1,511,103
Other Spring Wheat ($/Bu)	3.25	1,947,707
Soy Beans ($/Bu)	6.50	673,026
Sugar Beets ($/Ton)	25.00	1,965,992
Potatoes ($/Cwt)	4.25	5,205,688
Flax Seed ($/Bu)	6.40	3,328,151
Sunflowers ($/Ton)	10.00	340,537
Corn Grain ($/Bu)	2.40	440,128
Tame Hay ($/Ton)	55.00	2,357,250
Wild Hay ($/Ton)	45.00	2,109,463
Native Pasture ($/Ton)	45.00	662,492
Corn Silage ($/Ton)	18.33	1,272,899
TOTAL DIRECT		23,731,728
TOTAL (INCLUDING MULTIPLIER EFFECT)		71,409,872

Average annual economic impact (dollar increases) over North Dakota resulting from rainfall enhancement during the period 1976-1980 for the crops shown. Prices shown were approximate averages for the period.

*NOTE: The variations in rainfall increase downwind from the target area have not been considered at this point. When this adjustment is made, the dollar impacts will vary accordingly.

each day and averaged to one value. This value for the day was then apportioned to each CRD based on the proportion of the CRD which was in any seeded sector. Future work will take into account the diminishing downwind effect of the seeding and hence reapportion the economic benefits across the state.

Using the precipitation impact and acreage information, estimates of crop production responses were obtained. Using these production responses and the commodity prices, estimates of the value of the production changes were estimated. These values are also shown in Table 20.

The information is now in hand for the input-output analysis. The production value changes for the various crops were aggregated into two state level categories: (1) crops that would stimulate the crop processing sector (oats, barley, durum wheat, other spring wheat, soybeans, sugarbeets, potatoes, flaxseed, sunflowers, and corn grain); and (2) crops that would stimulate the livestock sector (tame hay, wild hay, native pasture, and corn silage). For each category, a stemming from effect was estimated. The total direct impact would also lead to a household consumption effect. The total direct and indirect impact would be the sum of the total direct impacts, and the household consumption effect. The relations among these various effects are summarized below:

D_c = direct production value impacts for category (1) crops

D_l = direct production value impacts for category (2) crops

$SFE_c = 0.2285*D_c$ = crop processing sector stemming from effect

$SFE_l = 1.31303*D_l$ = livestock sector stemming from effect

$SFE_t = SFE_c + SFE_l$ = total stemming from effect

$DE = D_c + D_l$ = total direct effect

$HCE = 1.4921*DE$ = household consumption effect

$TE = DE + SFE_t + HCE$ = total impact.

For average condition over the whole period, these effects are summarized in Table 21.

TABLE 21

AVERAGE STATEWIDE IMPACTS OVER 1976-1980 PERIOD ATTRIBUTED TO RAINFALL INCREASES FROM CLOUD SEEDING

Total Direct Impacts	23,731,728
Agricultural Processing "Stemming From" Effect	3,861,908
Livestock "Stemming From" Effect	8,406,156
Household Consumption Effect	35,410,096
TOTAL EFFECT	71,409,872

As was mentioned earlier, these figures will undergo an adjustment when the diminishing downwind effect is incorporated into the economics. This will show smaller production increases in the eastern part of the state and larger production increases in and immediately downwind from the seeded areas.

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