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Results of A Statistical Approach to Rainfall Estimation Using Nimbus 5 6.7μm and 11.5μm THIR Data

James P. Ormsby

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ABSTRACT

Nimbus 5 6.7μm and 11.5μm Temperature Humidity Infrared Radiometer (THIR) data were used in a simple multiple regression scheme to test the feasibility of using these data to estimate hourly rainfall. Throughout the test area (85°W to 105°W and 45°N to 30°N) subareas (8°X6°) were chosen from which point to point and areal statistics were obtained.

Four subsets of data were used. The first consisted of only those surface stations indicating precipitation whose latitude and longitude coincided with the THIR grid points. A second used surface stations 0.1 degree from the THIR grid points. The third was a combination of subsets one and two. A reciprocal distance weighting scheme was used to derive precipitation values in data sparse areas. A fourth subset was made using these data combined with the data from subsets one and two.

Point estimates resulted in negative correlations between estimated and grid derived "surface" precipitation. One degree areal estimates showed a slight improvement with a correlation coefficient of ~ 0.11. Single regression areal estimates resulted in correlations of ~ 0.11 and 0.20 for the 6.7μm and 11.5μm data respectively.

These poor results were attributed to problems which are inherent in the satellite data (location errors, short temporal span of data, wavelength of sensors, etc) and the lack of sufficient surface data to better verify the satellite estimate.

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RESULTS OF A STATISTICAL APPROACH TO RAINFALL ESTIMATION USING NIMBUS 5 6.7μm AND 11.5μm THIR DATA

Introduction

For over a decade, almost since the first meteorological satellite was successfully orbited, the idea of estimating rainfall from satellite data has been on many people's minds. Martin and Scherer (1973) provide a review of the satellite rainfall estimation methods up to that time. Since then, modifications have been made to existing techniques (Follansbee, 1976), as well as combining radar data with satellite data (Griffith et al, 1976). In addition, higher resolution visible and infrared (IR) data from geosynchronous meteorological satellites (Scofield and Oliver, 1977 and Scofield, 1978) have been used to estimate convective rainfall as well as the use of Nimbus 6, Electrically Scanning Microwave Radiometer ESMR data (Rodgers, et al, 1978).

The use of thermal IR data alone from a geosynchronous satellite provides a potential of 48 observations per day (one approximately every 30 minutes). In some situations rapid scan data (every 5 to 10 minutes) is available over limited areas. This would be ideal to follow rapidly changing systems and would eliminate the need of a cloud motion model (Follansbee, 1976) between less frequent observations.

On the later Nimbus satellites (Nimbus 4-7) a Temperature Humidity Infrared Radiometer (THIR) sensor was flown. This is a two channel high resolution scanning radiometer designed to provide day and night cloud top or surface temperatures (10.5-12.5μm), the window channel, and a water vapor channel (6.5-7.0μm) to provide information on the moisture content of the upper troposphere and stratosphere and the location of jet streams and frontal systems (Nimbus Project, 1972).

To test the feasibility of using these data in a rainfall estimation technique a simple linear multiple regression was performed using the two channel THIR data and surface-measured hourly precipitation. In a satellite cloud study by Shenk, et al (1976) using Nimbus 3 Medium Resolution Infrared Radiometer (MRIR) data similar to the THIR wavelengths they showed the ability to differentiate between cirrus overcast with clear scattered lower clouds and cumulonimbus but there was still a conflict between cirrostratus and cumulonimbus. As this study was done in the tropics Shenk, et al. indicate "concurrent temperature and moisture profiles will probably be required in the mid-latitudes . . . as well as cloud top height changes[3] to derive a cloud decision matrix within these latitudes. Despite these shortcomings efforts were still undertaken to see what the addition of another IR channel would do to help estimate rainfall amounts.

Data

Nimbus 5 (6.7μm and 11.5μm) Temperature Humidity Infrared Radiometer (THIR) data from June 16 to June 22, 1974, over the mid-United States (105°-85° W longitude/45° to 30° N latitude) were obtained along with hourly rainfall data. The surface data consisted of 1021 stations. The satellite overpass (Greenwich, Z) times are listed in Table 1.

TABLE 1
Dates and time of acquisition of surface and satellite data

Julian Day	Calendar Day	Overpass Time	Surface Observation Time Used
167	June 16	16:44-16:51	1700Z
168	June 17	17:45-17:53	1800Z
169	June 18	17:00-17:08	1700Z
170	June 19	16:14-16:22	1700Z
171	June 20	17:16-17:24	1800Z
172	June 21	16:31-16:38	1700Z
173	June 22	17:33-17:40	1800Z

The elapsed time for the satellite data ranged between seven and eight minutes. Due to the slightly varying overpass times and to keep things consistent, it was decided to use the hourly surface observations which were taken after the satellite overpass. The minor exception was on June 18. Here the hourly observations at the time of overpass were used. A check of the hourly values for the next hour revealed only slight changes in location and amount of precipitation.

The Nimbus 5 THIR 11.5μm and 6.7μm T_B values were mapped to a mercator projection at a scale of 1:2.5M. At this scale, for the higher resolution 11.5μm data (8km @ nadir), several values were averaged to produce data points every 0.3 to 0.4 degree in longitude and 0.2 to 0.3 degree in latitude. On the other hand due to the lower resolution of the 6.7μm data (22km) only 1 or 2 values were used to produce a grid value.

The 21 degrees of longitude and 16 degrees of latitude produced a 65 X 62 grid matrix. This area was too large to fit on a single width of computer printout. To provide ease in handling a smaller 26 X 26 grid matrix (approximately 8 X 6 degrees) was used. This sufficiently included a region of colder T_B temperatures. The subarea location changed from day to day within the larger grid matrix.

Method

The THIR (11.5μm and 6.7μm) T_B values were punched on computer cards for those subareas having colder T_B values. Seven hourly rainfall values, one for each day, plus the location in tenths of a degree for the 1021 meteorological stations were also put on computer cards for the time periods listed in Table 1. Within each subarea (a 676 grid matrix) an average of 26 ground stations coincided exactly (as specified to 0.1 degree) with a THIR grid point. Figure 1 illustrates the relationship of a portion of the THIR grid with surface precipitation stations.

From the original data three subsets were derived from which to perform regression analysis. The first used only surface stations whose latitude and longitude coincided with that of the THIR grid points as specified above. (See Figure 1, "A"). The second data set used only those stations whose latitude or longitude was 0.1 degree or less from a THIR grid point. (See Figure 1, "B"). A third data set used the data values from both data sets one and two.

In order to decrease the size and number of data sparse areas ("C" areas, for example, on Figure 1) a reciprocal distance weighting scheme was used to derive precipitation amounts. The routine used surface precipitation values from those stations that were within 0.4 degree in longitude and 0.3 degree in latitude away from the THIR grid points. These distances were chosen based on the maximum spacing of the THIR grid points. This did not alleviate all areas of missing data, but it did provide additional data values around the area. A fourth data set was then derived from a combination of these data and data sets one and two.

For those grid points indicating precipitation, regression analysis was performed against the THIR 6.7μm and 11.5μm T_B values for that precipitation value. The resulting equation from each data set was then used to estimate the next day's hourly precipitation at the time of satellite overpass. Data points from this day were then combined with the previous day's data to derive a new

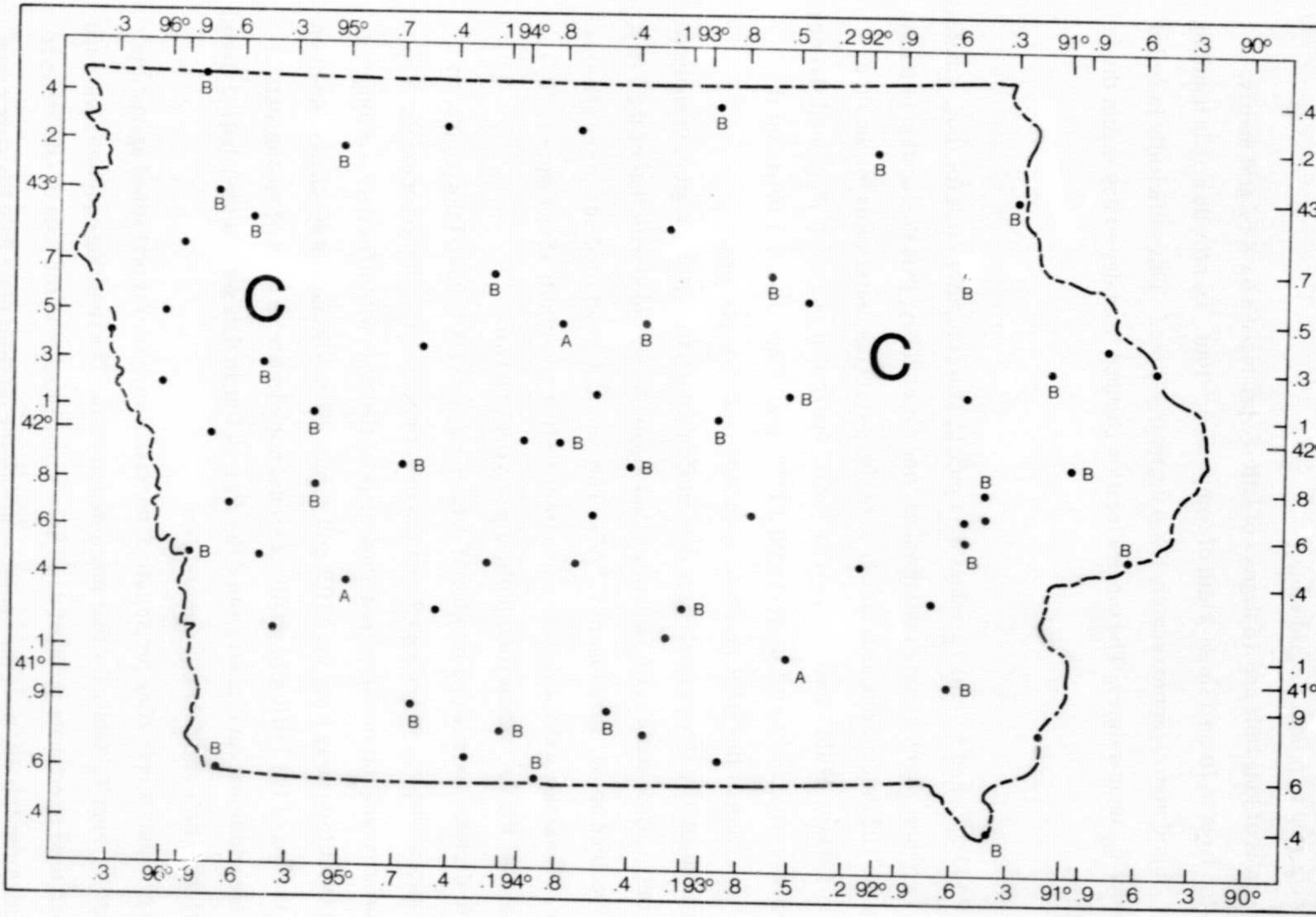

Figure 1. THIR grid location with respect to surface meteorological stations.
"A", designates a surface station coincident with THIR a grid point.
"B", designates a surface station 0.1 degree from a THIR grid point.
"C", a data sparce area.

regression equation. This was done for each data set over the seven day period. In this sense each successive day was an independent data source to check the running regression prior to regression of that day's data. The seventh day was used as the final independent data set.

As the study progressed it was noted that the colder T_B areas did not always coincide with the areas of actual precipitation (Figure 2). This could have been due to one or a combination of reasons to be discussed later.

Following the first computed run which indicated the mislocation of temperature versus precipitation area, a best fit of temperature versus rainfall area was attempted (Figure 3). The computer program was written such that the precipitation data could be translated (north/south and/or east/west) with respect to the THIR data thus obtaining a better temperature-precipitation relationship.

During the analysis several different sets of cut-off temperatures were used. Two will be shown here to illustrate the results. Table 2 indicates the wavelength and the cut-off temperature used.

TABLE 2

Temperature restrictions used during regression and estimates for the two THIR channels.

6.7μm	11.5μm
230	230
223	225

In addition single regression analysis was performed to determine whether one channel gave better results over the two channel analysis. Also, estimates were made and compared for one degree spatial averages.

Results

A limiting factor during the regression phase of the analysis was the lack of sufficient data for Data Type I and limited data for Types II and III. Prior to the last day the total number of data values for the four data types were 5, 20, 25 and 136 respectively when no temperature restriction was used at the time of regression. With a temperature restriction imposed during regression (e.g.

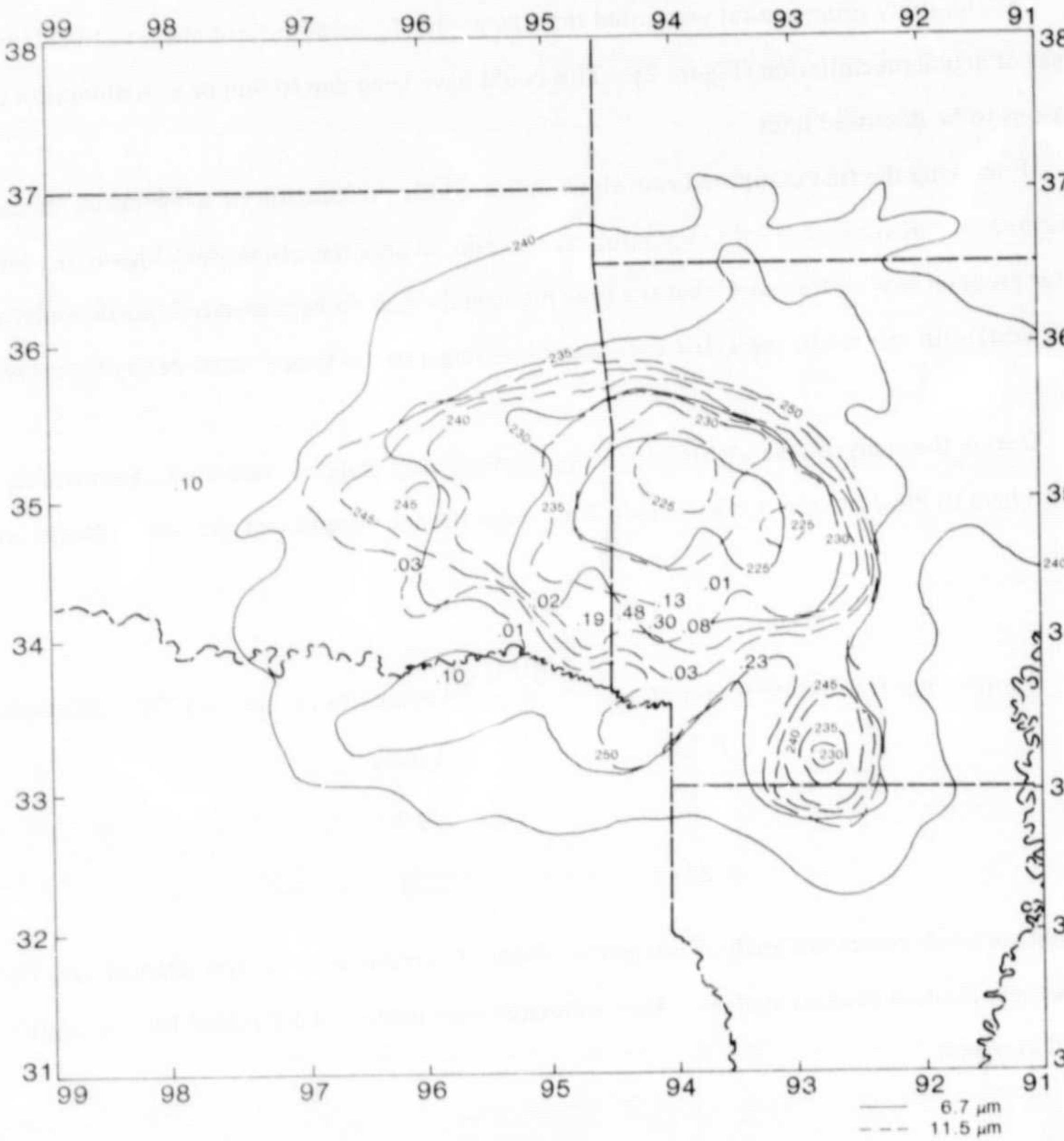

Figure 2. THIR 6.7μm and 11.5μm isotherms in relation to actual surface hourly precipitation for June 17, 1974, before adjustment was made

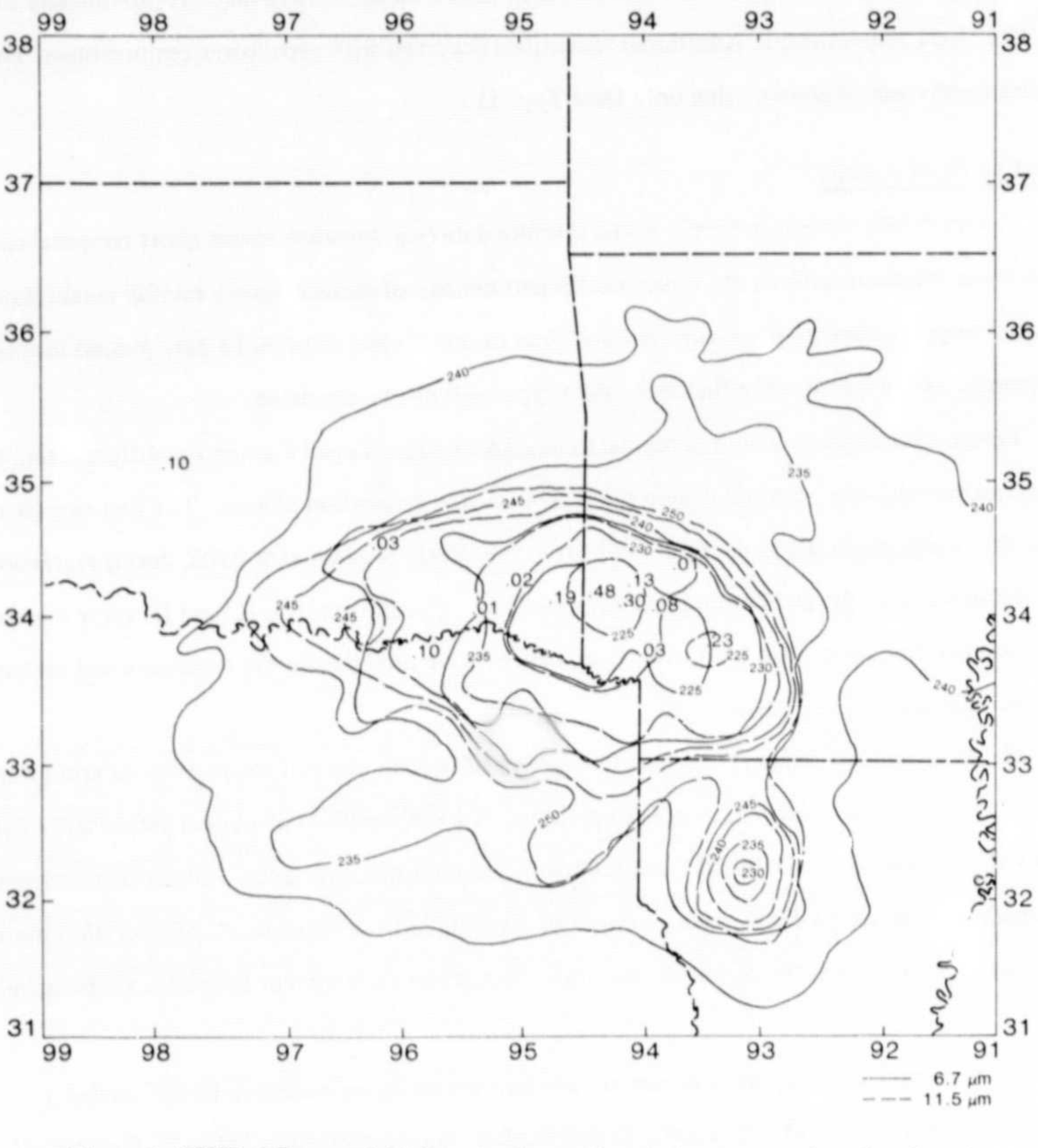

Figure 3. THIR 6.7μm and 11.5μm isotherms in relation to actual surface hourly precipitation for June 17, 1974 following adjustment.

6.7μm and 11.5μm $\leqslant$ 230K) the useable values in each data set were reduced approximately 50% (2, 11, 13, 61 respectively). Additional reductions occurred with even lower temperatures. Due to this results will be shown using only Data Type IV.

Point by Point Results

A variety of problems inherent in the satellite data (e.g. location errors, short temporal span of data, wave length of sensors, etc.) plus insufficient density of surface hourly rainfall measurements resulted in poor point by point correlations. Due to insufficient data ($\leqslant$ 13 data points) for regression purposes results from the first three data types will not be discussed.

Figure 4 combines the confusion matrix results for Data Type IV when the different temperature restrictions were imposed during the regression and e· ·ion phases. The first two (A and B) show the results when the temperature cut-off for the THIR was set at $\leqslant$ 230K during regression and estimation and the estimation phases respectively. The bottom two (C and D) show the results when temperatures indicated by Shenk, et al. (1976) were used during the regression and estimation and the estimation phases respectively.

The lower cut-off temperatures resulted in an under estimation of the number of grid points with precipitation. The higher cut-off temperature, $\leqslant$ 230K, resulted in an over estimation of grid points with precipitation. While the lower cut-off temperatures resulted in more correct no-rain responses there was actually a greater number of accurate (within range limits of confusion matrix) rain estimates (32) when the higher temperature restrictions were used at the time of estimation only.

The total rainfall as reported by surface stations for the hour ending at 1800Z on day 7 was 4.77 inches (12.12 cm). This is the Actual Surface value indicated in Table 3. The grid estimate value (2) is the sum of all precipitation at grid points whose THIR temperature fell within the temperature limits. The grid actual (3) value is the sum of precipitation at those grid points satisfying the Data Type criteria. For Data Type IV this included all grid points with precipitation (actual and portions of the data space areas that were filled in by the weighting scheme).

ESTIMATED	Actual 0.0	Actual 0.01 to 0.10	Actual > 0.10	Trial	Final results of estimation when:
0.0	415	53	16	A	Temperature for regression and estimation set at ⩽230K for both channels
0.01 to 0.10	0	0	0	A	
>0.10	56	66	8	A	
0.0	415	53	16	B	Temperature restriction set at ⩽230K for both channels at time of estimation only
0.01 to 0.10	38	30	6	B	
>0.10	18	36	2	B	
0.0	464	99	22	C	Temperature for regression and estimation set at ⩽223K for 6.7μm and ⩽225K for 11.5μm data.
0.01 to 0.10	0	1	0	C	
>0.10	7	19	2	C	
0.0	464	99	22	D	Temperature restriction set at ⩽223K for 6.7μm and ⩽225K 11.5μm data at time of estimation only.
0.01 to 0.10	0	0	0	D	
>0.10	7	20	2	D	

Figure 4. Confusion matrices showing the results from regression when different temperature restrictions were used for Data Type IV.

TABLE 3

Quantitative results of a point by point estimation using DATA TYPE IV. Temperature restrictions for the four trials the same as in Figure 4

PRECIPITATION REFERENCE TYPE	DATA TYPE IV			
1 Actual Surface	4.77	4.77	4.77	4.77
2 Grid Estimate	16.06	13.24	4.09	3.33
3 Grid Actual	11.49	11.49	11.49	11.49
TRIAL	A	B	C	D
r	−0.3336	−0.3276	−0.1352	−0.1381

Trial B resulted in the closest estimate (15% over) when compared to the grid actual (3) in Table 3. Since this is the total precipitation for all the grid values (actual and those filled in by the weighting scheme) the estimate is pretty good. The confusion matrix also bears this out (Figure 4, "B"). There were 32 correct estimates, with 75 underestimates and 92 overestimates with 415 correct no rain estimates.

The correlation coefficients are given below each trial at the bottom of Table 3. In all cases a negative correlation resulted.

Figure 5, a portion of the final days computer estimate, compares the estimated results (2) with the grid actual (3). The asterisks in the upper left corner indicate missing data.

Spatial Results

Isohyets were drawn for the estimated rainfall and compared with the actual rain gauge values. A map showing the results for Data Type IV when a temperature restriction of ≤ 230K for both THIR channels was used during the estimation phase only is shown in Figure 6. The use of lower cut-off temperatures (Shenk et al, 1976) decreases the estimated area of precipitation. This is shown in Figure 7.

In both cases the area of precipitation to the west (Illinois/Iowa border) is not picked up. The THIR Temperatures in that area ranged from 231K to 240K for the 6.7μm data and 231K to 250K for the 11.5μm data. These higher temperatures excluded the data so no rain estimate was made.

	88.4°	88.1°	87.8°	87.5°	87.2°	86.9°	86.6°	86.3°	85.9°	85.6°	
41.1°	0.0	0.09	0.10	0.10	0.11	0.11	0.10	0.11	0.11	0.11	2
	**	0.0	0.0	0.04	0.06	0.10	0.06	0.0	0.02	0.0	3
40.9°	0.0	0.08	0.09	0.10	0.11	0.12	0.12	0.11	0.11	0.11	2
	0.03	0.10	0.05	0.10	0.07	0.03	0.02	0.0	0.02	0.10	3
40.6°	0.0	0.0	0.09	0.11	0.11	0.11	0.12	0.11	0.13	0.13	2
	0.01	0.10	0.02	0.06	0.03	0.03	0.01	0.0	0.07	0.09	3
40.4°	0.0	0.0	0.09	0.10	0.11	0.11	0.12	0.11	0.11	0.13	2
	0.0	0.0	0.0	0.05	0.07	0.01	0.0	0.03	0.10	0.10	3
40.2°	0.0	0.0	0.08	0.10	0.12	0.12	0.11	0.10	0.11	0.11	2
	0.0	0.0	0.0	0.05	0.10	0.10	0.02	0.05	0.13	0.20	3
39.9°	0.0	0.0	0.0	0.09	0.11	0.12	0.11	0.11	0.10	0.10	2
	0.0	0.0	0.0	0.01	0.04	0.08	0.03	0.09	0.18	0.20	3
39.7°	0.0	0.0	0.0	0.08	0.09	0.09	0.10	0.10	0.09	0.09	2
	0.0	0.0	0.0	0.01	0.05	0.20	0.03	0.03	0.11	0.16	3
39.5°	0.0	0.0	0.0	0.0	0.09	0.10	0.0	0.0	0.0	0.0	2
	0.0	0.0	0.0	0.0	0.10	0.26	0.15	0.08	0.10	0.10	3
39.2°	0.0	0.0	0.0	0.0	0.0	0.0	0.09	0.09	0.09	0.10	2
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3

Figure 5. Portion of computer results for Trial B, Data Type IV comparing estimated (2) and synthesized grid total (3). ** indicates missing data.

The problem herein appears to lie in the temporal resolution of the satellite data. Eight minutes of data does not give a true picture of the dynamics producing the hourly precipitation amount.

The last day the satellite data over the area was acquired between 1733Z and 1740Z. The 1800Z observation was used for the hourly amount. Quite possibly the cloud(s) which produced this rain were short-lived and the cloud tops were lower and thus warmer at the time of satellite overpass. This would account for the lack of an estimate in this area.

Degree Averages

Average rainfall over a given area is useful in watershed management, soil moisture assessment, potential watershed runoff, etc. To assess the capability of the THIR data as a means of determining

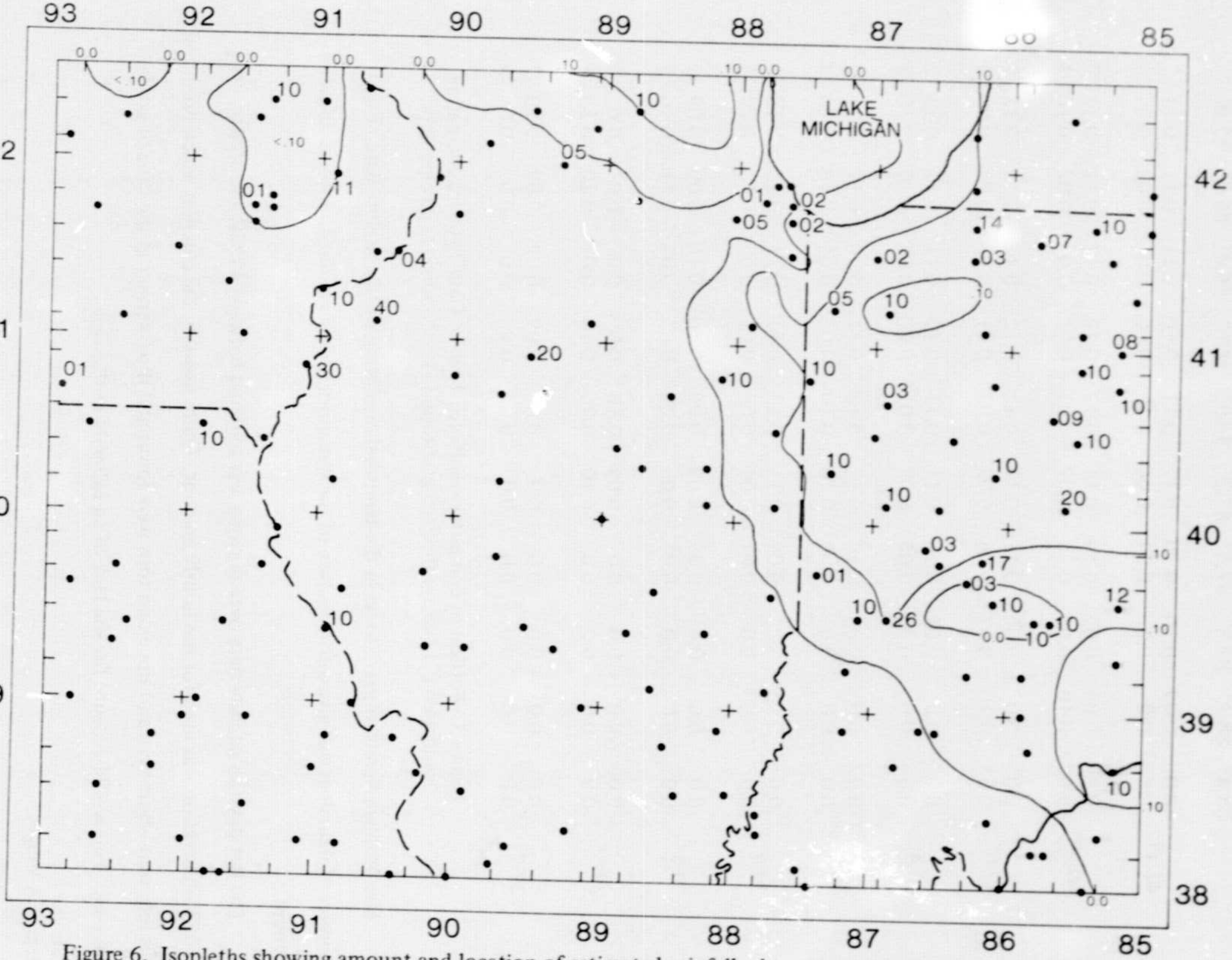

Figure 6. Isopleths showing amount and location of estimated rainfall when a temperature cutoff of ⩽ 230K was used during estimation only for both THIR channels. Actual surface station amounts for the hour ending 1800Z, June 22, 1974 are indicated next to surface location.

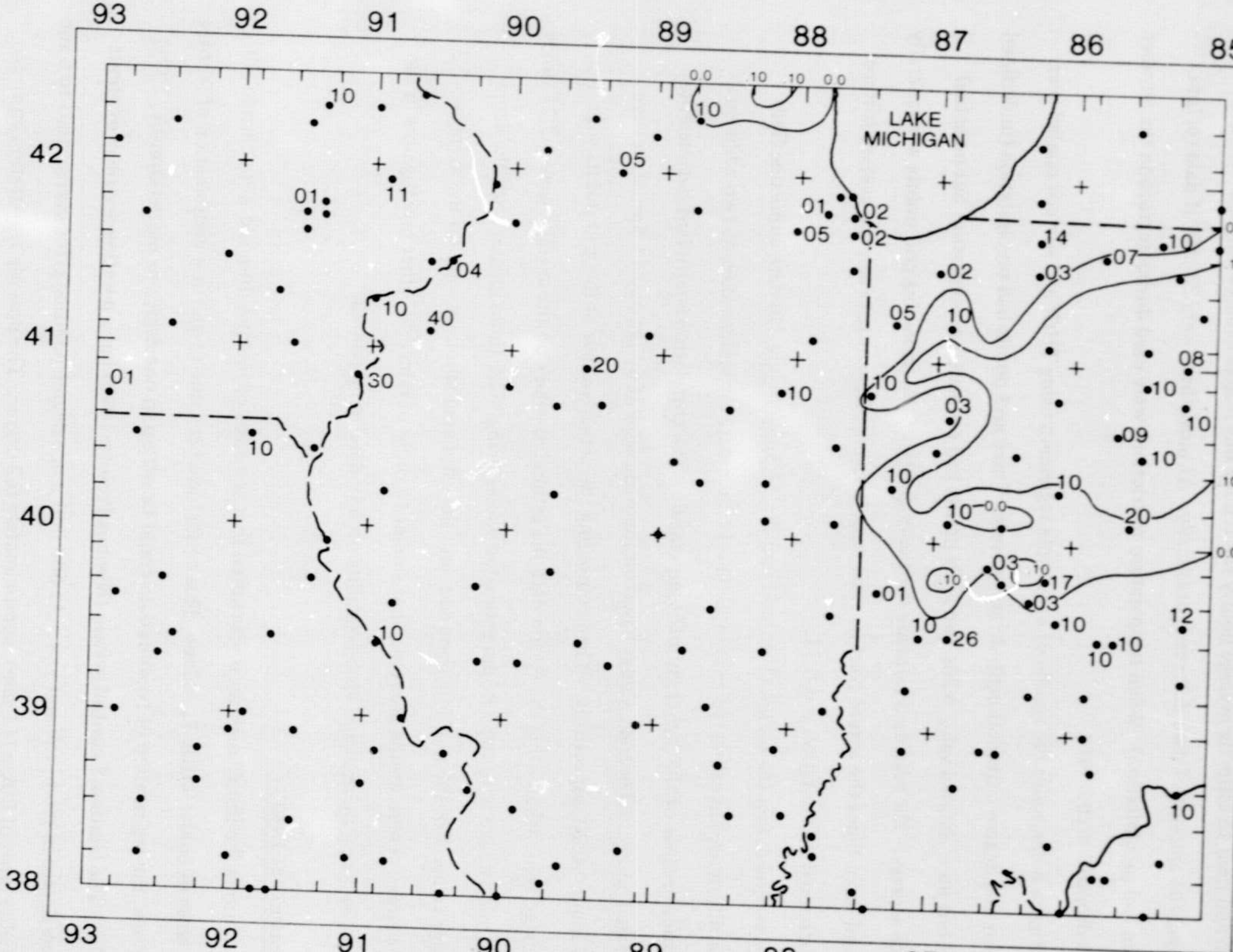

Figure 7. Isopleths showing amount and location of estimated rainfall when a temperature cutoff of ⩽ 223K (6.7μm) and ⩽ 225K (11.5μm) was used. Actual surface station amounts for hour ending 1800Z, June 22, 1974, are indicated next to surface location.

average rainfall one degree latitude and longitude averages of THIR and rain guage data were regressed and used to estimate average hourly rainfall for one degree squares. As a result of the averaging the amount of data decreased drastically. At most there were 23 sets of data (6.7μm, 11.5μm and precipitation). When temperature restrictions were used during regression the number of sets dropped even more.

Figure 8 illustrates the results of a multiple regression using THIR and surface rainfall averaged for one degree latitude/longitude grid points. Three grid points had precipitation (underlined value) but no estimated value while two grids points had estimated precipitation but no actual surface average. The regressed estimate for the majority of the remaining grid points was generally two and three times the actual average. The correlation coefficient between the average surface and estimated precipitation was 0.11.

Looking at just the 6.7μm (Figure 9) and the 11.5μm (Figure 10) data alone one finds minor differences in estimated amounts. The 11.5μm data estimates values at two additional locations because of the higher cut-off temperature. The correlation coefficient between the estimated and actual average values based on the regression of 6.7μm and 11.5μm data were ∿0.11 and ∿0.20 respectively. When comparing the actual average at the grid points with the estimated value when using the 6.7μm data the estimated values on the average were ∿2.25 times the actual average with the 11.5μm estimated values being ∿2.5 times greater than the actual average value. For the multiple regressed data the estimated amounts were on the average ∿2.3 times larger. These results are somewhat similar to those obtained by other investigators in the past when using thermal and visible satellite data to determine rainfall.

Discussion of Results

During the initial analyses it was noted that the areas of precipitation did not coincide with the areas of colder THIR T_B values. This could have been due to one or a combination of factors. For one, the registration of Nimbus data could be off up to one degree or more (Ormsby, 1973, 1975). The Nimbus 5 control system (Nimbus Project, 1972) has a pointing accuracy of about ± one degree in pitch, roll and yaw. At 600 nmi a one degree pointing error corresponds to a subsatellite error of 20km (11 nmi), approximately 0.2 degree. The possible registration error can

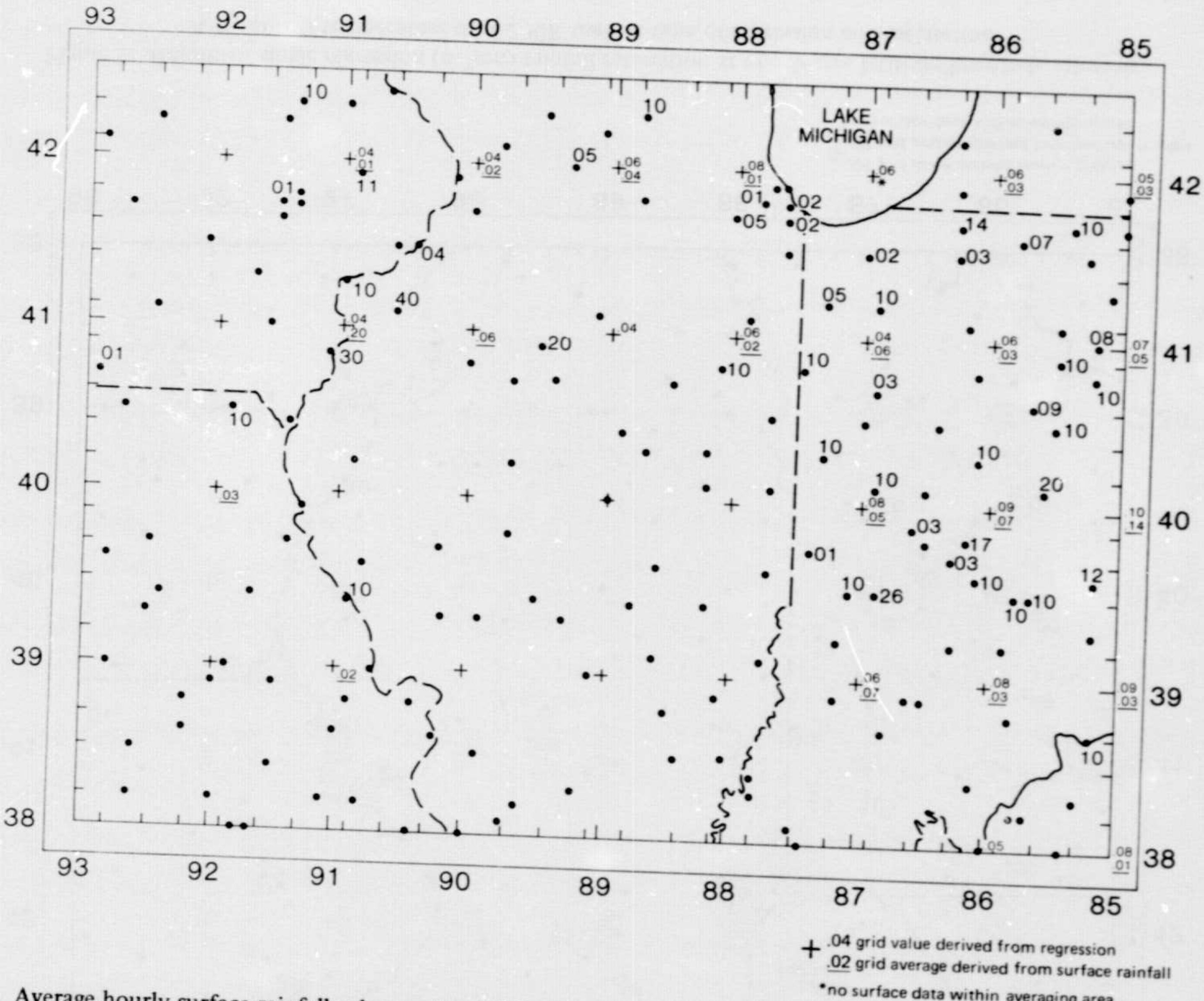

Figure 8. Average hourly surface rainfall values and multiple regression results at one degree latitude/longitude intervals. A temperature restriction of ≤230K (6.7μm) and ≤ 240K (11.5μm) was used during regression and estimation.

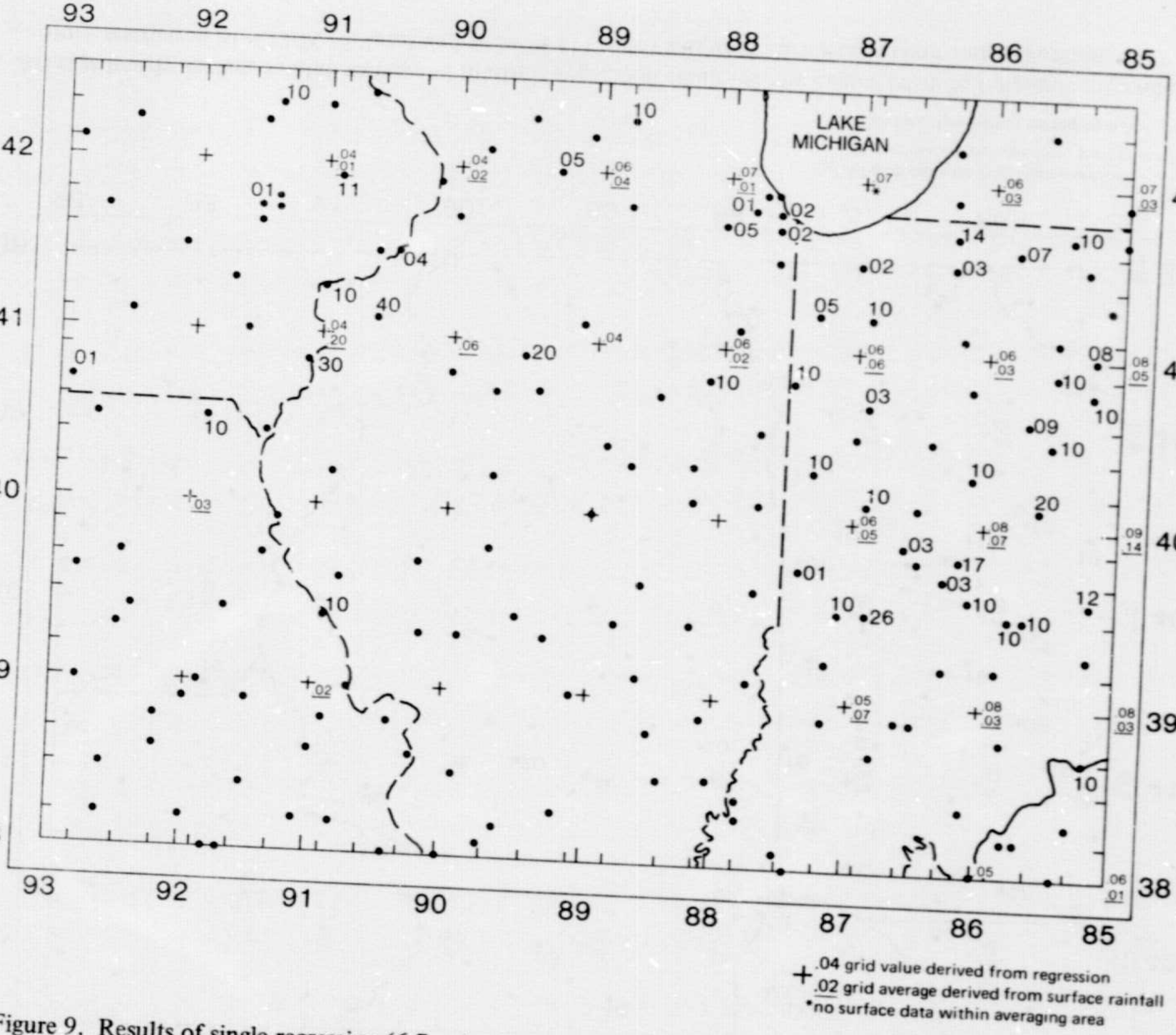

Figure 9. Results of single regression (6.7μm) rainfall estimation at one degree latitude/longitude intervals. A T_B cutoff temperature of $\leqslant$ 230K used at time of regression and estimation.

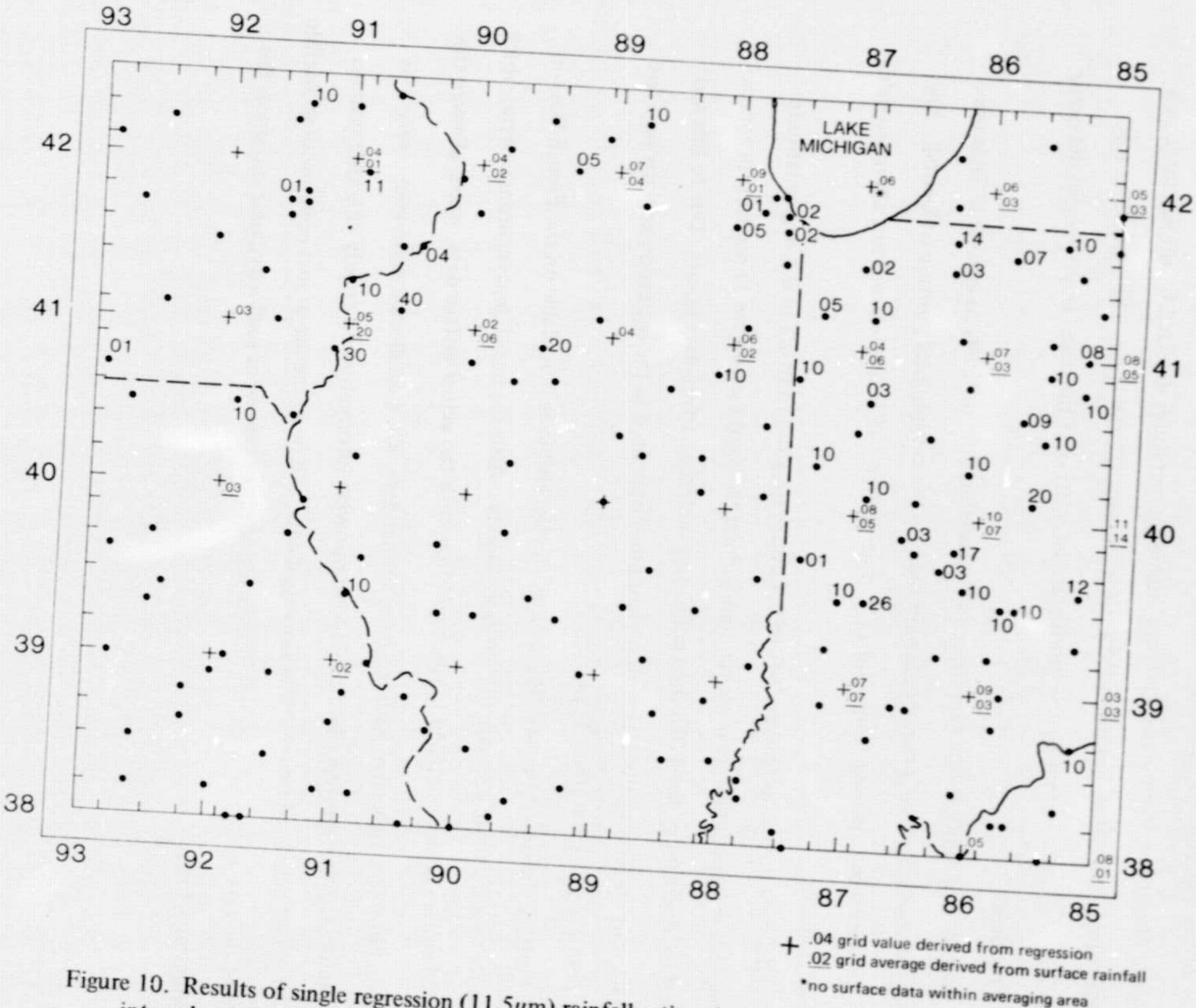

Figure 10. Results of single regression (11.5μm) rainfall estimation at one degree latitude/longitude intervals. A T_B cutoff temperature of $\leqslant$ 240K used at time of regression and estimation.

be compounded due to the fact that the satellite is observing a dynamic situation for only a few minutes during a given hour. Thus the storm or cloud system most likely moved with respect to the surface rainguages, dissipated (therefore, higher temperatures detected by the satellite), or a new one formed (detected, but displaced from a previous rainfall area). The movement was accounted for to some extent by the south and east shifting of the data. Improvement did occur with adjustment.

Another possibility is that rain from a cloud seldom falls vertically as assumed. Thus the location of colder T_B values may not always indicate the geographical position of landfall. Also cirrus blowoff results in cold temperatures, but no rainfall. This problem was not alleviated using the two channels.

THIR data points occur every 0.3 to 0.4 degree longitude and 0.2 to 0.3 degree latitude. The surface rainfall data were more random and less frequent (see Figure 1) resulting in approximately four percent of the THIR data coinciding with the surface data points. Due to this and the fact only surface data points with precipitation were used in the regression analysis very few data points were usable (Data Type I).

Possibly the use of the two IR channels and the visible as is available on the French Meteor Satellite would help to alleviate the cirrus ambiquity. Also the use of geosynchronous data, which could be more closely matched in space and time with the actual surface data, would alleviate the temporal problem associated with the polar orbiter data. On a small scale rapid scan (every 5 to 10 minutes) geosynchronous data could better provide information on rapidly changing systems which would be missed under longer time span data. All in all the use of just polar orbiting satellite data of the type used here does not provide a true set of values for such a dynamic process as the production of rain.

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