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National Environmental Satellite Service

Estimation of Average Daily Rainfall From Satellite Cloud Photographs

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ESTIMATION OF AVERAGE DAILY RAINFALL FROM SATELLITE CLOUD PHOTOGRAPHS

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ESTIMATION OF AVERAGE DAILY RAINFALL FROM SATELLITE CLOUD PHOTOGRAPHS

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ABSTRACT. This memorandum describes a simple technique for estimating the average daily rainfall over sub-synoptic scale areas in the tropics and subtropics. The procedure is to determine the percentage of a given area covered by each of three rain-producing cloud types (cumulonimbus, nimbostratus, and cumulus congestus); these percentages are multiplied by empirically established coefficients to obtain the rainfall contribution to be expected from each cloud type. The method was tested for Zambia, Thailand, California, Florida, and the south central United States; results were encouraging. Weighting factors to adapt the technique to the heaviest rainfall stations of India were derived. Further tests are planned for data-sparse areas in an attempt to solve hydrological problems.

1. INTRODUCTION

In the past 5 years a number of investigators have made progress in the development of techniques for estimating rainfall from meteorological satellite imagery. Lethbridge (1967) and Lethbridge and Panofsky (1969) have shown that the probability of precipitation increases (a) as temperature in the window radiation channel (8 to 12 μm) decreases and (b) as cloud brightness in the visible increases. They made no attempt to estimate rainfall amounts per se, although they did discriminate between amounts >0.04 inch and $\leq$0.04 inch.

Gerrish (1970) obtained significant correlations between average cloud cover, as determined from once-daily satellite mosaics, and mean daily rainfall over South Florida for the period June 14 to October 22, 1968. The average cloud cover also correlated well with the number of stations receiving rain and with average relative humidity between the 700- and 500-mb levels.

Woodley and Sancho (1971) and Woodley, Sancho, and Miller (1972) have developed a technique relating brightness in the satellite pictures to radar echoes and precipitation. Their results are encouraging. The method, however, depends heavily on careful control of brightness, which is subject to many technical constraints, including the variability of the satellite signal. Such control should be feasible when highly sophisticated equipment becomes available, but it may be a long time before hardware of this nature is in operation at Automatic Picture Transmission (APT) stations in remote corners of the globe. For a few years, at least, many APT stations will have to depend on imagery that falls short of Woodley's requirements. On the other hand, cloud types such as cumulonimbus, cumulus congestus, and nimbostratus are relatively easy to identify in the cloud photographs currently being received at APT stations. Identification of these cloud types is the essential requirement for using the technique discussed herein.

Using techniques similar to Woodley's, Sikdar et al. (1970) and Sikdar (1972) have found a good correspondence (a) between rainfall rate and the time change of cirrus shield area above active deep convection in mid-latitude frontal zones and (b) between the occurrence of rain at the ground and the brightness of cloud masses in satellite pictures. Measurement of the growth of the cirrus shield was accomplished using geostationary satellite imagery; such measurements currently are feasible only for areas photographed by geostationary satellites and at stations capable of receiving such imagery. Again this requirement rules out use of the technique at APT stations in many parts of the world.

Gruber (1971) uses a simple relation in which the percentage of a synoptic area covered by deep convection is the principal contributor to short-period rainfall estimation (about 1 hour or less). His method does not necessarily require satellite imagery; however, in the single case for which Gruber used satellite pictures to delineate the active convection areas, he obtained quite accurate short-period rainfall estimates.

Scherer and Hudlow (1971) have developed transfer functions which transform satellite nighttime infrared temperature maps into probable distributions of radar echo lengths. Their data are divided into three classes: disturbed, undisturbed, and intermediate weather conditions. These classifications are based on characteristics of the cloud distribution at various pressure levels aloft. Precipitation is estimated from the derived echo size and a three-dimensional model relating size to the vertical distribution and intensity of the echo.

Barrett (1970, 1971) uses satellite nephanalyses to estimate monthly rainfall for the area 90° to 180°E, 15°N to 15°S. He has derived an overall rainfall coefficient based on three criteria: (a) mean monthly cloud cover percentage derived from nephanalyses, (b) probabilities of rainfall from the neph cloud types "drawn up to quantify scientific intuition," and (c) intensities of rainfall from the different cloud categories drawn up in the same way (table 1). His contingency table relating estimated precipitation to recorded precipitation, on a monthly average basis, shows considerable skill.

In early March 1971 the Luangwa Valley in the Eastern Province of Zambia was designated a disaster area because of severe flooding caused by heavy rains during the preceding month. It is difficult to get rainfall reports from the Luangwa Valley in time for operational use. The Director of Meteorology, Zambia, suggested to the Administrator of the National Oceanic and Atmospheric Administration that the feasibility of a flood forecasting scheme using satellite data as proposed by Barrett be explored. The procedure outlined herein was developed in response to that suggestion. In the procedure, satellite photographs are used to estimate rainfall amounts for input to established flood forecasting models, and for a variety of other purposes.

2. METHOD

The technique is subjective but straightforward. Afternoon satellite photographs of the selected area (fig. 1) are examined to determine what percentage of the area is covered by each of three rain-producing cloud types (cumulonimbus, nimbostratus, and cumulus congestus). In practice, the percentage of the area that is either clear or covered by cloud types that normally produce no precipitation should be determined as a bias check. The four percentages should total 100%.

The 24-hr rainfall for the area is calculated by use of the equation

$$R_e = \frac{K_1C_1 + K_2\ C_2 + K_3C_3}{100}\ , \qquad (1)$$

where R_e is the 24-hr rainfall estimate for the area in inches, C_1 is the percentage (in whole numbers) of the area covered by cumulonimbus, C_2 the percentage covered by nimbostratus, C_3 the percentage covered by cumulus congestus, and K_1, K_2, and K_3 are empirical coefficients for cumulonimbus, nimbostratus, and cumulus congestus, respectively. Experience shows that the best values for these coefficients are:

$$K_1 = 1.0,\ K_2 = 0.25,\ \text{and}\ K_3 = 0.02.$$

A few examples of these rain-producing cloud types, photographed over Zambia, the south central United States, and southern California, are shown in figures 2, 3, and 4.

Nimbostratus (figs. 1 and 5) appears infrequently in the cases studied, and then usually in association with frontal systems. Of 342 days on which rain-producing clouds were seen, only 33 showed signs of nimbostratus. Most occurred in the south central United States, and 70% of these were in the vicinity of fronts (mainly quasi-stationary).

In estimating the percentage of cumulonimbus coverage, no attempt has been made to distinguish active cumulonimbus towers from anvil debris except in cases where it is obvious that the debris is old, and little or no active cumulonimbus is present.

3. DERIVATION OF THE COEFFICIENTS

Barrett's basic rainfall coefficient equation, adjusted to yield 24-hr rainfall rather than a monthly mean, may be written

$$R_e = \frac{0.72C_1 + 0.25C_4 + 0.02C_5}{100} \quad (2)$$

where C_1, C_4, and C_5 are the percentages of the area covered respectively by cumulonimbus, stratiform, and cumuliform cloud categories as shown in the nephanalysis (table 1). Direct application of equation (2) to afternoon satellite cloud pictures (rather than to nephanalyses) indicated the need for three changes. The first of these, established by trial and error, was an increase in the cumulonimbus coefficient from 0.72 to 1.0. The second change was the substitution of nimbostratus cloud (C_2) for stratiform (C_4), on the assumption that neither low stratus nor cirrostratus produce appreciable rain.

The third change was the substitution of cumulus congestus (C_3) for cumuliform (C_5). The 0.02 coefficient should be used only for cumulus congestus, not for cumulus humilis. Fortunately, it is relatively easy to distinguish between these two cloud types, as may be seen in figure 6. An individual cumulus humilis normally is too small to be resolved by satellite cameras, but groups of these small clouds exhibit a gray shade contrasting with the darker land or water surfaces in cloud-free areas. Cumulus congestus is brighter and whiter, and presents a mottled appearance when the cloud elements are closely spaced.

With these changes, the equation finally adopted is

$$R_e = \frac{1.0C_1 + 0.25C_2 + 0.02C_3}{100} \quad (3)$$

The cumulonimbus coefficient of 1.0, determined by trial and error, was subsequently tested for days on which cumulonimbus was the only rain-producing cloud present in the afternoon picture. Values of K were computed for each day using the formula K = R/C, where R is the average of the rain collected by all gauges in the area on a given day in hundredths of an inch, and C is the percentage of the area covered by cumulonimbus at picture time. The mean of all values of K derived in this manner (for 246 cases) was 1.04 (see table 2).

4. TESTS OF THE METHOD

The technique has been tested in widely separated areas of the tropics and subtropics. Figures 7 through 11 show the estimated daily rainfall versus observed average daily rainfall for peninsular Florida, Zambia, the Luangwa Valley (Zambia), Arkansas, Louisiana, Mississippi, and the coastal basin of southern California.

Uniformly good results are apparent in all but three months: Florida in April 1967; the Luangwa Valley in February 1971; and (especially) California in January 1969. Near-drought conditions prevailed over Florida in April 1967, so that all eight days on which the satellite pictures reveal significant amounts of cumulonimbus show little or no rainfall.

Estimates for the Luangwa Valley were made for the entire length of the river, from around 10°S 33°E to near 16°S 30°E. However, in almost every case, the 22 rain gauges used in verification were located in the southern half of the valley. Frost (1971) states that the 22 stations "may not be representative of the catchment area as a whole, as there are no stations on the escarpment where probably most of the rain fell, but it is very difficult, if not impossible, to set up precipitation stations there due to its inaccessibility and the presence of wild animals, including lions."

The southern California storm of January 1969 was chosen to test the technique on the 80-year record rainfall for the Los Angeles area brought by the storm. Since even 100% coverage of cumulonimbus would yield an estimate of only 1 inch of rain in 24 hours, the technique will always underestimate very heavy rains, as it did for this storm. The technique did, however, catch the onset and tapering off of the rain. When the estimates for this storm are added to the statistics derived from all other areas tested, the average absolute error only increases from 0.11 to 0.13 inch, but the root-mean-square error increases from 0.21 to 0.31 inch. The area in California that was tested is outlined in figure 4.

The contingency table (table 3) relates observed daily rainfall to estimated daily rainfall for all areas studied. The selected class intervals, in inches of rainfall, are zero, .01 to .10, .11 to .20, .21 to .30, .31 to .50, .51 to 1.00, 1.01 to 2.00, and 2.01 to 5.00 inches. In 215 cases out of 488, or 44% of the cases, the class interval of estimated rain is the same as the class interval of observed rain. When the class intervals coincide, the estimates are considered perfect. Thirty-five percent of the cases differ by just one class interval; that is, 79% of all the cases differ by one class interval or less. Ninety-three percent differ by two class intervals or less.

In this study, afternoon satellite pictures for the current day are used to estimate rain amounts for the period beginning the morning of the current day and ending the next morning; this, in effect, is a very short-range forecast. With this in mind, table 4 has been drawn up as a categorical rain-no rain verification, where amounts $\geq$ .005 inch are considered rain, and amounts < .005 are considered no rain. For 488 cases, 399 are correctly forecast. The skill score is 0.59, the threat score 0.76, the post agreement 0.83, the prefigurance 0.90, and the bias 1.08.

On strictly convective days the range of rain amounts was great, as would be expected. For example, on July 4, 1971, 66% of the reporting stations in Louisiana had no rain, while the largest amounts reported were 1.92 and 1.01 inches. Despite this wide range, the estimate was 0.10 inch, and the average observed rainfall of the 87 stations was also 0.10 inch. On July 24, Louisiana stations reported as high as 3.90 and 2.63 inches, while a dozen stations had no rain, yet the cloud pictures showed 50% cumulonimbus and 30% nimbostratus, which computes to 0.57 inch. The observed mean was 0.64 inch.

Using their highly successful "bright spot enhancement" technique, Woodley, Sancho, and Miller (1972) estimated daily mean areal rainfall for the Caribbean region extending from 10° to 20°N and 70° to 80°W for the period May 15 to June 15, 1971. Their estimates are based on the ATS-3 picture nearest in time to 1700 GMT (local noon). Table 5, column 1 shows their daily estimates. Columns 2 and 3 show daily estimates derived by the author's technique using the ATS-3 local noon picture (column 2) and the NOAA-1 picture taken near 3 p.m. local time (column 3). Agreement is fairly good. Comparing columns 1 and 2, the absolute mean difference is 0.12 inch, and the algebraic mean difference is -0.04 inch. For columns 1 and 3, the absolute mean difference also is 0.12 inch and the algebraic mean difference is +0.01 inch. Columns 2 and 3 show corresponding differences of 0.07 and +0.05 inch. ATS-3 pictures were not available near 1700 GMT on June 10; therefore the totals do not include amounts for that date.

The technique can be learned rapidly. Four meteorologists, given 2 hours of instruction in the procedure, made rainfall estimates that compared favorably with the author's. For 9 July days in Alabama, Georgia, and South Carolina (27 cases), mean absolute errors were 0.17, 0.17, 0.13, and 0.12 inch. Mean algebraic errors, indicating bias, were +0.06, +0.03, -0.01, and -0.03 inch.

No tropical storms or hurricanes crossed any of the test areas during the time periods under consideration. Such storms, which produce torrential rains, are a special category requiring more experience and skill on the part of the meteorologist. Estimating tropical storm rainfall on an individual storm basis would seem the wisest course.

5. APPLICATION OF THE METHOD

The technique will have optimal usefulness in areas which, for various reasons, have meager, undependable, or habitually late data, and particularly in those areas where the need for precipitation information is acute. One such region is the Sutlej River Basin above the Bhakra Dam in northeastern Punjab (fig. 12). Twenty percent of this basin lies in the Indian Punjab, where rain observations are adequate; 80% lies in Tibet and inaccessible slopes of the Himalayas, where rainfall reports are non-existent. Heavy snows and subsequent snowmelt complicate the hydrological problem. This problem was discussed with Indian meteorologists and hydrologists in New Delhi and Geneva, where the potential usefulness of satellite estimates of rainfall was unanimously recognized.

The Mekong River Basin in Southeast Asia is another region in which the method would prove useful (fig. 13). In the southern part of the Mekong Valley there are ample rainfall reports, both from gauges and radar. In the northern part there are almost none. The United Nations Mekong Committee headquartered in Bangkok has made tentative arrangements to receive from the Thai Meteorological Department daily rain estimates based on their APT satellite pictures. These estimates will be used as input to the Committee's computer program for river discharge and flood forecasting, supplementing or replacing bogus data derived from climatological means, extrapolation, and the like. Personnel of the Thai Meteorological Department were taught the technique, and subsequently prepared daily estimates for Thailand for the period July 3, 1970 to May 31, 1971. These estimates have not been compared with daily rainfall reports, but the estimated monthly totals have been compared with monthly means for 79 Thai stations for the 30-year period 1931-1960 (fig. 14).

United Nations hydrologists have cited inaccessible regions of the Parana and Paraguay River Basins as areas where the technique might also be used to good advantage (Nemec 1971).

6. LOCAL ADAPTATIONS

The largest 24-hour rainfall amount that can be estimated from the technique is 1 inch. This is the amount estimated for an area showing 100% coverage by cumulonimbus cloud. Three procedures have been derived to adapt this technique to areas or stations that receive unusually heavy rainfall in the normal course of events.

The first and simplest of these procedures is to determine the ratio between the mean recorded rainfall for a single heavy rainfall station, $\overline{R_s}$, and for the larger area in which the heavy rainfall station is located, $\overline{R_a}$. This ratio, $\overline{R_s/R_a}$, can be used as a weighting factor to increase the estimates obtained by the regular technique. The ratios of the monthly means should be more sensitive than the ratios of annual means.

The rainfall records of the 47 Indian stations listed in the publication World Weather Records (Environmental Data Service 1967) have been used to compute $\overline{R_a}$. When available, the World Meteorological Organization's CLINO data[1] were used for deriving the daily means; otherwise the means for the full period of record have been averaged and used. Of the 47 stations, the eight having the heaviest annual rainfall were assigned weighting factors for the southwest monsoon months (May through September). The $\overline{R_s}$ for each of these eight stations appears on line 2 of tables 7 through 14. $\overline{R_a}$ is on the bottom line of table 6. The weighting factor, $\overline{R_s/R_a}$, for Cherrapunji appears on line 6 of table 7. The corresponding weighting factors for Mangalore, Silchar, Ft. Cochin, Darjeeling, Dibrugarh, Bombay (Santa Cruz station) and Dhubri are listed on line 4 of tables 8 through 14. These stations are presented in descending order of mean annual rainfall.

Weighting factors for these eight rainy stations of India also were derived by a second procedure. Daily visual estimates of bright (rain-associated) cloudiness over India, Pakistan, and northwest Burma for May through September, 1967-70 inclusive, were available from a previous study of the southwest monsoon using satellite pictures. The average daily cloudiness for this area, $\overline{C_a}$, for each of the 5 months was computed from these data (see line 1 of table 6).

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[1]CLINO data are long-term means taken from the World Meteorological Organization publication, Climatological Normals (CLINO) WMO/OMM-No. 117 T.P. 52 or are values supplied by the respective authorities. (Environmental Data Service 1967.)

An estimate of mean daily rainfall for the Indian area might be found by applying the regular technique to $\overline{C_a}$, provided we could successfully apportion $\overline{C_a}$ among the three rain-producing cloud types on some reasonable percentage basis. The factor to apply to $\overline{C_a}$ would be F_a, where

$$F_a = \frac{1.0P_1 + 0.25P_2 + 0.02P_3}{100} \qquad (4)$$

(P_1 is the percentage of bright clouds that might normally be cumulonimbus, P_2 is the percentage that might normally be nimbostratus, and P_3 the percentage that might be cumulus congestus.)

In arriving at an optimal apportionment of the mean daily cloudiness among the three rain-producing cloud types, several sets of percentages were tested. These are shown in table 15. The first set was 70% cumulonimbus, 20% nimbostratus, and 10% cumulus congestus. These percentages, multiplied by the mean daily cloudiness, $\overline{C_a}$, appeared to overestimate the rainfall for every month except May. In table 6, line 2 shows these estimates, which may be compared with the mean daily recorded rainfall for the 47 Indian stations shown on line 7. Of the remaining four sets of percentages and their corresponding factors, the last, apportioning 55% to cumulonimbus, 20% to nimbostratus, and 25% to cumulus congestus, giving a factor of 0.605, proves to be the most useful. The factor 0.605, multiplied by C_a, gives rainfall estimates that agree quite well with the mean daily recorded rainfall for each of the 5 months, May-September. (Compare line 6 with line 7 in table 6.)

$\overline{R_s}/0.605\overline{C_a}$, the ratio of the mean daily rainfall for the individual heavy rain station to the rain estimate derived by this second procedure, may be used as the required weighting factor. Line 7 of table 7 shows this ratio for Cherrapunji, India, for each of the summer monsoon months. Line 5 in tables 8 through 14 gives the corresponding weighting factors for the other seven heavy rainfall stations.

Since $\overline{C_a}$ is the average daily cloudiness for a large area--Pakistan, northwest Burma, and all of India--it is not related very closely to the local heavy rain area. The average daily cloudiness over the heavy rain station ($\overline{C_s}$) might be preferable. Therefore automated mean cloudiness charts by Miller (1971, 1971a) for the period 1967-1970 were examined to determine the mean cloud amounts at each of the heavy rainfall stations for each of the five monsoon months. This provides a third procedure for obtaining a weighting factor using the formula $\overline{R_s}/0.605\overline{C_s}$, where $\overline{C_s}$ is the mean cloudiness over the heavy rainfall station taken from Miller's charts.

Miller's relative cloud cover in mean octas is supposed to represent all cloud types, not just rain-producers. Yet Miller emphasizes the difficulty in detecting cirrus and small cumulus in this type of satellite picture, and states that these "satellite data consistently show lower cloud amounts than concomitant surface observations. These differences are due to differences in resolution, sensitivity, and field of view of the surface observer when compared to the brightness values viewed in the satellites' cameras" (Miller 1971). This tendency to underestimate cloudiness in general and to mask out cirrus and small fair weather cumulus suggests that Miller's automated cloud cover closely approximates rain-producing cloud cover alone.

The weighting factors obtained by this third procedure are entered on line 8 of table 7, and on line 6 in tables 8 through 14. Finally, an adjusted weighting factor, based on the three methods, has been entered on the bottom line of each table. The equation for this adjusted weighting factor, W_s, is

$$W_s = \frac{1}{3}\frac{\overline{R_s}}{R_a} + \frac{1}{6}\frac{\overline{R_s}}{F_aC_a} + \frac{1}{2}\frac{\overline{R_s}}{F_aC_s} \qquad (5)$$

Each of the three right-hand terms of the equation for W_s represents a different way of obtaining a weighting factor for the heavy rainfall stations, except that they have been multiplied by 1/3, 1/6, and 1/2. These fractional values are used to make their individual contribution proportional to the author's confidence in them. The monthly values of W_s have been rounded out to facilitate their use operationally. The weighting factors should be tested on actual day-to-day rain reports for a full monsoon season to determine which are best, and to explore possible ways to improve the method.

The regular technique (eq 3) was tested on rainy season data for 1970-71 over the Suriname River basin above the Afobaka Dam in Surinam. The ITC moves northward across the basin during this period. It was found that the cumulonimbus coefficient of 1.0 should be tripled to get the best rainfall estimates for this area. The 3.0 coefficient for cumulonimbus will be tested in other areas dominated by the ITC.

7. CONCLUSION

The technique described constitutes a step toward the goal of estimating tropical and subtropical rainfall by the use of satellite imagery alone. Its operational use as an aid to hydrologists and meteorologists in regions in which conventional rainfall measurements are largely or completely lacking seems warranted by the test results.

A number of obvious refinements have been avoided in the interest of operational usefulness. For example, the cloud content of the afternoon pictures should be better correlated to the rain occurring within an hour or two of picture-taking time than to the 24-hour rain amounts; yet a rough idea of the 24-hour totals is so important to operational interests that the technique has been slanted in that direction.

Oliver (1972) has suggested that the good relationship between the amount of cumulonimbus at 3 p.m. and the 24-hour rainfall might be explained if we consider that an average thunderstorm lasts for 3 hours and precipitates at the rate of one-third of an inch per hour over its entire area (about 1 inch per hour at its center and a trace at its edges). This gives the correct answer for thermally caused thunderstorms, the usual type that forms the backbone of these statistics. In the event of a storm of greater duration than the ordinary afternoon thundershower, the rain amount estimated by the method described herein should be multiplied by the ratio of actual duration to 3 hours to get a higher estimate.

The technique also could be improved by carefully discriminating between cumulonimbus cells and inactive cloudiness far removed from active towers. This would require an increase in the cumulonimbus coefficient plus a much greater effort by the meteorologist making the estimates. Whether results would justify the added effort is questionable.

Input to the technique has been strictly limited to cloud types and amounts observed in satellite pictures. In operational use, however, it should be supported and modified by any tool available. This includes all features of the synoptic situation that may affect the area under consideration, both local and large scale climatological considerations, radar scans, spot rainfall reports within and near the area, orographic effects and other pertinent terrain features, and persistence of various parameters. Winds at various levels, humidity, pressure patterns and changes, and similar parameters might be incorporated into the technique. In any case, the technique estimates should be considered as supplementing rather than replacing established forecast procedures. It is in this sense that the method should be useful.

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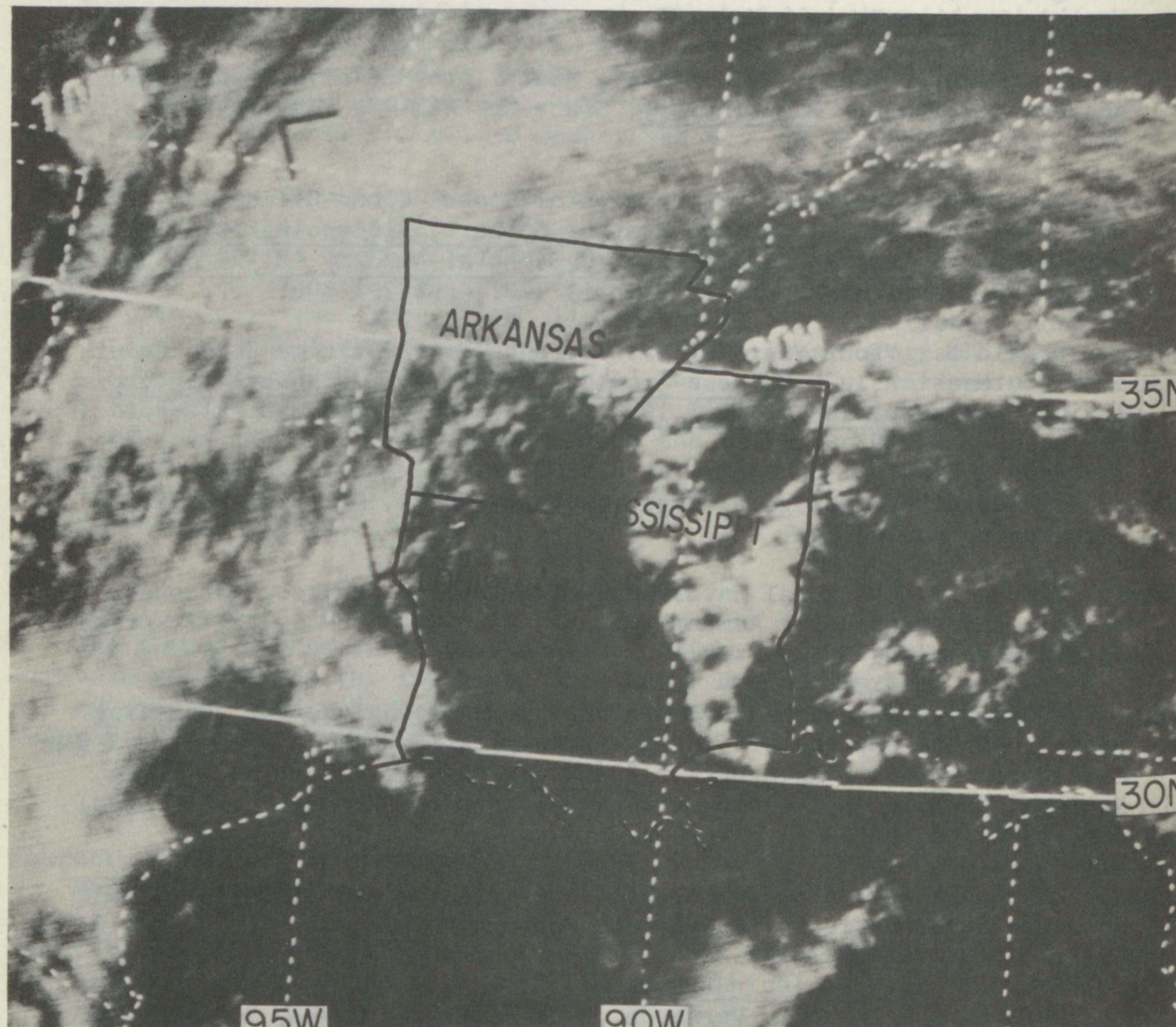

Figure 1.--ESSA-9 Orbit 11135-5 2006 GMT, August 6, 1971. Cumulonimbus covers about 60% of Mississippi. Nimbostratus covers the northwestern corner of Arkansas. A mixture of cumulonimbus and cumulus congestus is distributed over southwestern Arkansas.

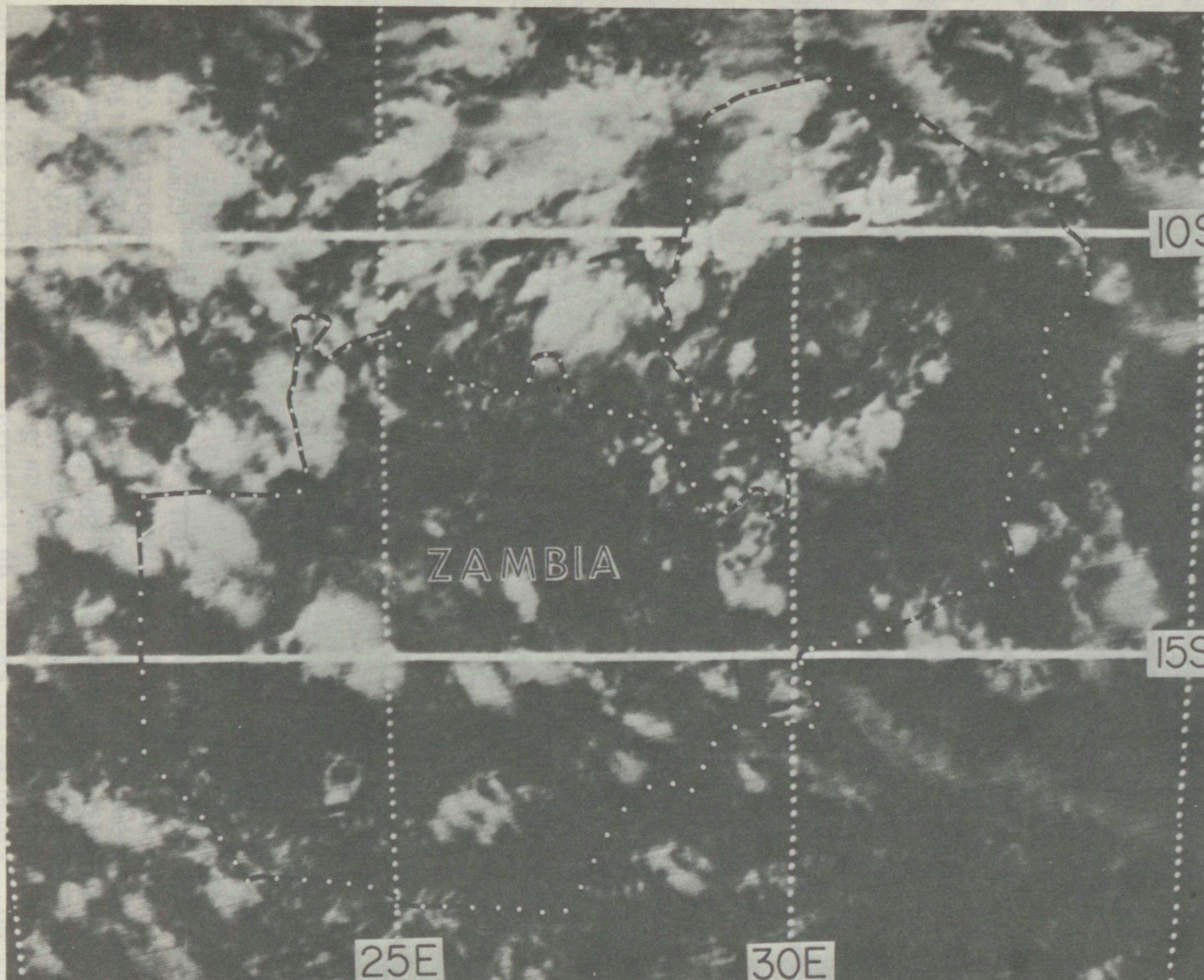

Figure 2.--ESSA-9 Orbit 4711-7 1247 GMT, March 10, 1970. Rain-producing clouds over Zambia. Estimated cloud cover: 30% cumulonimbus, 10% cumulus congestus, 45% cumulus humilis, 15% cloud-free. This yields an average estimate of 0.30 inch of rain. Observed rainfall (average), based on six representative Zambian stations, was 0.33 inch.

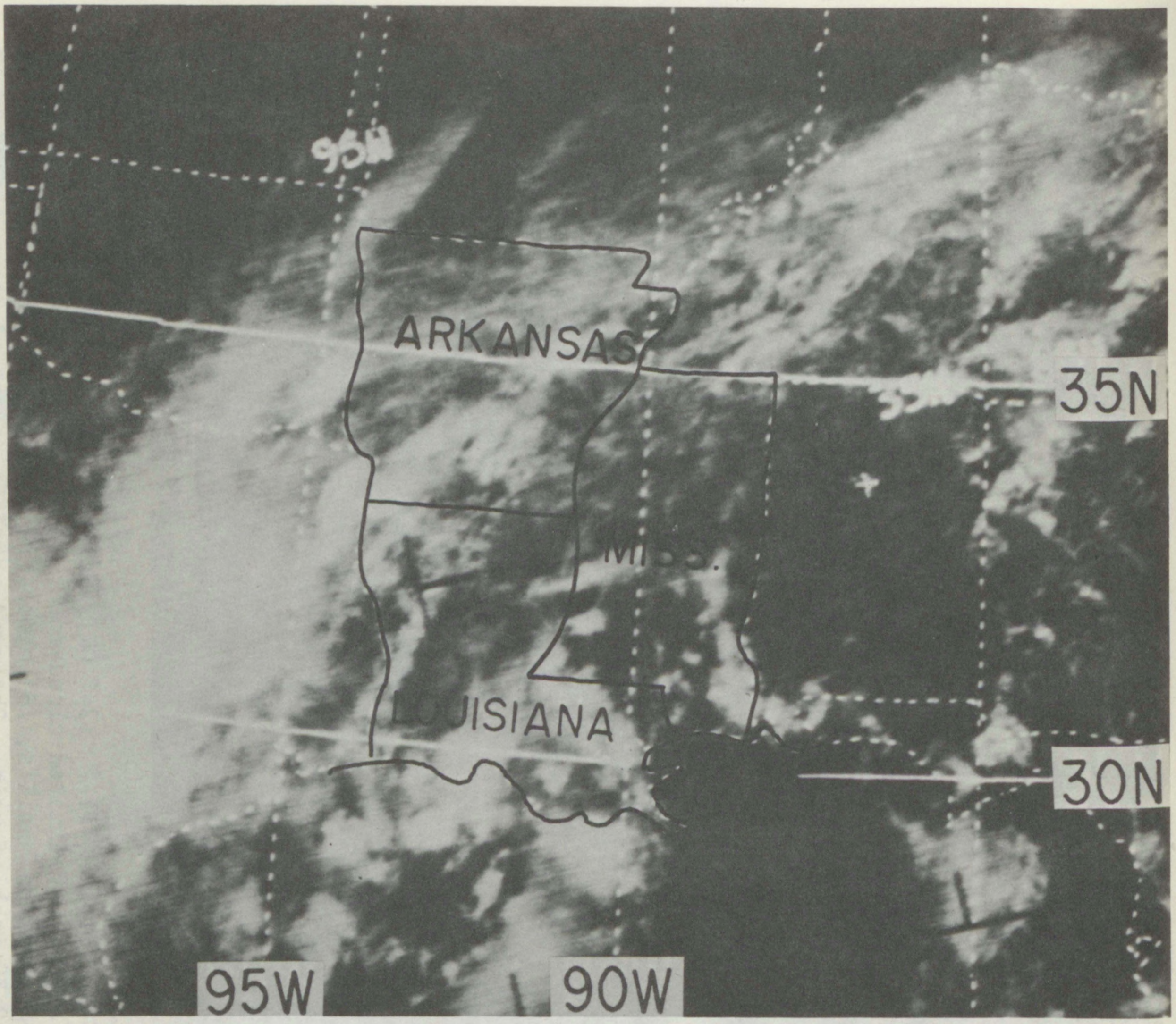

Figure 3.--ESSA-9 Orbit 11085-5 2002 GMT, August 2, 1971. Cumulonimbus is predominant over Arkansas and Louisiana, but a larger proportion of the clouds over Mississippi are cumulus congestus. Average observed 24-hour rainfall for Arkansas was 0.70 inch, for Louisiana 0.54 inch, and for Mississippi 0.30 inch. Estimated amounts were, respectively, 0.65 inch, 0.63 inch, and 0.41 inch.

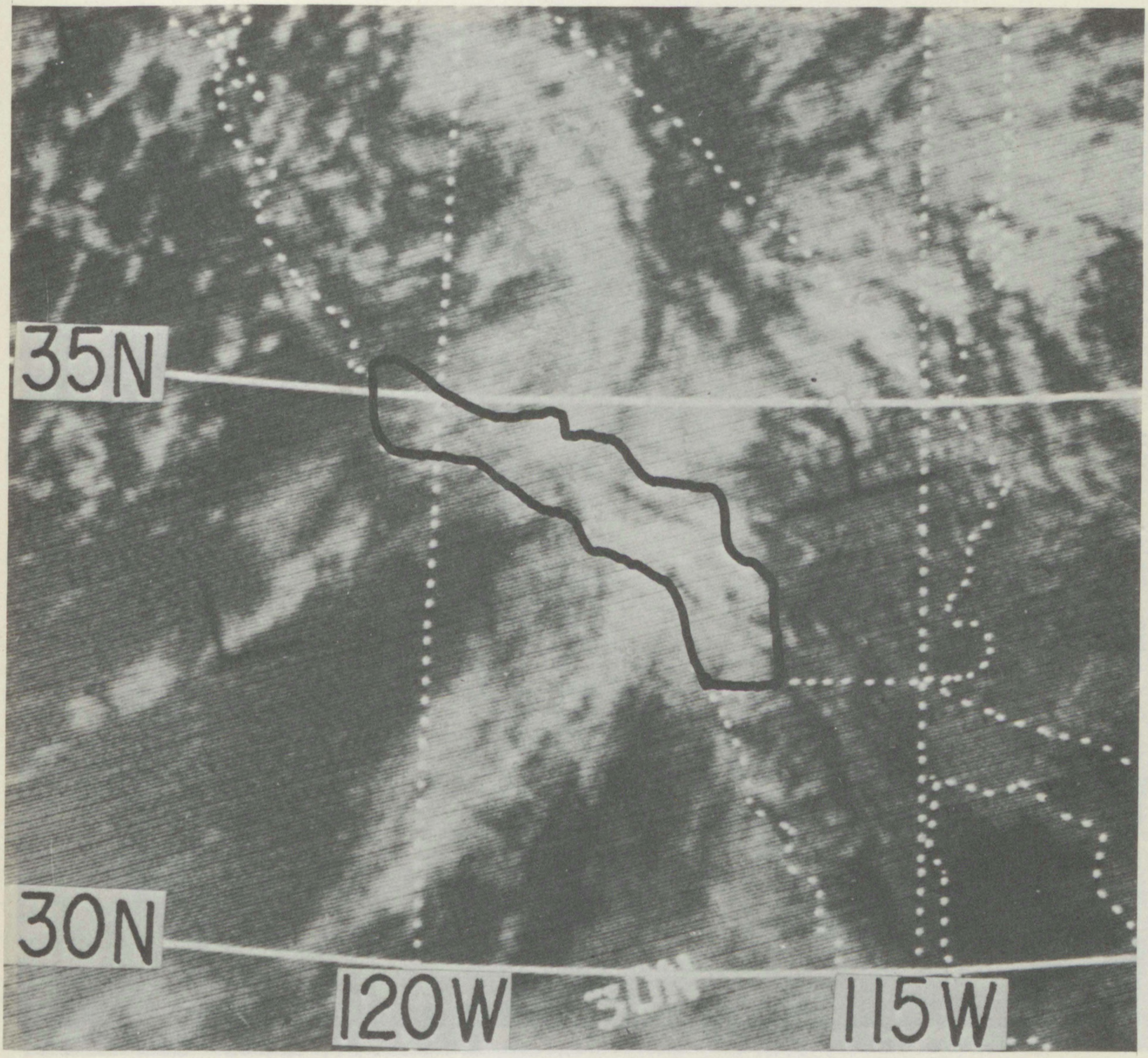

Figure 4.--ESSA-7 Orbit 2046-2 2207 GMT, January 26, 1969. Rain clouds over southern California, near the end of a record 2-week rainstorm. The South Coast Drainage Area (outlined in black) shows 60% cumulonimbus and 20% cumulus congestus, giving an estimated rainfall amount of 0.60 inch. One hundred forty gauges averaged 1.66 inches in 24 hours. On the previous day the same stations averaged 4.34 inches, with one station recording 21.61 inches.

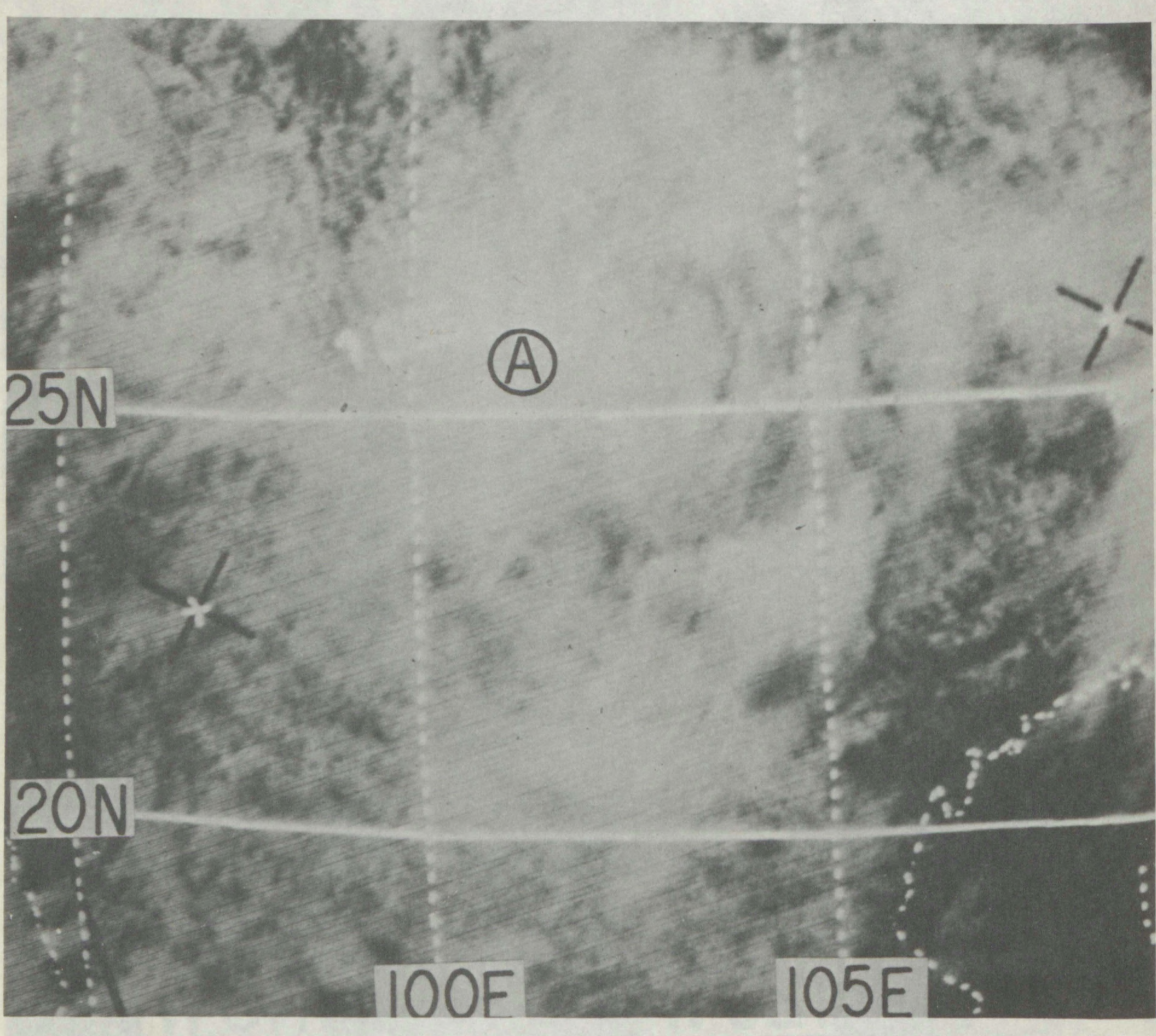

Figure 5.--ITOS-1 Orbit 2099-5 0735 GMT, July 10, 1970. Masses of cumulonimbus over China. A sheet of nimbostratus (A) covers the area from 99°E to 103°E between 24°N and 26°N.

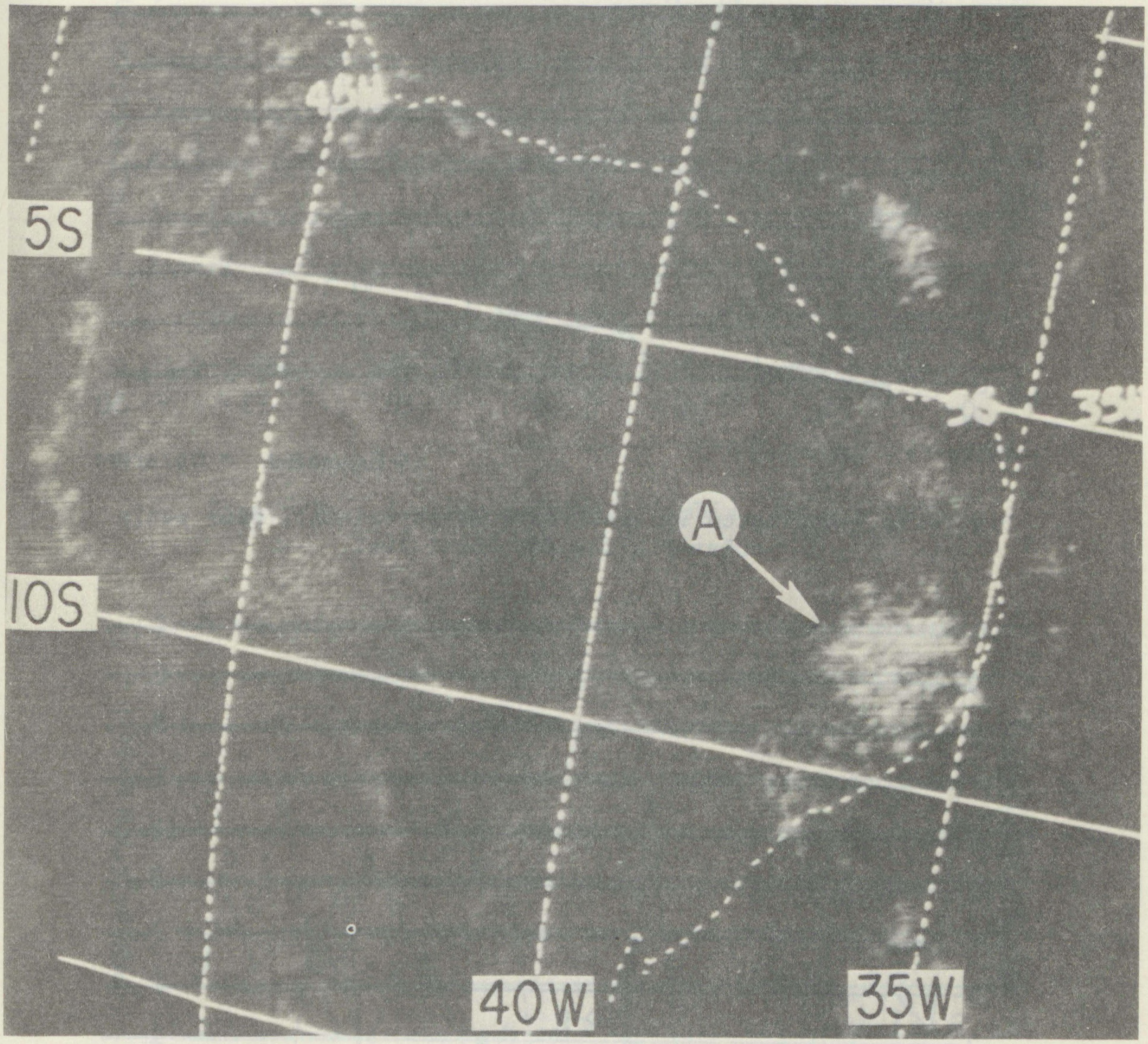

Figure 6.--ESSA-9 Orbit 11196-8 1706 GMT, August 11, 1971. The dark mottled gray cover over most of Brazil is cumulus humilis. Individual cloud elements are too small to be distinguished. A cluster of cumulus congestus appears near the coast just north of 10°S (A).

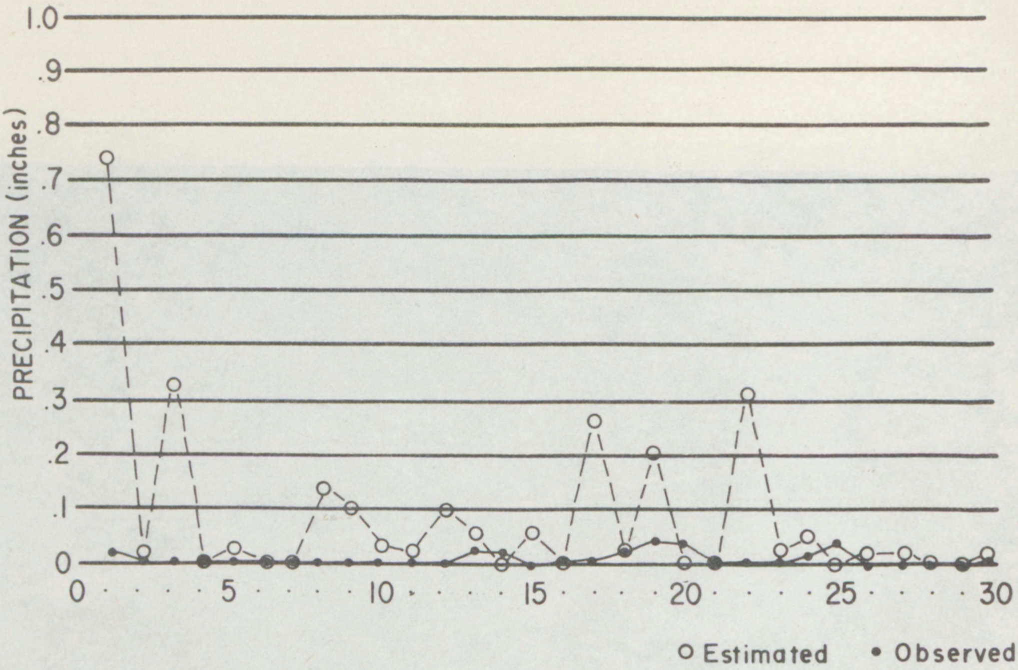

Figure 7a.--Estimated vs observed average rainfall over peninsular Florida for April 1967

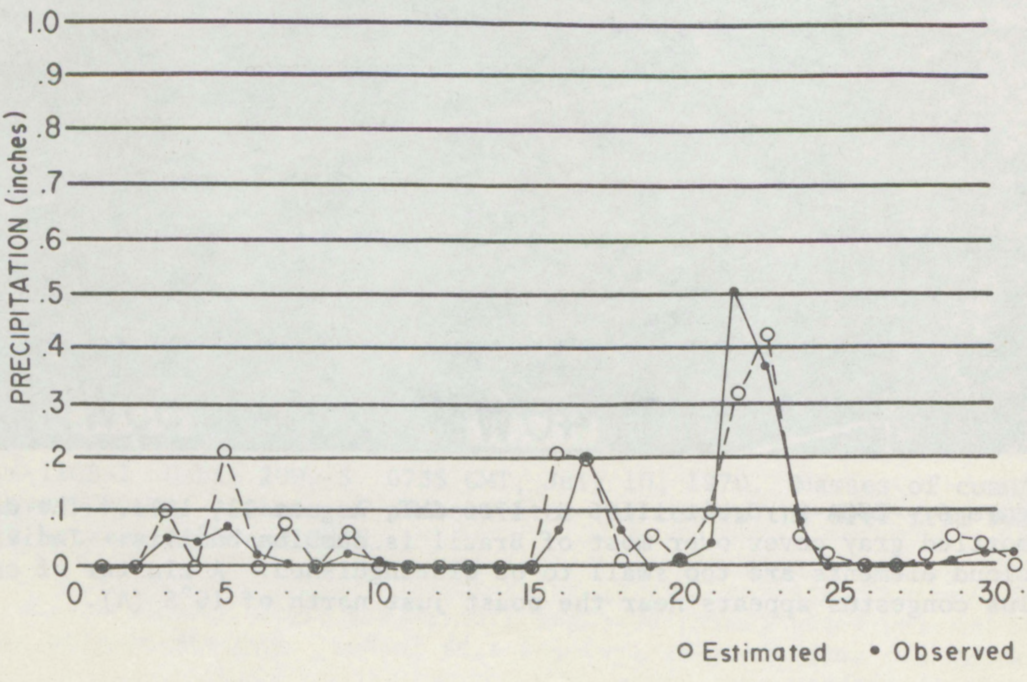

Figure 7b.--Estimated vs observed average rainfall over peninsular Florida for May 1967

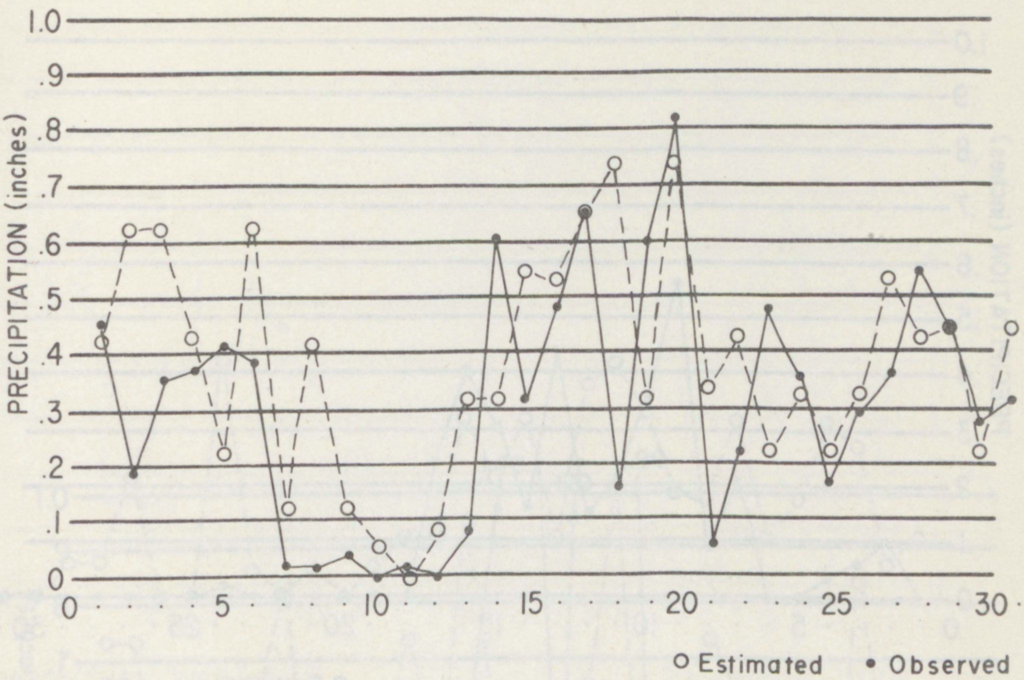

Figure 8a.--Average rainfall, Zambia, January 1970

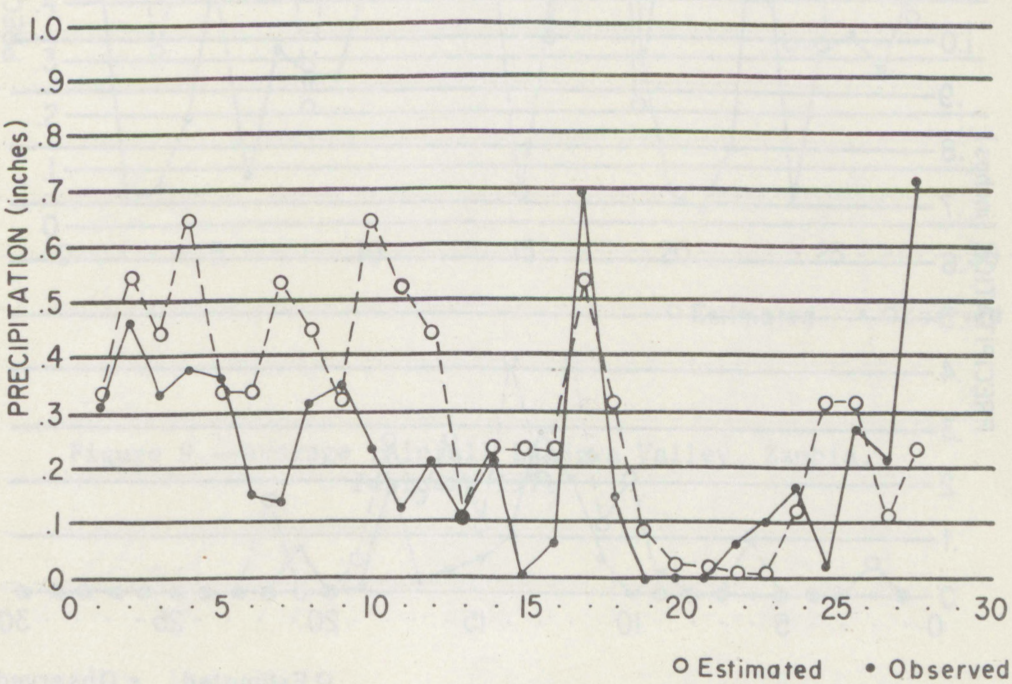

Figure 8b.--Average rainfall, Zambia, February 1970

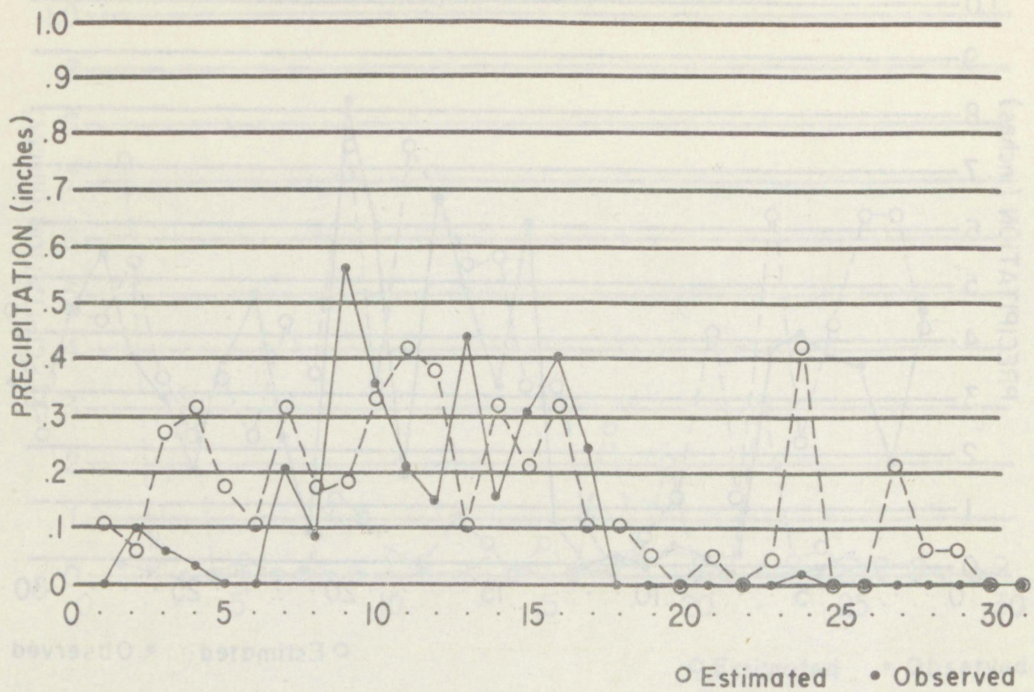

Figure 8c.--Average rainfall, Zambia, March 1970

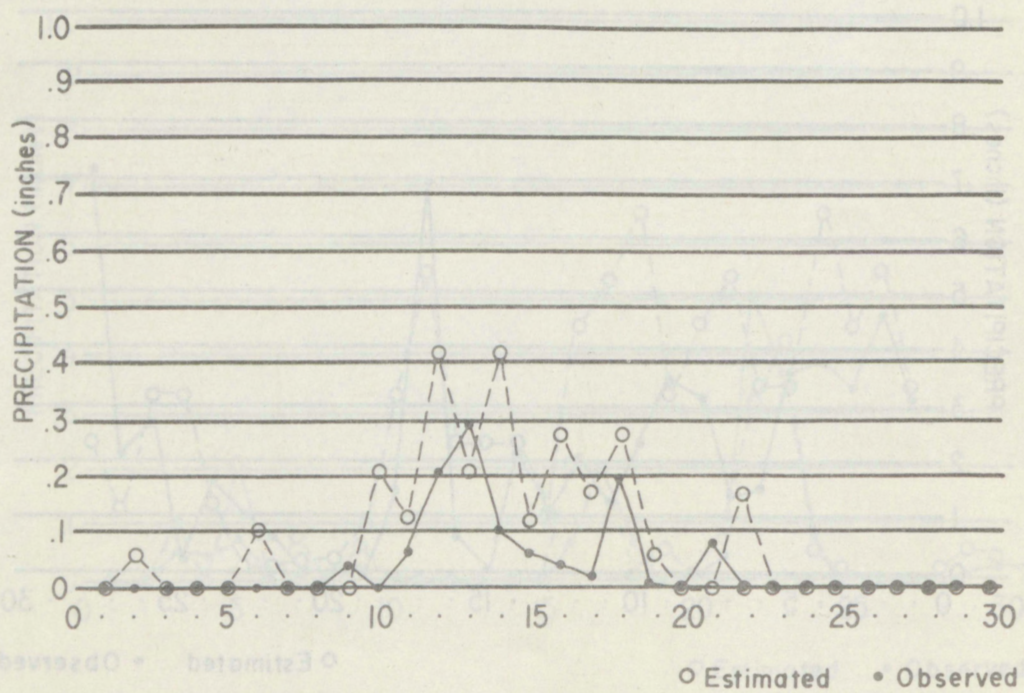

Figure 8d.--Average rainfall, Zambia, April 1970

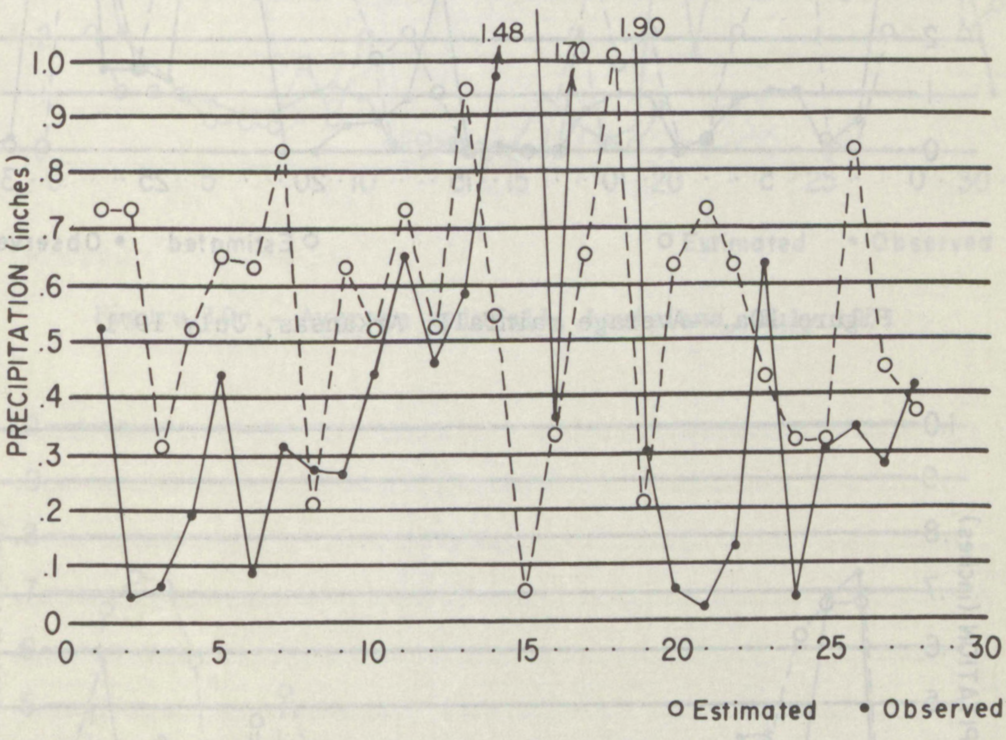

Figure 9.--Average rainfall Luangwa Valley, Zambia, February 1971

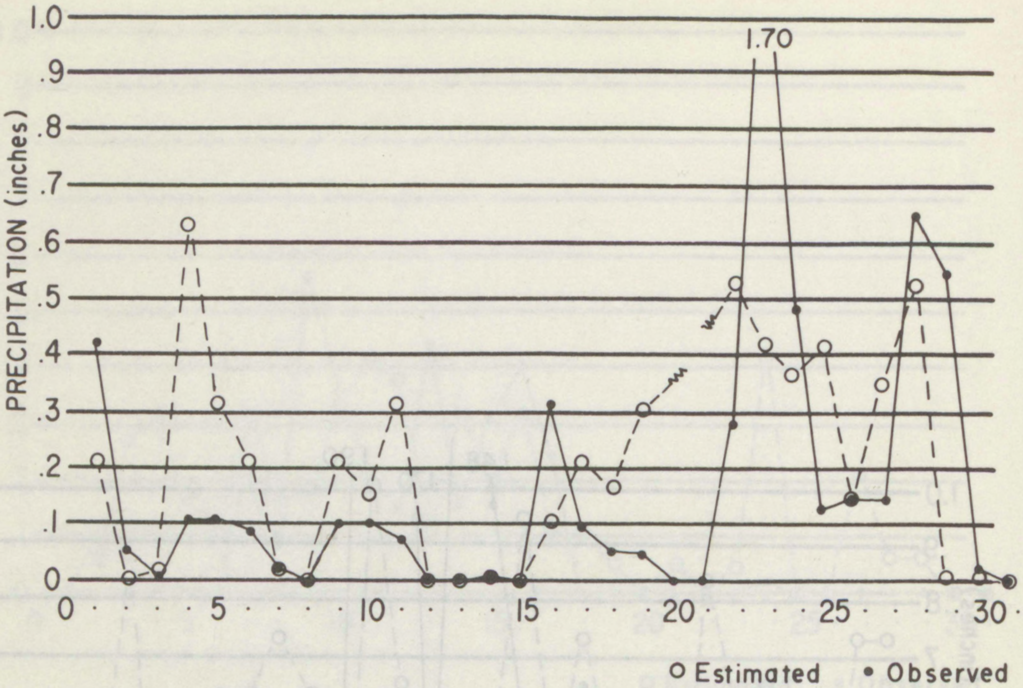

Figure 10a.--Average rainfall, Arkansas, July 1971

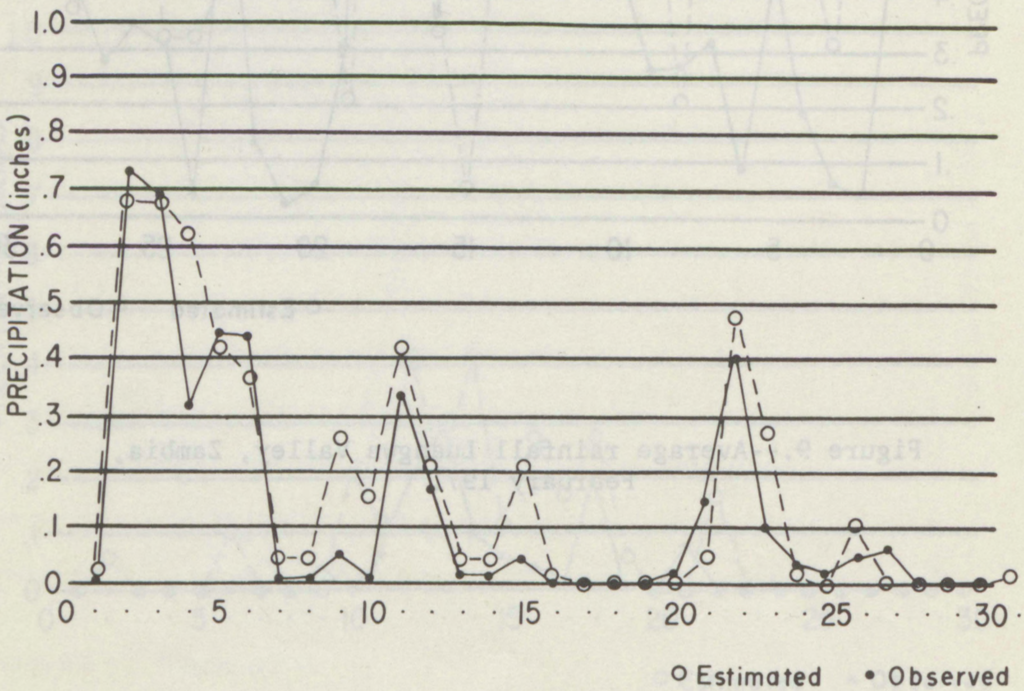

Figure 10b.--Average rainfall, Arkansas, August 1971

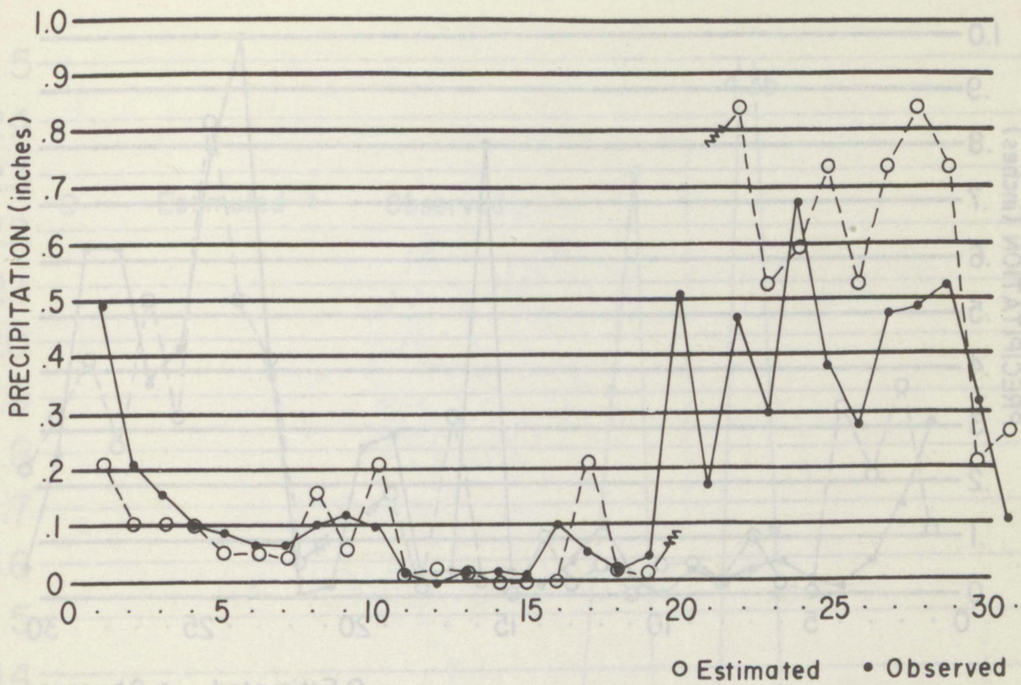

Figure 10c.--Average rainfall, Louisiana, July 1971

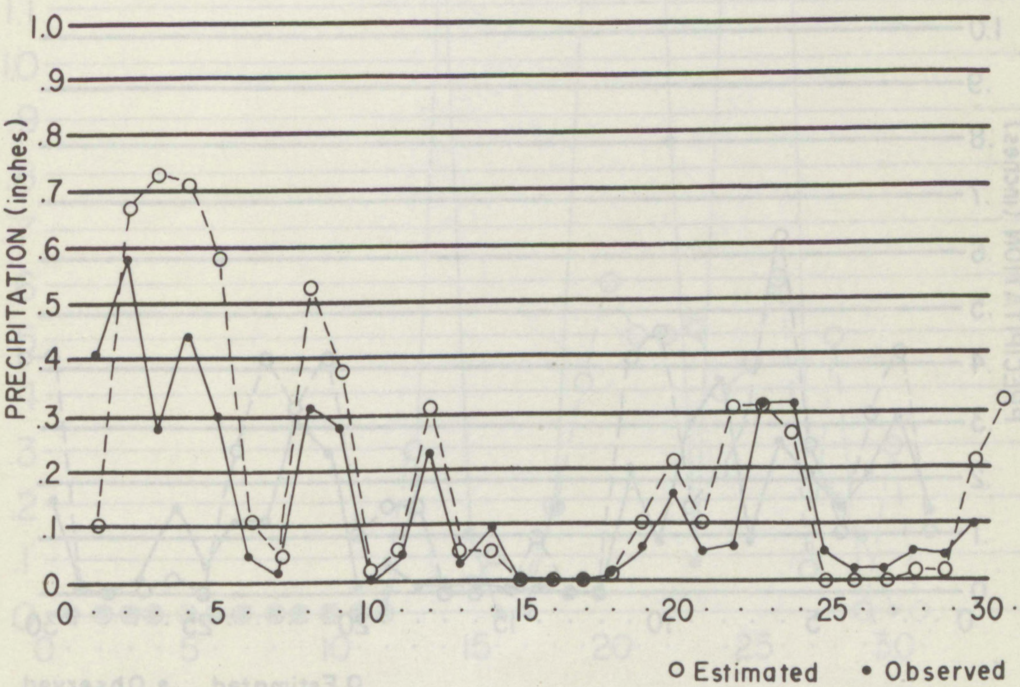

Figure 10d.--Average rainfall, Louisiana, August 1971

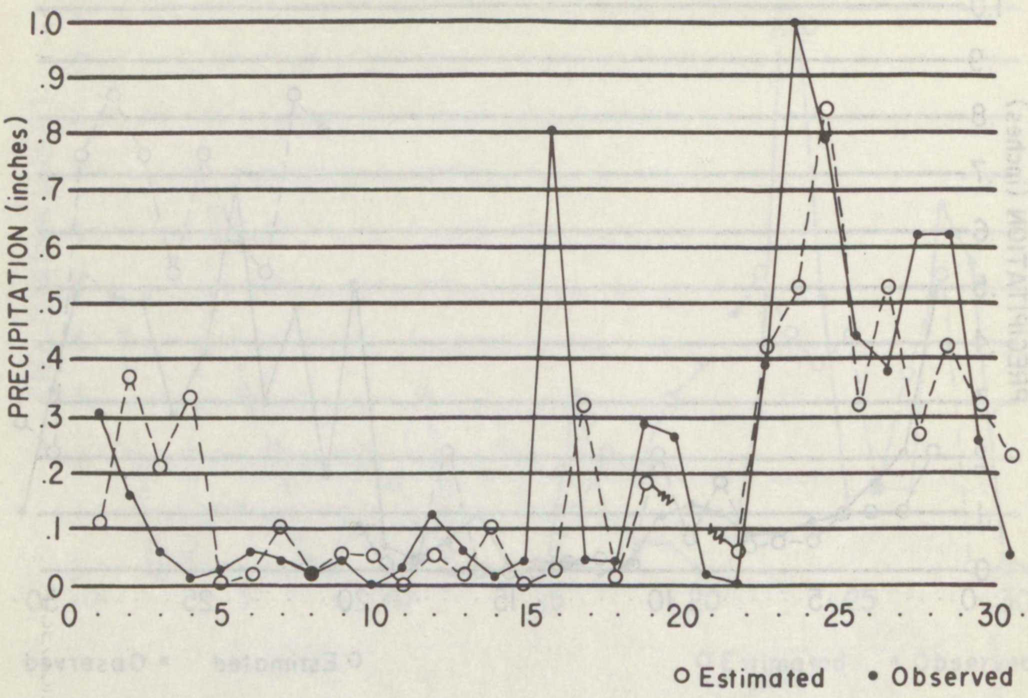

Figure 10e.--Average rainfall, Mississippi, July 1971

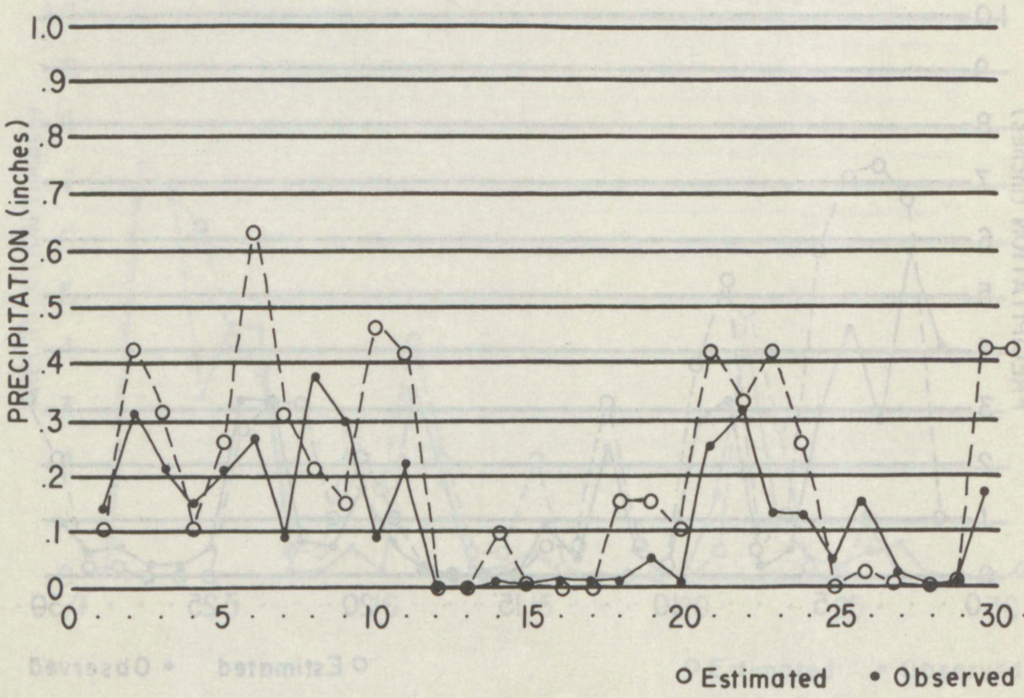

Figure 10f.--Average rainfall, Mississippi, August 1971

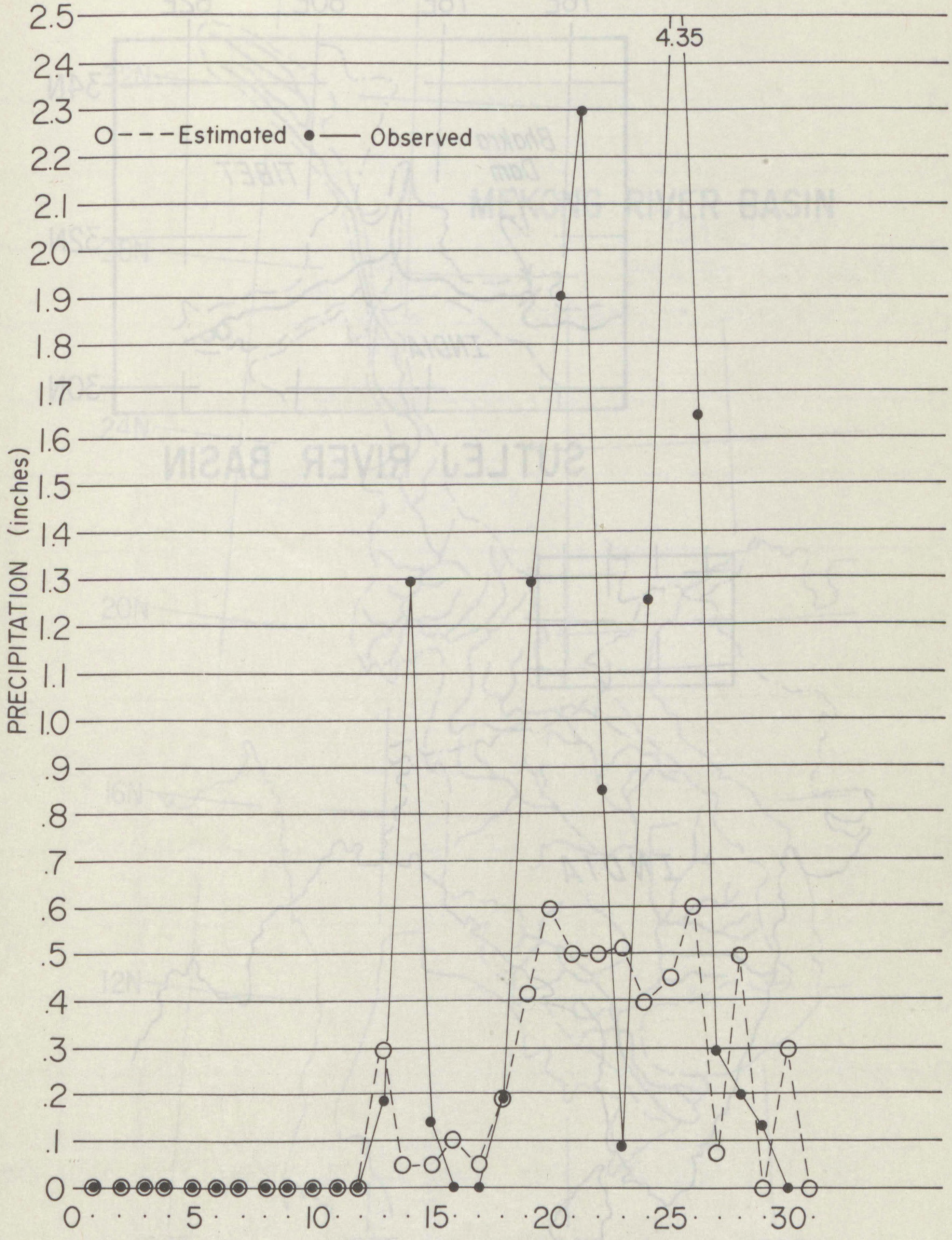

Figure 11.--Estimated vs observed average rainfall over the coastal drainage area of southern California for January 1969

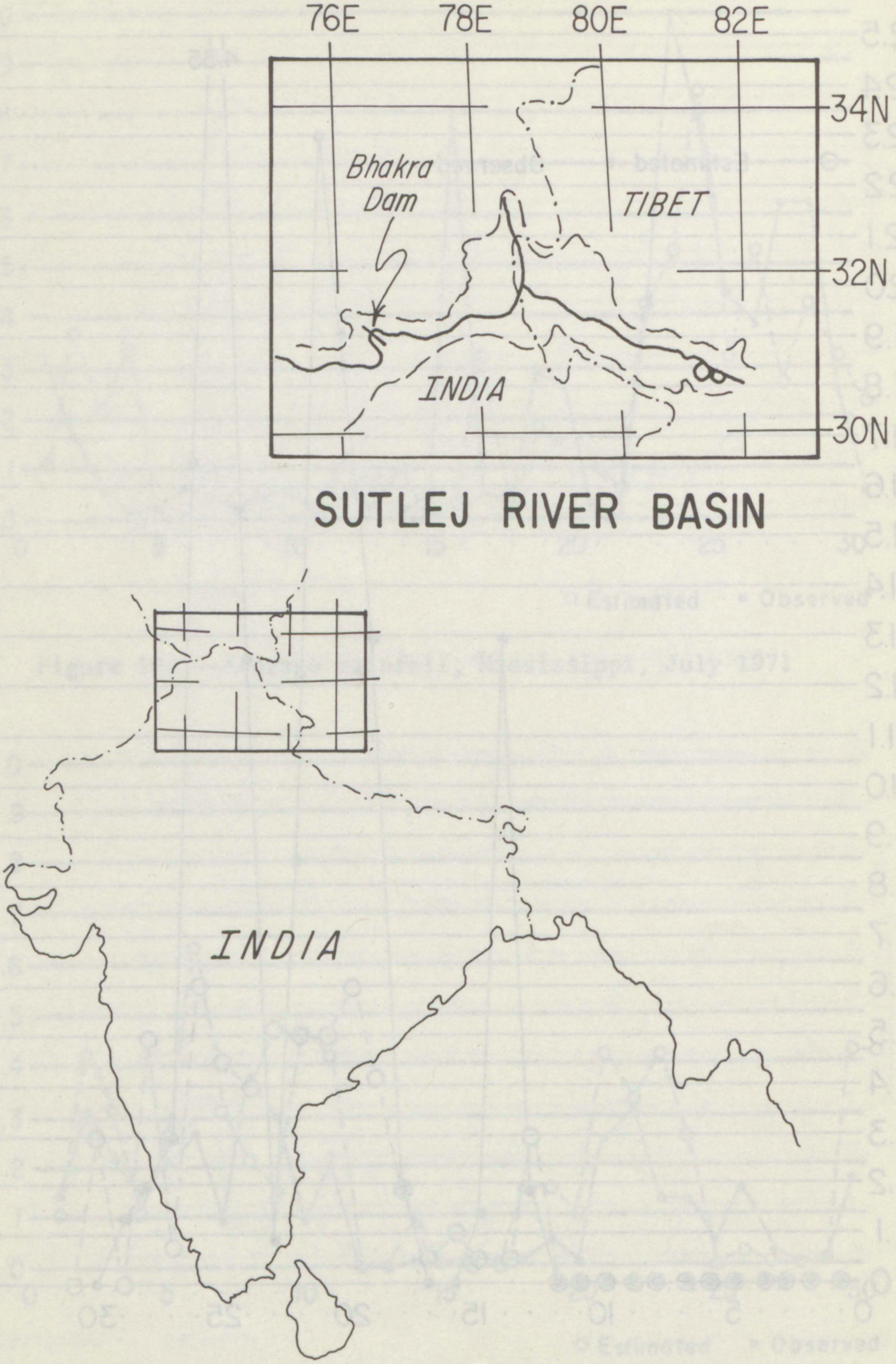

Figure 12.--Sutlej River Basin

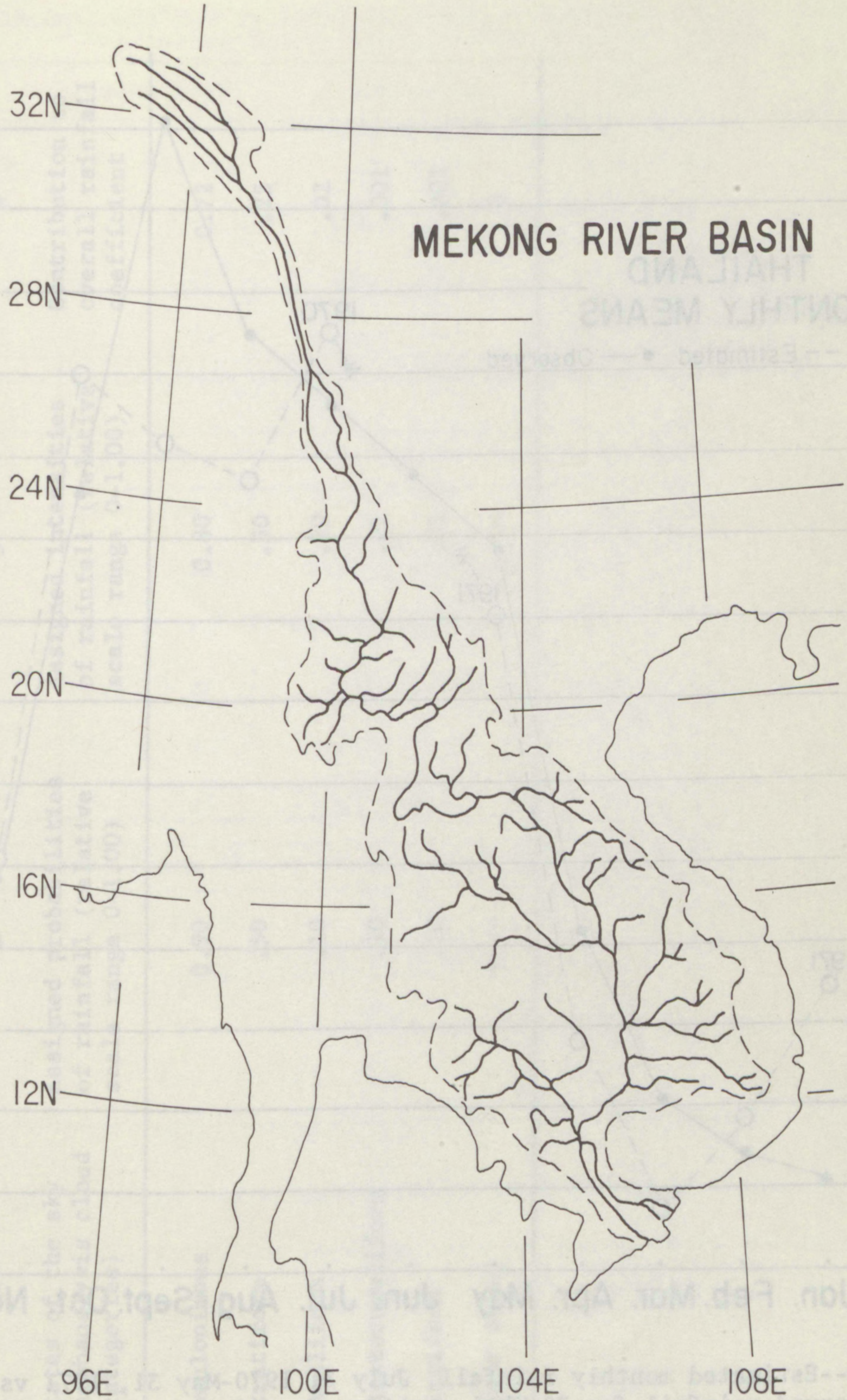

Figure 13.--Mekong River Basin

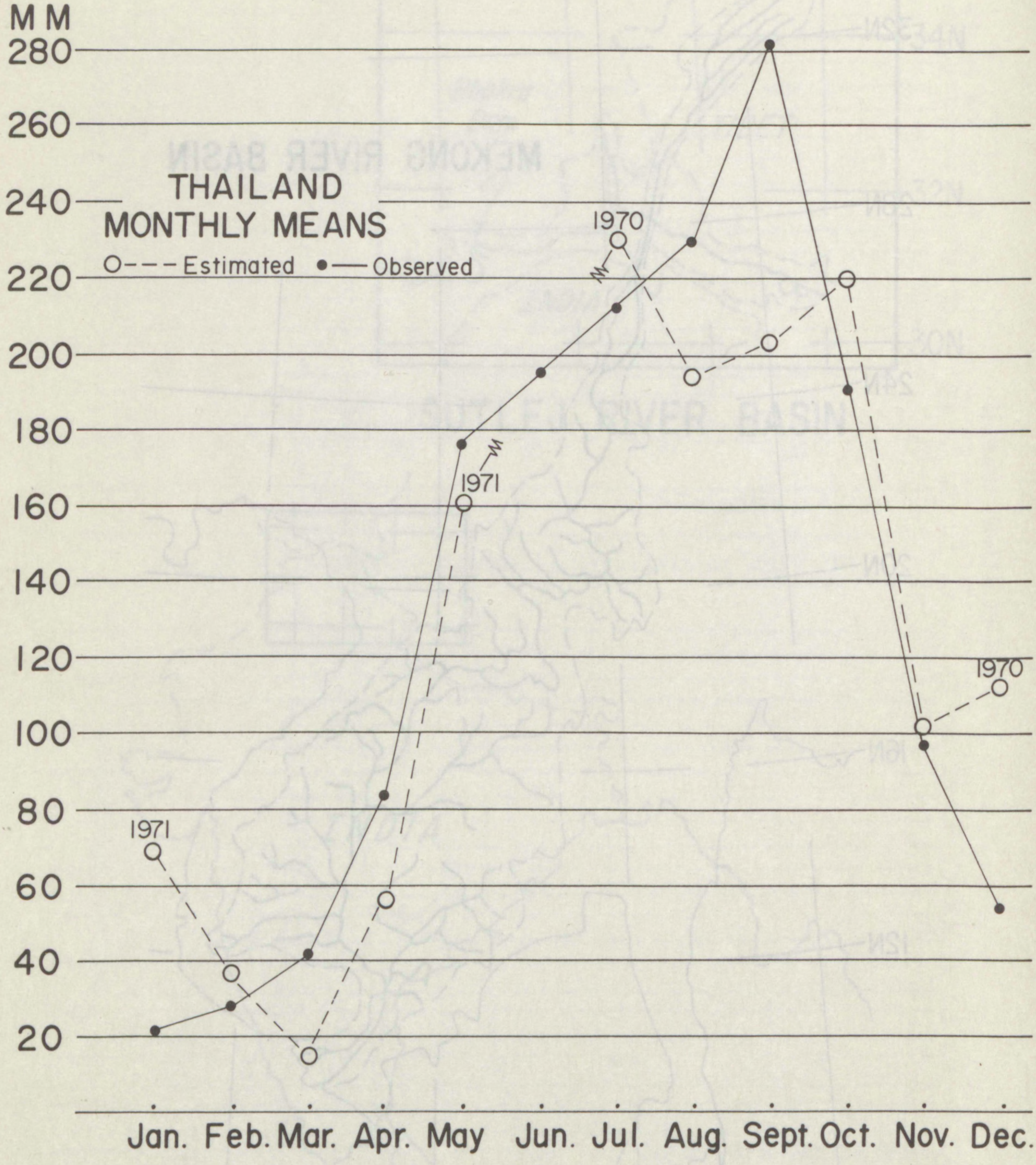

Figure 14.--Estimated monthly rainfall, July 3, 1970-May 31, 1971 vs monthly mean observed rainfall for 79 Thai stations for 30-year period, 1931-1960

Table 1.--Rainfall probabilities and intensities as related to states of the sky (After Barrett)

1	2	3	4
States of the sky (nephanalysis cloud categories)	Assigned probabilities of rainfall (relative scale range 0-1.00)	Assigned intensities of rainfall (relative scale range 0-1.00)	Contribution to overall rainfall coefficient
Cumulonimbus	0.90	0.80	0.72
Stratiform	.50	.50	.25
Cumuliform	.10	.20	.02
Stratocumuliform	.10	.01	.001
Cirriform	.10	.01	.001
Clear skies	----	----	0

Table 2.--K_c, the computed rainfall coefficient for cumulonimbus

	Arkansas		Louisiana		Mississippi		3 states	
	Cases	K_c*	Cases	K_c	Cases	K_c	Cases	K_c
July 1971	13	0.70	22	1.05	19	1.32	54	1.06
August 1971	15	.62	22	.95	23	.94	60	.86
July-August	28	.66	44	1.00	42	1.14	114	.96

Florida			Zambia		
	Cases	K_c		Cases	K_c
April 1967	6	0.80	January 1970	28	0.95
May 1967	11	1.32	February 1970	23	.87
April-May	17	1.13	March 1970	16	1.20
			April 1970	9	.49
			January-April	76	.92

Luangwa Valley			All areas studied	
	Cases	K_c	Cases	K_c
February 1971	28	1.82	246	1.04
March 1971	11	.51		
February-March	39	1.45		

* $K_c = \frac{\Sigma \frac{R_o}{A_c}}{N}$, where R_o is daily observed average areal rainfall, A_c is the fraction of the area covered by cumulonimbus, and N is number of cases.

Table 3.--Contingency table relating observed daily rainfall to estimated daily rainfall for all areas studied

Observed	Estimated: 0	.01-.10	.11-.20	.21-.30	.31-.50	.51-1.00	1.01-2.00	2.01-5.00	Total
0	114	45	9	3					171
.01-.10	30	54	22	20	11	7			144
.11-.20	1	10	9	10	16	4			50
.21-.30		4	6	7	12	9			38
.31-.50		1	4	5	21	18			49
.51-1.00	1	1	1	2	10	10			25
1.01-2.00		2			3	4			9
2.01-5.00					2				2
Total	146	117	51	47	75	52	0	0	488

Difference in class interval

			Cumulative
Zero	215	44%	
One	172	35	79%
Two	68	14	93
Three	22	5	98
Four	8	2-	99+
Five	3	1-	100
Total	488		

Table 4.--Categorical rain-no rain verification for all areas. Rain = $\geq$ .005 inch. No rain = $<$ .005 inch.

OBSERVED		ESTIMATED		
		Rain	No Rain	Total
	Rain	285 (a)	32 (b)	317 (a+b)
	No Rain	57 (c)	114 (d)	171 (c+d)
	Total	342 (a+c)	146 (b+d)	488 (a+b+c+d)

Total Estimates Correct = R = a + d = 285 + 114 = 399

Total Estimates = T = a + b + c + d = 285 + 32 + 57 + 146 = 488

$$\text{Expected No. Correct by Chance} = E = \frac{(a+b)(a+c) + (c+d)(b+d)}{a+b+c+d}$$

$$E = \frac{(317)(342) + (171)(146)}{488} = \frac{108414 + 24966}{488} = 273$$

$$\text{Percent Correct} = \frac{R}{T} \times 100 = \frac{399}{488} = 82\%$$

$$\text{Skill Score} = \frac{R-E}{T-E} = \frac{399-273}{488-273} = .59$$

$$\text{Threat Score} = \frac{a}{a+b+c} = \frac{285}{285+32+57} = .76$$

$$\text{Post Agreement} = \frac{a}{a+c} = \frac{285}{285+57} = .83$$

$$\text{Prefigurance} = \frac{a}{a+b} = \frac{285}{285+32} = .90$$

$$\text{Bias} = \frac{a+c}{a+b} = \frac{342}{317} = 1.08$$

$$\text{Percent Occurrence of Rain in Sample} = \frac{a+b}{a+b+c+d} \times 100 = 65\%$$

Table 5.--Estimated daily mean rainfall for ten-degree square in the Caribbean, May 15-June 15, 1971

1971	1 Woodley et al.	2 Follansbee ATS-3	3 Follansbee NOAA-1
	Rainfall estimates for 10° square, 10-20°N, 70-80°W		
May 15	0.33	0.18	0.10
16	.09	.12	.05
17	.34	.20	.07
18	.24	.27	.25
19	.04	.42	.15
20	.40	.37	.25
21	.52	.38	.25
22	.05	.13	.15
23	.10	.27	.28
24	.23	.40	.40
25	.26	.40	.42
26	.08	.38	.20
27	.04	.03	.15
28	.02	.15	.15
29	.02	.15	.12
30	.02	.20	.13
31	.11	.15	.15
June 1	.15	.12	.11
2	.27	.28	.20
3	.03	.08	.05
4	.58	.10	.08
5	.13	.06	.10
6	.14	.22	.05
7	.02	.27	.07
8	.11	.11	.10
9	.05	.11	.12
10	---	---	.06*
11	.04	.02	.08
12	.04	.20	.17
13	.33	.40	.46
14	.41	.35	.20
15	.42	.40	.38
TOTAL	5.61	6.92	5.44

* June 10 amount not included in total.

Column 1: Woodley, Sancho and Miller's bright spot enhancement technique - ATS-3 pictures.

Column 2: Follansbee's technique - ATS-3 pictures.

Column 3: Follansbee's technique - NOAA-1 pictures.

Table 6.--Rain estimates vs. mean daily recorded rain - second procedure for deriving weighting factors for heavy rainfall stations in India

	May	June	July	Aug.	Sept.	All
1. $\overline{C_a}$ Mean daily bright clouds (estimated for period 1967-70)	0.17	0.59	0.76	0.76	0.58	0.57
2. $F_a\overline{C_a}$ Rain estimate (F_a = .752)	.13	.44	.57	.57	.44	.43
3. $F_a\overline{C_a}$ Rain estimate (F_a = .654)	.11	.39	.50	.50	.38	.37
4. $F_a\overline{C_a}$ Rain estimate (F_a = .631)	.11	.37	.48	.48	.37	.36
5. $F_a\overline{C_a}$ Rain estimate (F_a = .616)	.10	.36	.47	.47	.36	.35
6. $F_a\overline{C_a}$ Rain estimate (F_a = .605)	.10	.36	.46	.46	.35	.35
7. $\overline{R_a}$ Mean daily recorded rain (for 47 Indian stations)	.16	.37	.49	.39	.28	.34

Table 7.--Derivation of three weighting factors for Cherrapunji

Cherrapunji (25°15'N, 91°44'E)	May	June	July	Aug.	Sept.
1. $\overline{R_m}$ (Mean monthly rainfall, station)	67.13	113.19	96.65	71.93	48.46
2. $\overline{R_s}$ (Mean daily rainfall, station)	2.17	3.77	3.12	2.32	1.62
3. $\overline{R_a}$ (Mean daily rainfall, area)	.16	.37	.49	.39	.28
4. $F_a\overline{C_s}$ (.605 x station mean cloudiness)	.23	.38	.38	.38	.30
5. $F_a\overline{C_a}$ (.605 x area mean cloudiness)	.10	.36	.46	.46	.35
6. $\overline{R_s}/\overline{R_a}$ (Weighting factor 1)	13.6	10.2	6.4	5.9	5.8
7. $\overline{R_s}/F_a\overline{C_a}$ (Weighting factor 2)	21.7	10.5	6.8	5.0	4.6
8. $\overline{R_s}/F_a\overline{C_s}$ (Weighting factor 3)	9.4	9.9	8.2	6.1	5.4
9. W_s (Suggested weighting factor)	13.0	10.0	7.5	6.0	5.5

Table 8.--Derivation of three weighting factors for Mangalore

Mangalore (12°52'N 74°51'E)	May	June	July	Aug.	Sept.
1. $\overline{R_m}$	9.17	38.58	41.68	22.72	10.98
2. $\overline{R_s}$	.30	1.29	1.34	.73	.37
3. $F_a\overline{C_s}$	.15	.38	.45	.30	.23
4. $\overline{R_s}/\overline{R_a}$	1.9	3.5	2.7	1.9	1.3
5. $\overline{R_s}/F_a\overline{C_a}$	3.0	3.6	2.9	1.6	1.1
6. $\overline{R_s}/F_a\overline{C_s}$	2.0	3.4	3.0	2.4	1.6
7. W_s	2.0	3.5	3.0	2.0	1.5

Table 9.--Derivation of weighting factors for Silchar

Silchar (24°49'N 92°48'E)	May	June	July	Aug.	Sept.
1. $\overline{R_m}$	19.41	23.39	21.54	19.21	14.88
2. $\overline{R_s}$	.63	.78	.69	.62	.50
3. $F_a\overline{C_s}$	.23	.30	.38	.38	.30
4. $\overline{R_s}/\overline{R_a}$	3.9	2.1	1.4	1.6	1.8
5. $\overline{R_s}/F_a\overline{C_a}$	6.3	2.2	1.5	1.5	1.4
6. $\overline{R_s}/F_a\overline{C_s}$	2.7	2.6	1.8	1.6	1.7
7. W_s	3.7	2.5	1.5	1.6	1.7

Table 10.--Derivation of weighting factors for Ft. Cochin

Ft. Cochin (9°58'N 76°14'E)	May	June	July	Aug.	Sept.
1. $\overline{R_m}$	14.33	29.76	22.52	15.20	9.25
2. $\overline{R_s}$	.46	.99	.73	.49	.31
3. $F_a\overline{C_s}$	.15	.30	.38	.30	.23
4. $\overline{R_s}/\overline{R_a}$	2.9	2.7	1.5	1.3	1.1
5. $\overline{R_s}/F_a\overline{C_a}$	4.6	2.7	1.6	1.1	.9
6. $\overline{R_s}/F_a\overline{C_s}$	3.1	3.3	1.9	1.6	1.3
7. W_s	3.3	3.0	1.7	1.5	1.2

Table 11.--Derivation of weighting factors for Darjeeling

Darjeeling (27°03'N 88°16'E)	May	June	July	Aug.	Sept.
1. $\overline{R_m}$	7.36	20.55	28.07	22.56	16.50
2. $\overline{R_s}$	.24	.68	.91	.73	.55
3. $F_a\overline{C_s}$	.15	.30	.38	.45	.38
4. $\overline{R_s}/\overline{R_a}$	1.5	1.8	1.9	1.9	2.0
5. $\overline{R_s}/F_a\overline{C_a}$	2.4	1.9	2.0	1.6	1.6
6. $\overline{R_s}/F_a\overline{C_s}$	1.6	2.3	2.4	1.6	1.4
7. W_s	1.7	2.0	2.2	1.7	1.6

Table 12.--Derivation of weighting factors for Dibrugarh

Dibrugarh (27°28'N 94°55'E)	May	June	July	Aug.	Sept.
1. $\overline{R_m}$	15.53	18.70	21.04	15.39	12.83
2. $\overline{R_s}$	.50	.62	.68	.50	.43
3. $F_a\overline{C_s}$	.23	.30	.38	.30	.30
4. $\overline{R_s}/\overline{R_a}$	3.1	1.7	1.4	1.3	1.5
5. $\overline{R_s}/F_a\overline{C_a}$	5.0	1.7	1.5	1.1	1.2
6. $\overline{R_s}/F_a\overline{C_s}$	2.2	2.1	1.8	1.7	1.4
7. W_s	3.0	2.0	1.6	1.5	1.4

Table 13.--Derivation of weighting factors for Bombay (Santa Cruz station)

Bombay (Santa Cruz) (19°07'N 72°51'E)	May	June	July	Aug.	Sept.
1. $\overline{R_m}$	0.78	25.49	37.22	26.00	12.18
2. $\overline{R_s}$	.03	.85	1.20	.84	.41
3. $F_a\overline{C_s}$	.08	.30	.45	.45	.38
4. $\overline{R_s}/\overline{R_a}$	0.2	2.3	2.4	2.2	1.5
5. $\overline{R_s}/F_a\overline{C_a}$	0.3	2.4	2.6	1.8	1.2
6. $\overline{R_s}/F_a\overline{C_s}$	0.4	2.8	2.7	1.9	1.4
7. W_s	None	2.5	2.5	2.0	1.4

Table 14.--Derivation of weighting factors for Dhubri

Dhubri (26°01'N 89°59'E)	May	June	July	Aug.	Sept.
1. $\overline{R_m}$	18.94	25.35	17.64	12.01	12.91
2. $\overline{R_s}$	.61	.84	.57	.39	.43
3. $F_a\overline{C_s}$	.15	.38	.38	.38	.38
4. $\overline{R_s}/\overline{R_a}$	3.8	2.3	1.2	1.0	1.5
5. $\overline{R_s}/F_a\overline{C_a}$	6.1	2.3	1.2	0.8	1.2
6. $\overline{R_s}/F_a\overline{C_s}$	4.1	2.2	1.5	1.0	1.1
7. W_s	4.3	2.3	1.4	None	1.2

Table 15.--Trial apportionment of average daily cloudiness for Indian Southwest Monsoon among rain-producing types

Cumulonimbus	Nimbostratus	Cumulus congestus	Factor (Fa)
70%	20%	10%	.752
60	20	20	.654
60	10	30	.631
55	25	20	.616
55	20	25	.605

(Continued from inside front cover)

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