NOAA Technical Memorandum NESDIS 5

A TROPICAL CYCLONE PRECIPITATION ESTIMATION TECHNIQUE USING GEOSTATIONARY SATELLITE DATA

Satellite Applications Laboratory
Washington, D.C.
July 1984

U.S. DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration / National Environmental Satellite, Data, and Information Service

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LeRoy E. Spayd, Jr.
Roderick A. Scofield

Guidelines for using the Tropical Cyclone Precipitation Estimation Technique

I. Computing the Rainfall Potential

1. Generally use the underlined rainfall amount. If the tropical cyclone is weakening and you expect it will continue weakening before, during, and after landfall then use lower amounts. For strengthening cyclones use higher amounts.

2. In a small, compact tropical cyclone it may be difficult to distinguish the wall cloud from the active area of the CDO. In this case just draw one isoline and use the following rainfall amounts.

0.75" - 1.50" - 2.50"

3. The active precipitating area of the CDO usually does not extend to the tight IR temperature gradient along the outer cirrus edge. If you cannot determine the active area from the visible imagery, draw the CDO isoline about 1/2 to 2/3's the way out from the eye.

4. Computing the speed of the cyclone.

- Always use 3 or 6 hourly interval imagery. Do not use hourly interval imagery as small scale loops of the eye may yield a wrong speed.

- Do not use a speed lower than 5 knots (1/12° lat/hour) or the rainfall potential equation yields results too high.

II. Computing Rainfall Estimates

1. As a rule of thumb analysts generally overestimate the rainfall in the offshore flow portions of the CDO; reduce the estimates in the offshore flow by using values less than the underlined amounts.

2. Once the tropical cyclone is inland beware of relatively dry air over the land which could reduce the precipitation efficiences on the offshore side of the cyclone.

3. If possible, monitor the radar data to determine which portions of the CDO and outer banding area are active VIP 3 or higher.

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UNITED STATES DEPARTMENT OF COMMERCE
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National Environmental Satellite, Data, and Information Service
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ABSTRACT. This memorandum presents a technique for estimating precipitation from tropical cyclones using visible and infrared geostationary satellite data. The technique assigns rainfall rates to tropical cyclone cloud features, yields a rainfall potential of the cyclone prior to landfall and hourly rainfall estimates during landfall. These estimates are compared with ground-truth precipitation reports and operationally produced rainfall estimates using the Scofield/Oliver convective technique for hurricanes Greta (1978), Frederic (1979) and Allen (1980). Initial results indicate that this technique is an improvement over the convective technique for tropical cyclones and produces an acceptable predicted maximum rainfall while the cyclone is still over the open waters.

I. INTRODUCTION

Scofield and Oliver (1977, 1980) developed a technique for estimating precipitation from flash flood producing convective systems. The Scofield/Oliver technique is a manual procedure using half-hourly visible and enhanced infrared (IR) GOES images. The Synoptic Analysis Branch of the National Environmental Satellite, Data, and Information Service (NESDIS) has been using the Scofield/Oliver technique operationally since 1978. The rainfall estimates are sent on a half-hourly basis to the appropriate National Weather Service Forecast Office (WSFO) for use in monitoring heavy rainfall situations and in issuing flash flood warnings.

Since 1978, the Scofield/Oliver convective technique has been used operationally on hurricanes and tropical cyclones. The current technique is reproduced in Appendix B. It has proven to be most accurate for tropical cyclones with cold, expanding convective tops. The convective technique is least accurate in estimating rainfall from warm-top rainbands and distributing the rainfall within the Central Dense Overcast area.

Other scientists have studied hurricanes and tropical cyclones and their associated rainfall. Schoner and Molansky (1956) compiled data on rainfall associated with hurricanes and tropical cyclones. Schoner (1968) studied rainfall characteristics and produced generalized isohyetal patterns for East Coast and Gulf Coast hurricanes after landfall. Oliver (through personal communications) showed where in the geostationary satellite imagery to expect various intensities of hurricane rainfall. Waters et al. (1977) and Griffith et al. (1978) developed automatic methods of estimating rainfall from tropical cyclones based on cloud top temperatures. Griffith's technique is being used operationally by the National Hurricane Center as an aid in predicting rainfall amounts accompanying tropical cyclone landfall.

Dvorak (1975) developed a satellite-observed hurricane and tropical cyclone classification scheme. Dvorak related how the satellite-observed hurricane and tropical cyclone cloud signatures change with time as compared to surface pressure and wind speed.

This tropical cyclone precipitation estimation technique uses terminology, concepts, and results from these above mentioned scientists. Precipitation cannot be directly measured from the GOES visible and IR data; it must be inferred. A satellite meteorologist must identify various cloud signatures and features in the visible and enhanced IR data, and observe how these signatures and features change with time in order to infer a rainfall rate.

II. THE TROPICAL CYCLONE PRECIPITATION ESTIMATION TECHNIQUE

This technique was developed for estimating hourly precipitation amounts using enhanced IR and visible data; it is presented in its entirety in Appendix A. The IR enhancement Mb curve is used in the following images and temperature range of each gray shade is indicated in Figure 1. The tropical cyclone technique is now presented in a decision tree format.

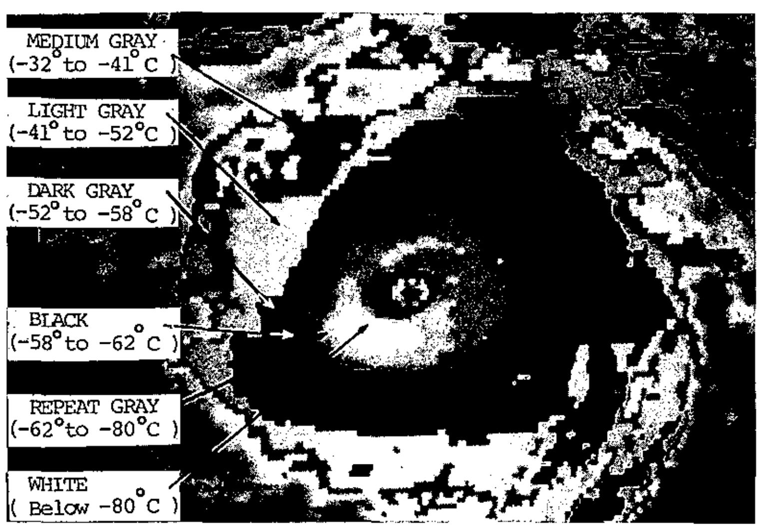

Figure 1. *Enhanced IR image of hurricane Allen at 1630 GMT, August 7, 1980. The temperatures of the Mb enhancement curve are annotated.*

Step 1. Identify the presence of a tropical cyclone. (Figure 2)

Examine the shapes and types of clouds in the visible and IR satellite imagery to determine if a tropical cyclone is present. If present, go to Step 2a; if not, stop. A tropical cyclone normally has a sharply defined comma configuration with cyclonically spiraling cloud bands encircling the eye or cloud system center. An anticyclonic outflow of cirrus may be seen at the periphery of the cyclone.

Step 2a. Identify and locate the satellite observed cloud features in the tropical cyclone. (Figures 3 and 4)

When a curved convective cloud band encircles a relatively cloud-free area, the "eye" pattern is defined as the cloud system's center. The eye appears as a relative warm spot in the infrared imagery. If an eye is not present, the cloud system center is located near the counter-clockwise extremity of the comma shaped cloud pattern that can be seen in most organized tropical cyclones (Dvorak, 1982). The Wall Cloud (WC) encircles the eye; the average radius of the wall cloud is approximately 20 n.mi. The heaviest rainfall occurs in the wall cloud and is often associated with very cold temperatures in the IR and very bright areas in the VIS. The Central Dense Overcast (CDO) area is the dense overcast mass which encircles the wall cloud. The Outer Banding Area (OBA) may consist of several convective cloud bands extending several hundred miles outward from the eye. These bands are often seen curving evenly around the CDO separated by relatively cloud-free areas. Part of the OBA may be masked by an anticyclonic outflow of cirrus clouds from the CDO. Areas of embedded cold convective cloud tops (ECT) can be seen in the OBA.

Step 2b. Compare two consecutive hourly images and draw isolines around the cloud features on the second image. (Figures 5 and 6)

Both visible and enhanced IR data should be used to draw the isolines. Within each cloud feature, the coldest and brightest areas should be analyzed. Areas of rapid growth or expansion and areas of rapid decrease or warming should also be analyzed.

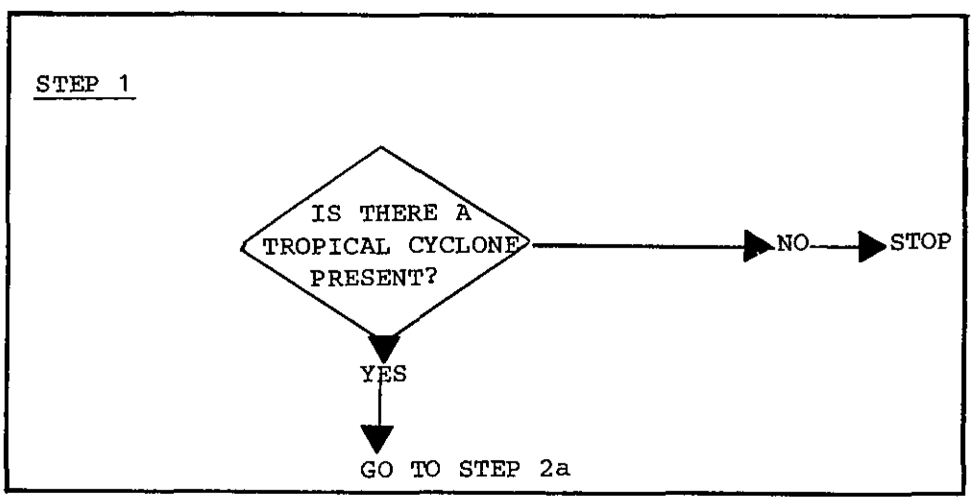

Figure 2. *Step 1 of the technique.*

STEP 2a

Identify and locate the following cloud features in the tropical cyclone:

- o Eye (or cloud system center)
- o Wall cloud (20 n miles either side of the eye or the cloud system center)
- o Central Dense Overcast (CDO) area
- o Outer Banding Area (OBA)
- o Area of embedded cold convective cloud tops (ECT) in the OBA area

GO TO STEP 2b

Figure 3. *Step 2a of the technique.*

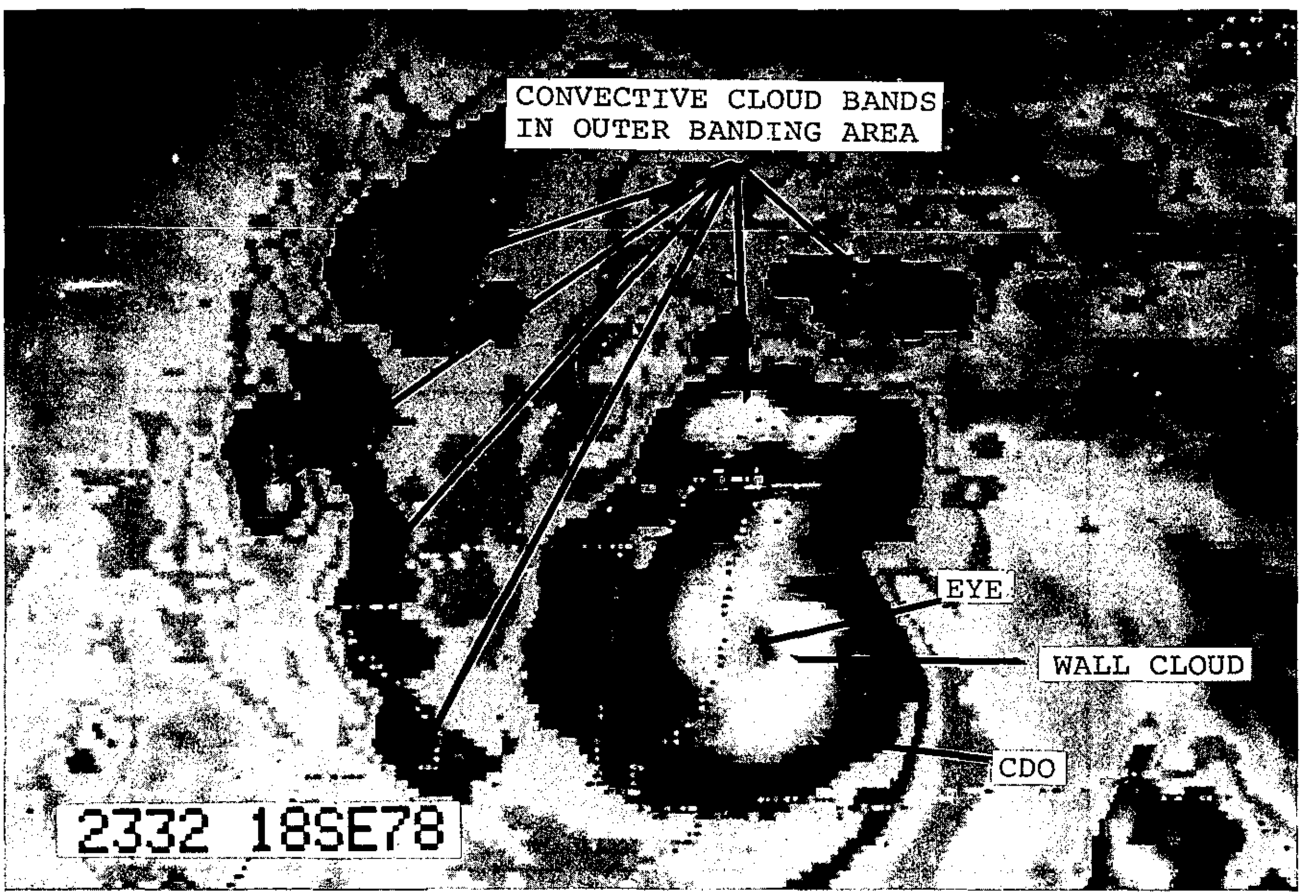

Figure 4. *Enhanced IR image (Mb curve) of hurricane Greta at 2330 GMT, September 18, 1978. The cloud features of a tropical cyclone are annotated.*

In small, compact tropical cyclones it may be difficult to distinguish the wall cloud from the active area of the CDO. In these cases only one isoline should be drawn to include both features.

STEP 2b

From comparing two consecutive pictures, draw isolines in the second picture around the following:

- o Wall cloud (approximately 20 n miles either side of the eye or the cloud system center).
- o A 50 n mile radius either side of the cloud system center within the CDO; heavy rain often occurs within this radius. Use IR and VIS to help modify the size and location of the isoline. Within this isoline, coldest and brightest areas should also be analyzed; these areas often locate the heaviest rainfall within the CDO.
- o Bands in the OBA that are convective.
- o Within the OBA, areas of embedded cold convective cloud tops in the convective cloud bands.

↓

GO TO STEP 3

Figure 5. *Step 2b of the technique.*

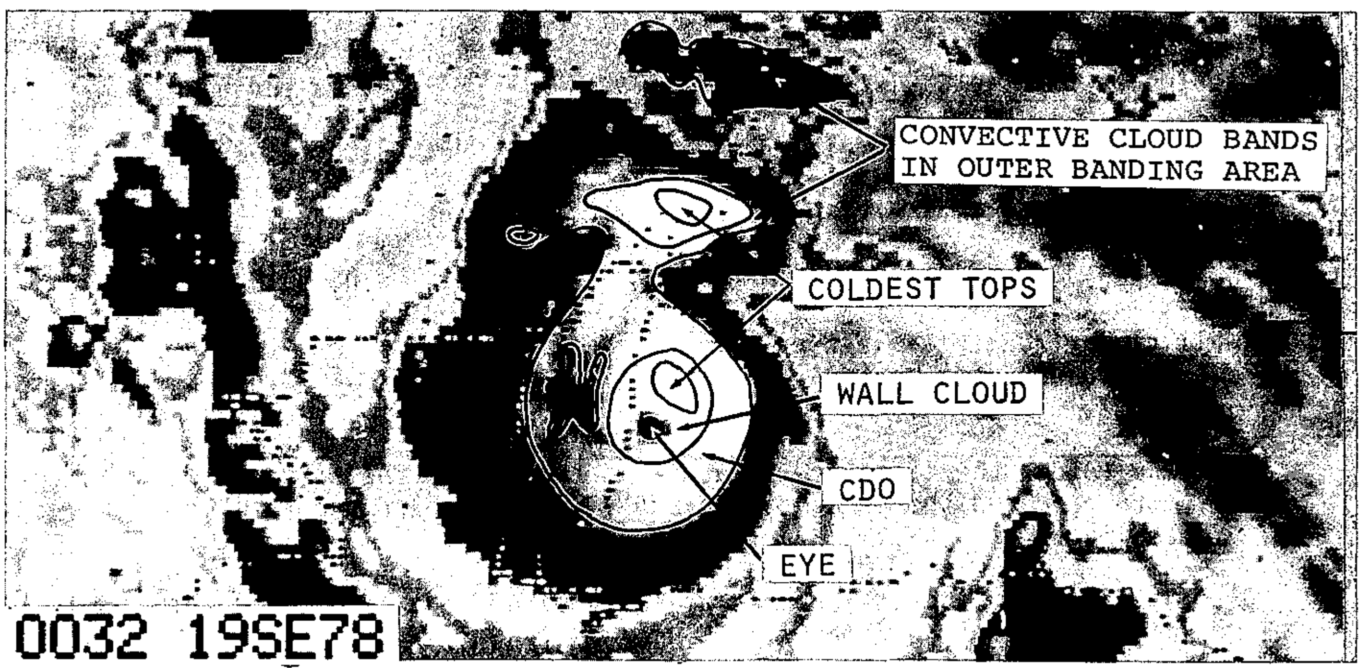

Figure 6. *Enhanced IR image (Mb curve) of hurricane Greta at 0030 GMT, September 19, 1978. Isolines are drawn around the tropical cyclone's cloud features.*

Step 3. Compute rainfall estimates for the isolines drawn in Step 2b. (Figures 7 and 8)

Rainfall estimates are assigned to the isolines drawn based on the cloud features analyzed in the satellite pictures. The underlined rainfall estimate (Figure 7) is normally the value used in the computation. Features growing in size or becoming colder should be assigned the higher rainfall rates. Cloud tops diminishing in size or becoming warmer should be assigned the lower rainfall rates. The rainfall estimates should be adjusted to account for upslope, downslope, onshore, and offshore flow. Cloud features located in areas of onshore flow with an upslope component should be assigned the higher rainfall rates; while cloud features associated with offshore flow and a downslope component should be assigned the lower rainfall rates.

In the OBA, the first rainband from the CDO located in the onshore flow has been observed to produce more rainfall than the other rainbands (Figure 8).

Therefore, higher rainfall rates are assigned to this first rainband; these rainbands can possess warm tops. The values of the estimates for the area of cold convective tops embedded in the OBA are obtained from the Scofield/Oliver convective technique. Rapidly growing, very cold convective tops can be assigned up to 4.0 inches per hour. Tops decreasing in area or becoming warmer would be assigned lower rainfall estimates. The warm-top modification to the convective technique may be necessary for warm-top rainbands (Scofield et al., 1980, and Scofield, 1981). The warm-top modification procedure is presented in Appendix C.

STEP 3

From comparing two consecutive pictures, compute rainfall estimates for the isolines drawn above; the underlined rainfall accumulation is normally the value used in the estimate.

Estimates for the CDO Area and Wall Cloud	Rainfall Accumulations [1] (inches per hour)
CDO (a 50 n mile radius either side of the cloud system center; this radius can be modified by the IR and VIS.)	[3] 0.50-1.00-2.00 [2]
Outer edge of the CDO.	0.01-0.05-0.10
Wall cloud (20 n miles either side of the eye or cloud system center)	[3] 1.00-2.00-3.00

1. The colder the canopy temperature in the IR and the brighter and more textured the canopy is in the VIS, the higher the rainfall estimate.

2. Colder and brighter features analyzed within the CDO should be given higher rainfall estimates.

3. Cloud tops that are becoming warmer should have lower rainfall estimates.

Figure 7. *Step 3 of the technique.*

STEP 3 (Continued)

Estimates for the OBA	Rainfall Accumulations[1] (inches per hour)
Outer Banding Area	0.10-0.30-0.50
The first band from the CDO located in the onshore flow.[2]	0.50-1.00-2.00
Area of cold convective cloud tops embedded in the convective cloud bands. [3]	
Growing, becoming colder, or remaining the same. [4]	0.25-1.00-4.00 [5]
Decreasing in area. [4]	0.10-0.50-1.00
Becoming warmer. [4]	0.05-0.20-0.50

1. The colder the canopy temperature in the IR and and the brighter and more textured the canopy is in the VIS, the higher the rainfall estimate.

2. Only considered when the OBA is moving onshore.

3. These estimates are obtained from the convective technique for estimating rainfall from convective systems.

4. These categories are determined from the changes observed in the thunderstorm anvil in two consecutive pictures.

5. The more rapid the convective cloud tops grow and/or become colder, the higher the estimate.

GO TO STEP 4

Figure 8. *Step 3 of the technique continued.*

Step 4. Compute the rainfall potential of the cyclone before landfall. (Figure 9)

After the hourly rainfall rates have been computed, the rainfall potential of the tropical cyclone can be calculated while the cyclone is still over the open waters. The diameter of the rainfall rates along the direction of motion can be measured on the satellite imagery. The actual speed of the tropical cyclone's center can be measured using consecutive satellite images. The speed of the cyclone's center is usually most accurately measured using imagery 3 or 6 hours apart.

STEP 4

Compute the Rainfall Potential along the tropical cyclone track before landfall.

Rainfall Potential =

$$\frac{R_{CDO} D_{CDO} + R_{WC} D_{WC}}{V} + \frac{R_{OBA} D_{OBA} + R_{ECT} D_{ECT}}{V}$$

Where,

R_{CDO}, R_{WC}, R_{OBA}, and R_{ECT}: Rainfall rates (R) of the CDO, wall cloud (WC) area, significant bands in the OBA, and embedded cold convective tops (ECT), respectively

D_{CDO}, D_{WC}, D_{OBA}, and D_{ECT}: Diameter (D) of the rainfall rates in the direction of motion

V: Speed of the tropical cyclone

Figure 9. *Step 4 of the technique.*

This rainfall potential could be computed for any number of projected points passing through the tropical cyclone. The analyst usually selects several projected points passing through the wall cloud and CDO of the cyclone along the direction of motion of the cyclone's center. As the points are passing through the cyclone, the analyst measures the diameter of the rainfall rates of the cloud features. The rainfall rates and diameter of the rainfall rates are entered into the rainfall potential equation in figure 9. Since embedded convective tops have life cycles on the order of a few hours, the analyst must determine the fractional coverage of the embedded cold tops within the convective cloud band. This fraction is multiplied by the diameter of the rainfall rates of the convective cloud band (D_{OBA}) to obtain the average diameter of the embedded cold tops (D_{ECT}). For example, if embedded cold tops are present in 50% of the convective cloud band, the term (D_{ECT}) would be one half of (D_{OBA}). To compute the average rainfall rate of the embedded cold tops (R_{ECT}), a rainfall rate must be used that is representative of the convective cloud band or portions of the convective cloud band. The rainfall potential of the cyclone could be adjusted up or down if the meteorologist can anticipate any future trends in the cyclone's speed or in the diameter and rainfall rates of the cloud features.

III. CASE STUDY, HURRICANE GRETA

On September 17-19, 1978, hurricane Greta travelled on a west-northwesterly path along the northern coast of Honduras. The eye of the storm came onshore just south of Belize City, Belize, at 0130 GMT on September 19. Figure 10 shows Greta at 0830 GMT on September 18, 16 hours before landfall of the eye and 5 hours before Greta's rainbands came onshore in Belize.

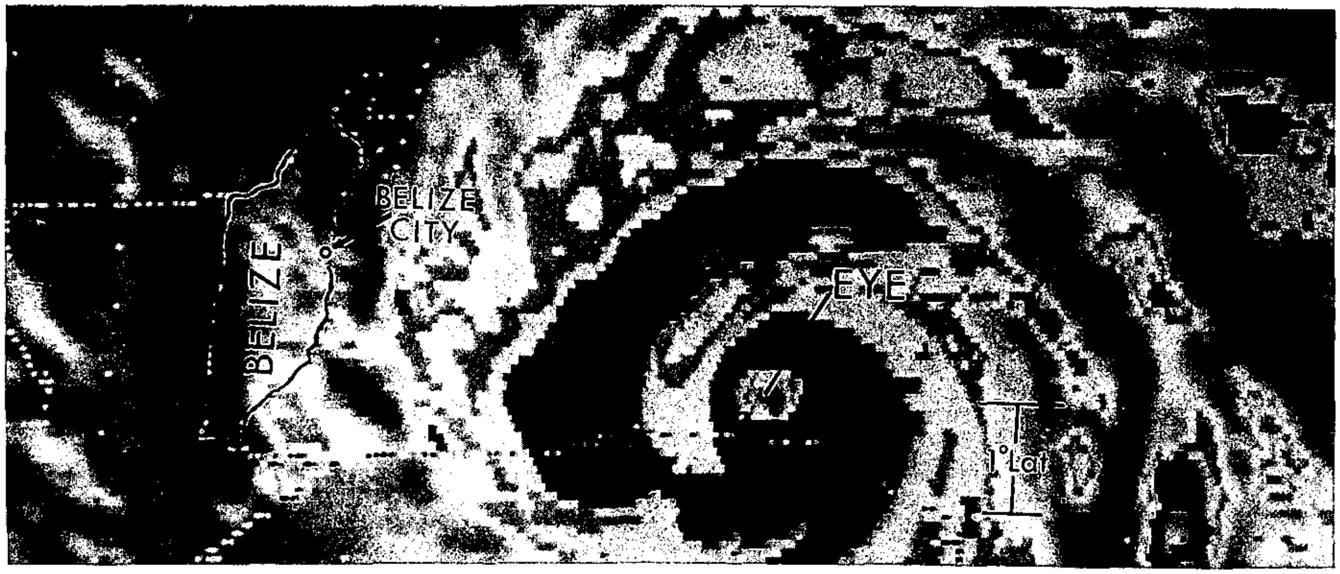

Figure 10. *Enhanced IR image (Mb curve) of hurricane Greta at 0830 GMT, September 18, 1978. The eye of the hurricane and Belize City, Belize, are annotated.*

Figure 11. *Enhanced IR image (Mb curve) of hurricane Greta at 0730 GMT September 18, 1978.*

By comparing the previous 0730 GMT image (Figure 11) to the 0830 GMT image, hourly rainfall rates (R) were computed (Figure 12). The cross-section of the cloud signatures (D) in the direction of motion and the speed of the eye (V) were also measured. The rainfall potential of Greta was calculated to be 12.4 inches at 0830 GMT.

Figures 13a and 13b show a sequence of IR images as Greta made landfall just south of Belize City. Rainfall estimates were computed hourly from 1430 GMT to 0330 GMT and summed to produce a total cyclone rainfall estimate. Note that at 0330 GMT, Greta was still affecting Belize. However, the geostationary satellite entered the eclipse mode and images were not taken again until 0600 GMT. By 0600 GMT Greta had rapidly weakened and moved west of Belize.

RAINFALL POTENTIAL OF HURRICANE GRETA AT 0830 GMT, SEPTEMBER 18, 1978

	R (inches/hour)	D (degrees latitude)
CDO	1.0	0.45
WC	2.0	0.75
OBA	1.0	0.80
ECT (30% Coverage)	1.5	0.24

$V = 0.25°$ latitude/hour (15 knots)

$$\frac{R_{CDO}\, D_{CDO} + R_{WC}\, D_{WC}}{V} + \frac{R_{OBA}\, D_{OBA} + R_{ECT}\, D_{ECT}}{V} = 12.4 \text{ inches}$$

Figure 12. *A calculation of the rainfall potential in inches of hurricane Greta at 0830 GMT, September 18, 1978.*

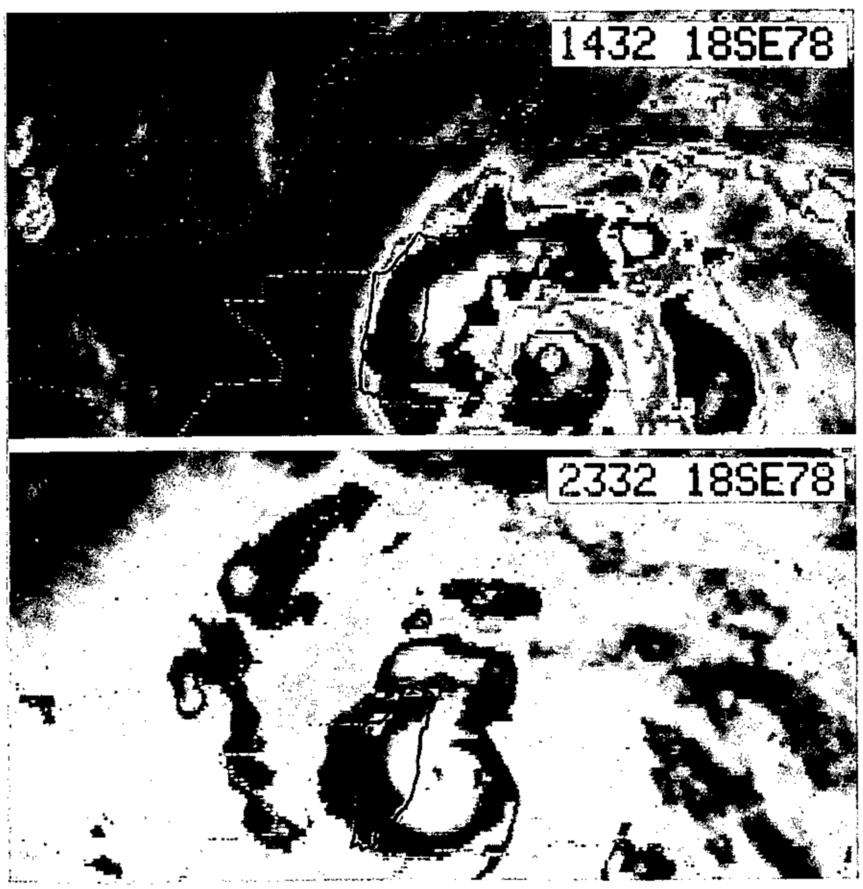

Figure 13a. *Enhanced IR images (Mb curve) of hurricane Greta at 1430 GMT and 2330 GMT, on September 18, 1978 with the nation of Belize outlined.*

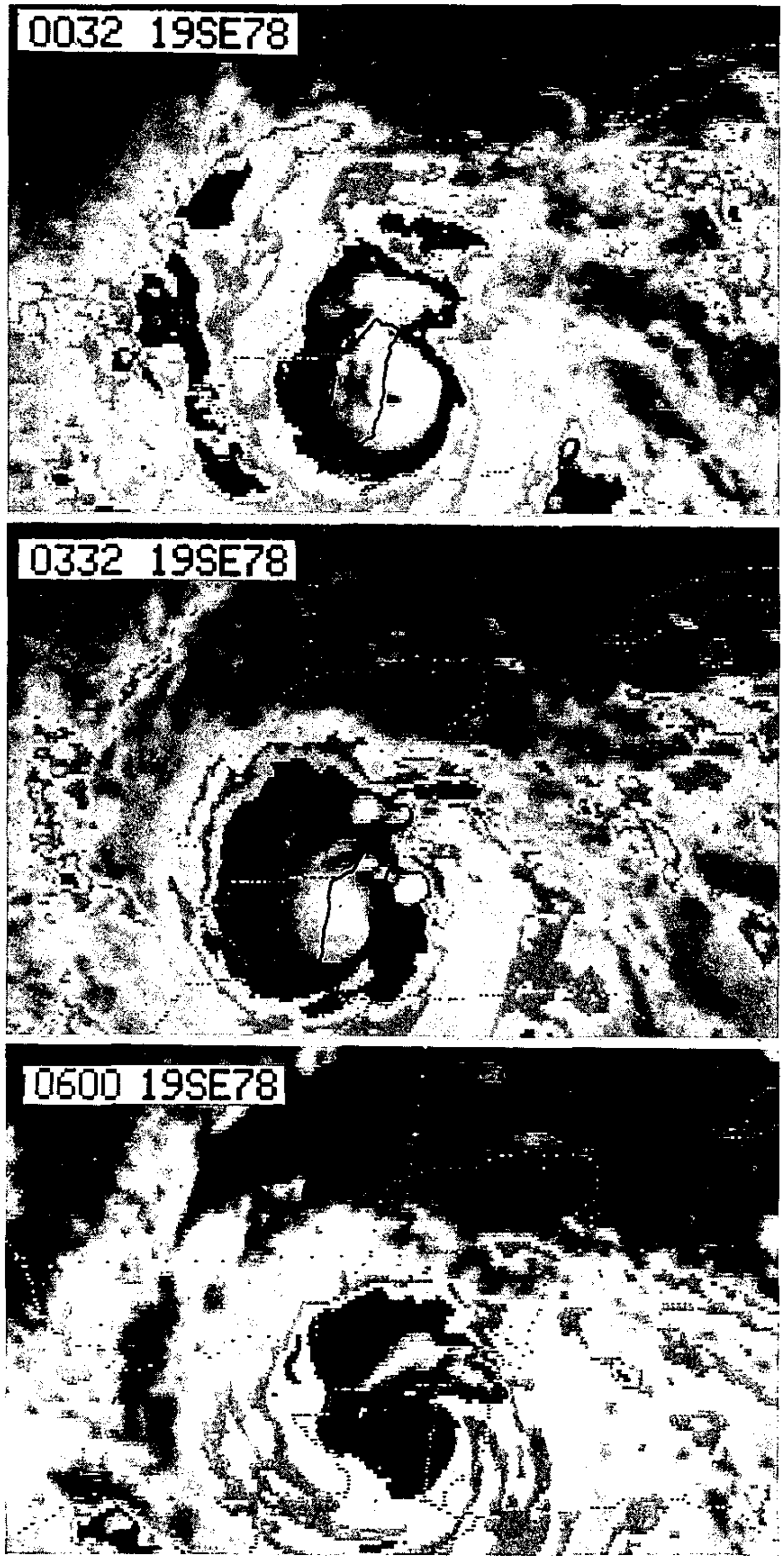

Figure 13b. *Enhanced IR images (Mb curve) of hurricane Greta at 0030 GMT, 0330 GMT, and 0600 GMT, September 19, 1978 with the nation of Belize outlined.*

Notice the changes between the 2330 and 0030 GMT images in Figures 13a and 13b. As the eye approached the coastline, the very cold (below -80°C) thunderstorms in the eyewall to the northeast of the eye expanded rapidly. This rapidly expanding cold eyewall is associated with the hurricane's heaviest precipitation and is assigned 3.0 inches per hour. A complete 1-hour rainfall estimate is shown in Figure 14.

Observed rainfall amounts for hurricane Greta were analyzed using 22 reporting rain guages in Belize (Figure 15). Half-hourly rainfall estimates produced operationally using the Scofield/Oliver convective technique are shown in Figure 16. Hurricane Greta was one of the first systems analyzed in real-time using the Scofield/Oliver convective technique. Note that the operationally produced estimates caught the position of the maximum rainfall fairly well but was about 2 1/2 times too large in magnitude. This can be attributed to the fact that the convective technique was designed for isolated thunderstorms not for tropical cyclones. The hourly rainfall estimates using the tropical cyclone technique produced reasonable results (Figure 17). These estimates were produced after the fact by a visiting Bangladesh scientist, who had no prior knowledge of the observed rainfall amounts. Both the position of the maximum rainfall and the gradient of the rainfall correspond well to the observed. However, too much rainfall was assigned to the cold tops in the CDO to the south of the eye of the storm. If the downslope conditions and the frictional divergence due to the offshore flow had been more adequately weighted by the analyst, the precipitation estimates in this area could have been adjusted downward, resulting in amounts closer to the observed. Note that the maximum isohyets would have extended further west into Belize if the satellite had not entered the eclipse mode resulting in the loss of 2 hours of imagery. Also note that the rainfall potential of Greta was calculated to be 12.4 inches at 0830 GMT which corresponds well to the observed amounts.

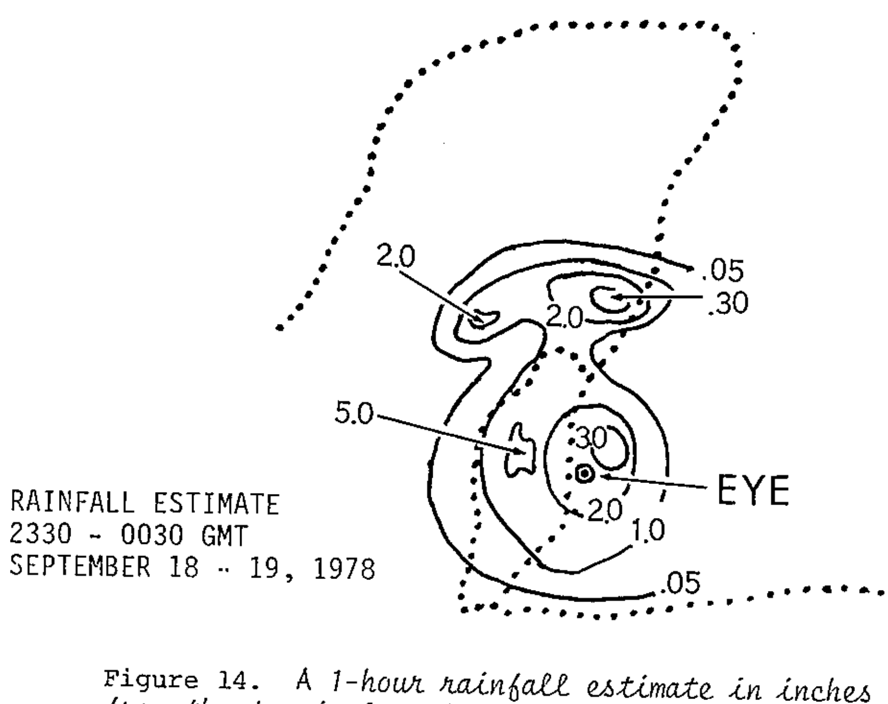

Figure 14. *A 1-hour rainfall estimate in inches from the tropical cyclone technique.*

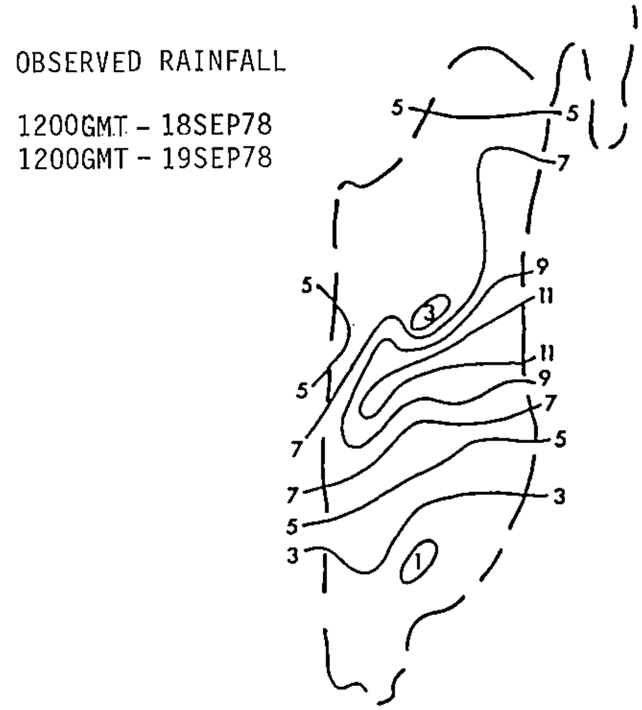

Figure 15. *An isohyetal analysis of the observed rainfall in inches for hurricane Greta in the nation of Belize from 1200 GMT, September 18, 1978 to 1200 GMT September 19, 1978.*

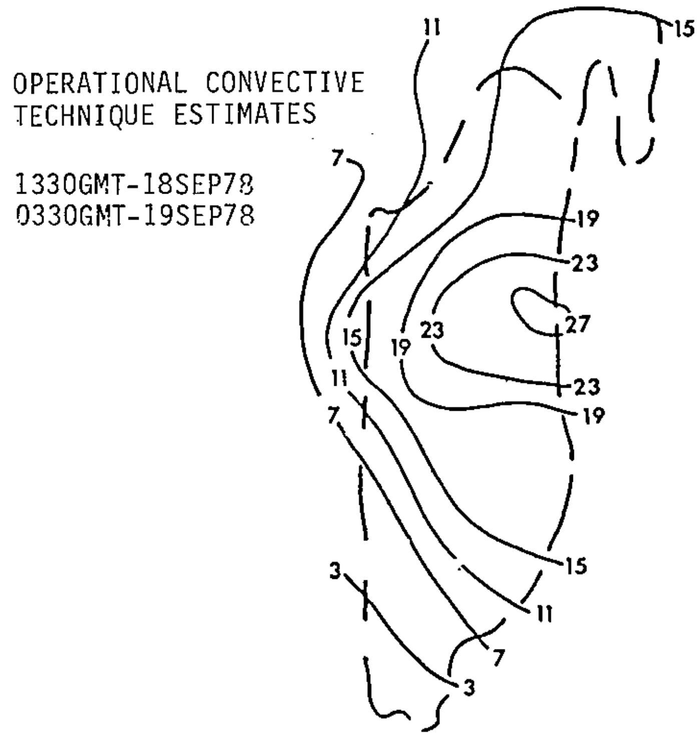

Figure 16. *Operationally produced rainfall estimates in inches from the Scofield/Oliver convective technique for hurricane Greta in the nation of Belize from 1330 GMT, September 18, 1978 to 0330 GMT, September 19, 1978.*

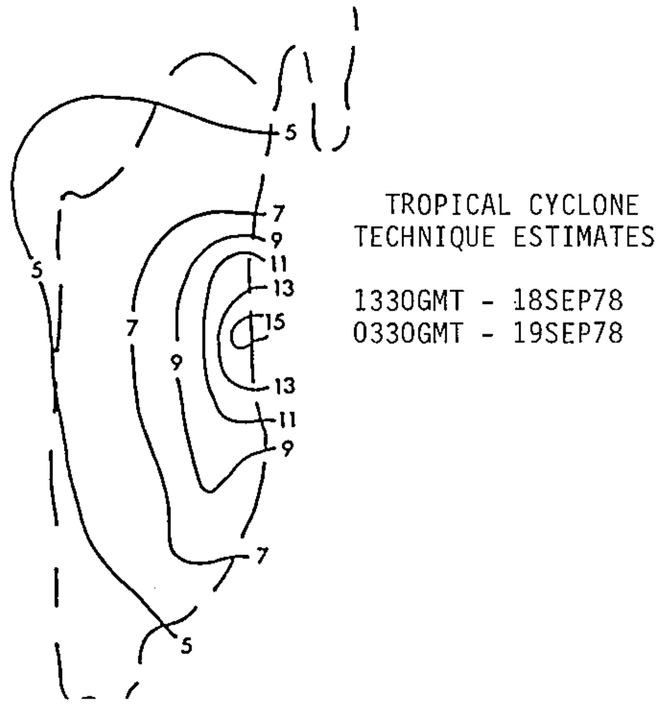

Figure 17. *Tropical Cyclone technique rainfall estimates in inches for hurricane Greta from 1330 GMT, September 18, 1978 to 0330 GMT September 19, 1978 for the nation of Belize.*

IV. CASE STUDY, HURRICANE FREDERIC

On September 12-13, 1979, hurricane Frederic crossed Cuba and travelled north-northwesterly until the eye made landfall near Mobile, Alabama, at 0300 GMT on September 13. A sequence of IR images of the hurricane before and after landfall is shown in Figures 18a, 18b and 18c. The rainfall potential of hurricane Frederic was calculated from the 2100 and 2200 GMT images to be 12.9 inches, 5 hours before landfall of the eye (Figure 19). This rainfall potential was calculated using a cross-section through the eyewall to the left of the eye.

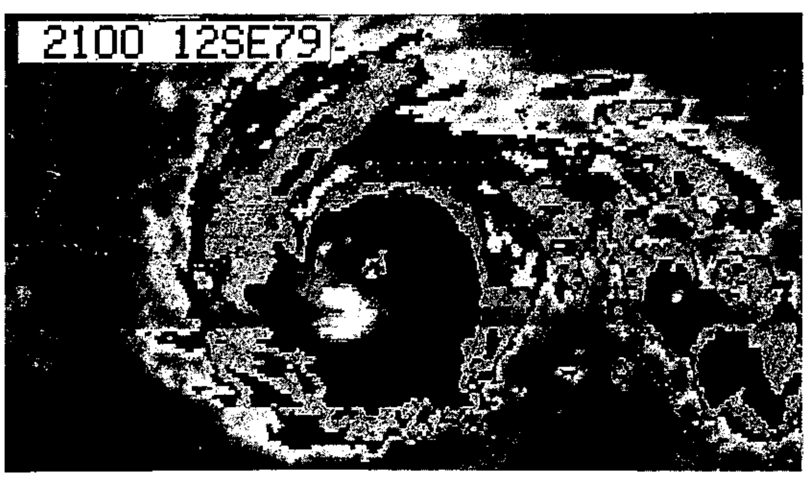

Figure 18a. *Enhanced IR image (Mb curve) of hurricane Frederic at 2100 GMT on September 12, 1979.*

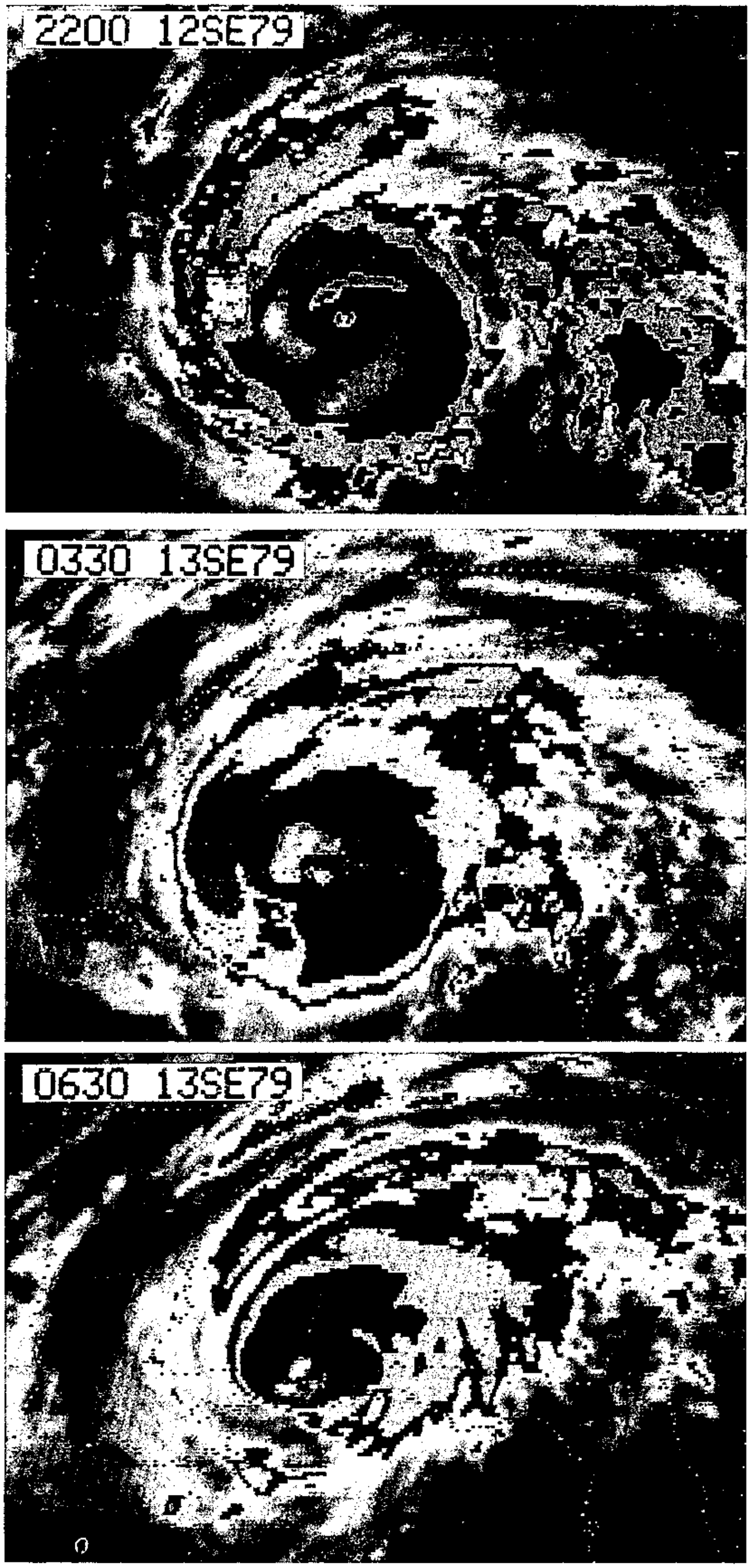

Figure 18b. *Enhanced IR images (Mb curve) of hurricane Frederic at 2200 GMT on September 12 and 0330 GMT and 0630 GMT on September 13, 1979.*

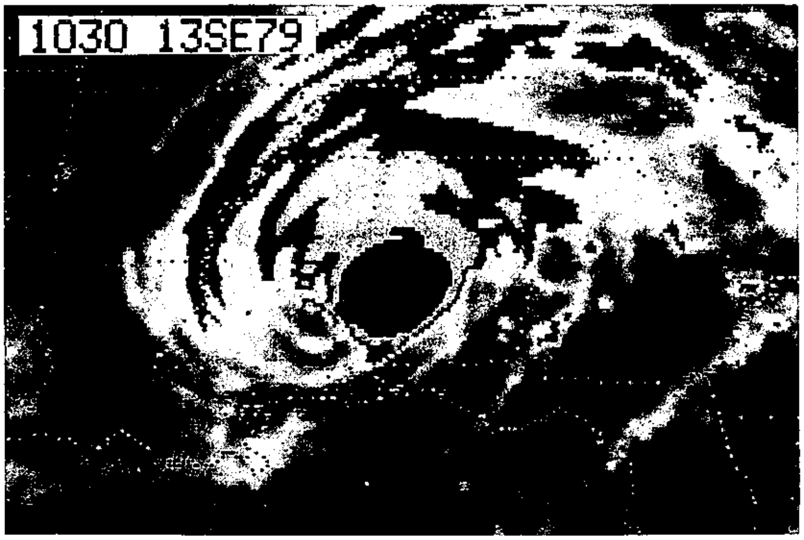

Figure 18c. *Enhanced IR image (Mb curve) of hurricane Frederic at 1030 GMT on September 13, 1979.*

RAINFALL POTENTIAL OF HURRICANE FREDERIC AT 2200 GMT, SEPTEMBER 12, 1979

	R (inches/hour)	D (degrees latitude)
CDO	0.5	0.2
	1.0	1.5
	1.5	0.4
WC	2.0	0.2
	3.0	0.35
OBA	0.3	0.7
ECT (0% Coverage)	---	---

V = 0.3° latitude/hour (18 knots)

$$\frac{R_{CDO}\ D_{CDO}\ R_{WC} + D_{WC}}{V} + \frac{R_{OBA}\ D_{OBA}}{V} = 12.9 \text{ inches}$$

Figure 19. *A calculation of the rainfall potential in inches of hurricane Frederic at 2200 GMT, September 12, 1979.*

Operational half-hourly rainfall estimates using the Scofield/Oliver convective technique were computed in real time and sent to the WSFO's for use in issuing flash flood warnings (Figure 20). These half-hourly estimates were graphically added to produce a storm total of over 12 inches just to the left of the track of the eye. Observed rainfall reports revealed an 11 inch guage which had overflowed near Pascagoula, Mississippi, (to the left of the track of the eye) (Figure 21). Hourly rainfall estimates computed using the tropical cyclone technique also yielded over 12 inches near the same location (Figure 22). In this case study the calculated rainfall potential of the cyclone, the hourly tropical cyclone technique estimates, and the operational convective estimates all corresponded accurately to the magnitude and placement of the observed heaviest rainfall.

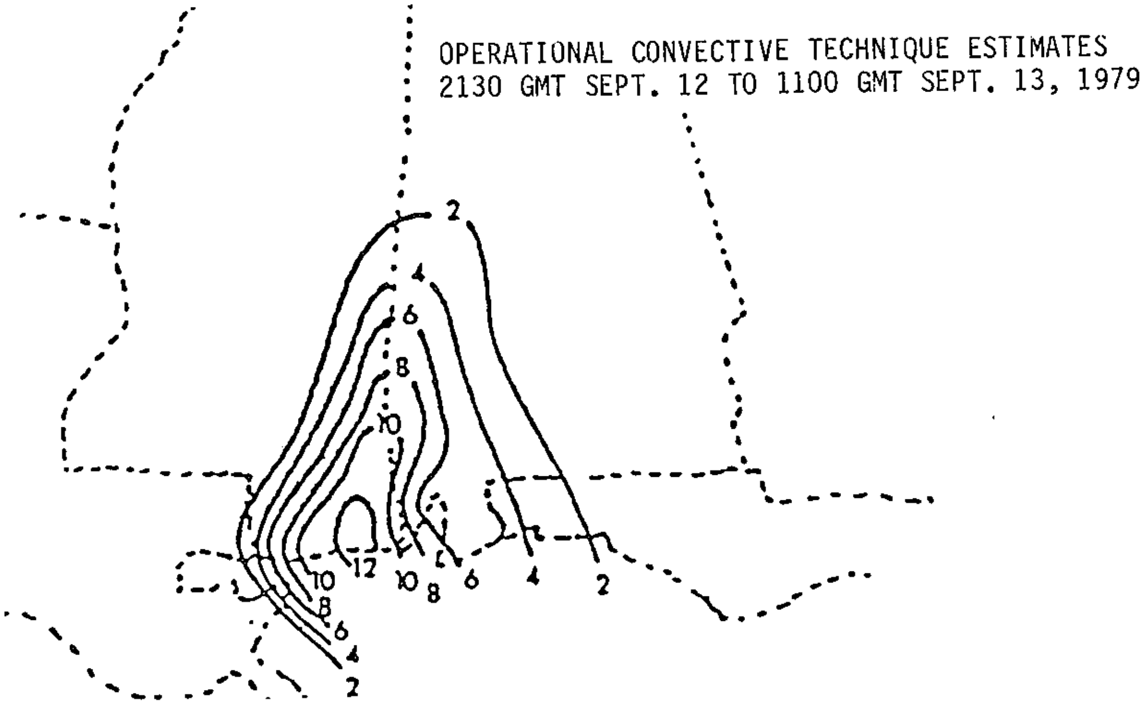

Figure 20. *Operationally produced rainfall estimates in inches from the Scofield/Oliver convective technique for hurricane Frederic from 2130 GMT, September 12, 1979 to 1100 GMT, September 13, 1979.*

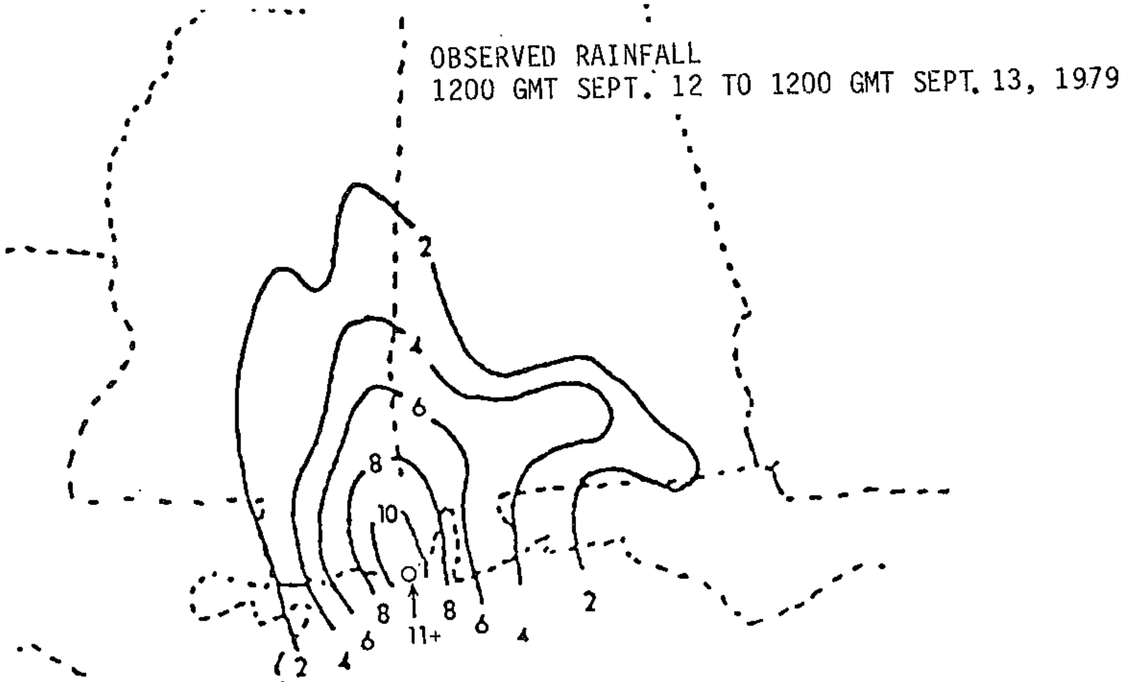

Figure 21. *An isohyetal analysis of the observed rainfall in inches for hurricane Frederic from 1200 GMT, September 12, 1979 to 1200 GMT, September 13, 1979.*

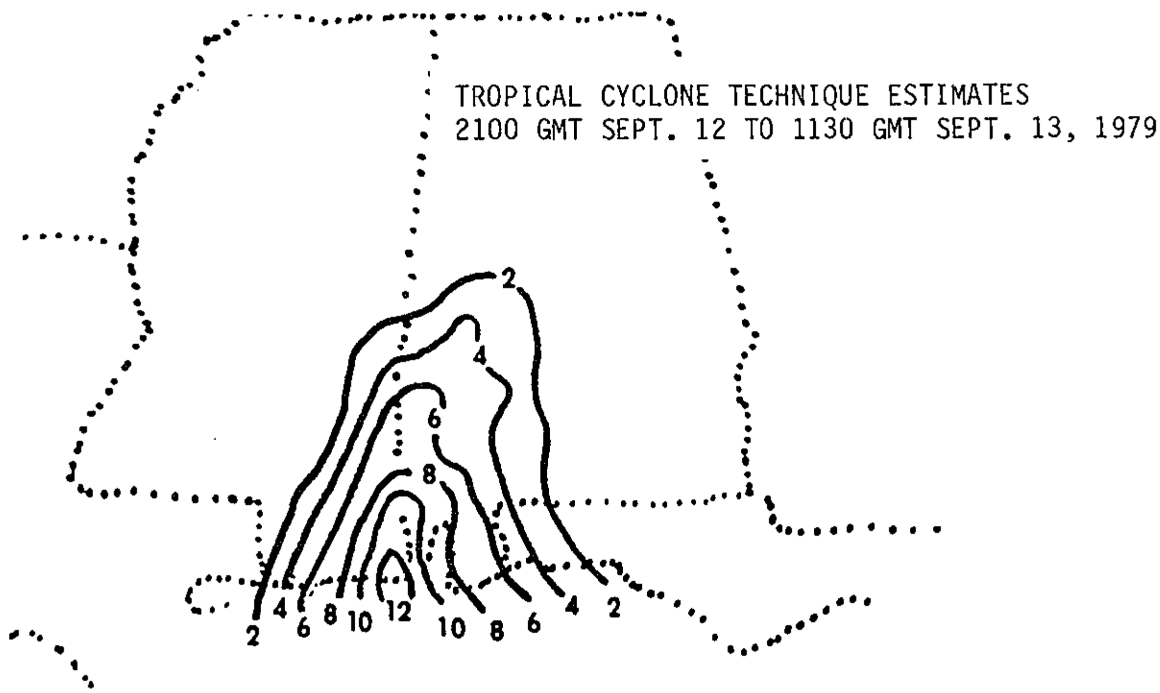

Figure 22. *Tropical Cyclone technique rainfall estimations in inches for hurricane Frederic from 2100 GMT, September 12, 1979 to 1130 GMT, September 13, 1979.*

V. MODIFICATIONS TO THE TECHNIQUE

This technique could be modified for use every 3 or 6 hours for those areas not receiving hourly imagery. To compute rainfall estimates for stationary cloud features using 6 hourly imagery, multiply the values in step 3 (Figures 7 and 8) by six; multiply by three for images available every 3 hours. For cloud features that are moving, extrapolate the number of hours each cloud feature was over each geographic area. Multiply the number of hours by the values in step 3. Cloud features such as embedded cold tops have individual life spans of less than 6 hours; so rainfall estimates for these features should tend towards the normal (underlined) amounts.

This technique may be applied manually or used on a man - machine interactive computer system. Unenhanced IR data could also be used in this technique, but using enhanced imagery yields a more detailed analysis. The isolines may need to be displaced to take into account the strong winds associated with the tropical cyclone circulation.

As the tropical cyclone moves inland, the wall cloud and CDO may become unrecognizable. If identifiable thunderstorm tops are seen growing, dissipating, or merging; use the Scofield/Oliver convective technique. If no individual thunderstorm tops are identifiable, use the rainfall estimates for the Outer Banding Area (OBA) in figure 8.

VI. CASE STUDY, HURRICANE ALLEN, USING 6 HOURLY IMAGERY

On August 3-10, 1980, Hurricane Allen crossed the Gulf of Mexico and travelled west-northwesterly towards southern Texas. A sequence of IR images during the lifetime of the hurricane is shown in figures 23a, 23b, and 23c. The rainfall potential of Hurricane Allen was calculated at 0000 GMT and 1200 GMT on August 9 and 0130 GMT, August 10 to be 22.0, 20.4, and 23.3 inches, respectively (Figure 24). As Allen approached the coastline, the cloud tops in the wall cloud and CDO decreased in size and became warmer. This corresponded to a lowering of the hurricane's intensity (Dvorak, 1982), rainfall rates, and diameter of cloud features. The forward motion of the cyclone decreased from 12 knots to 4 knots as measured from 6-hourly satellite imagery. Nearly all the terms in the equation (Figure 24) decreased by the same factor, so the rainfall potential Hurricane Allen remained nearly constant.

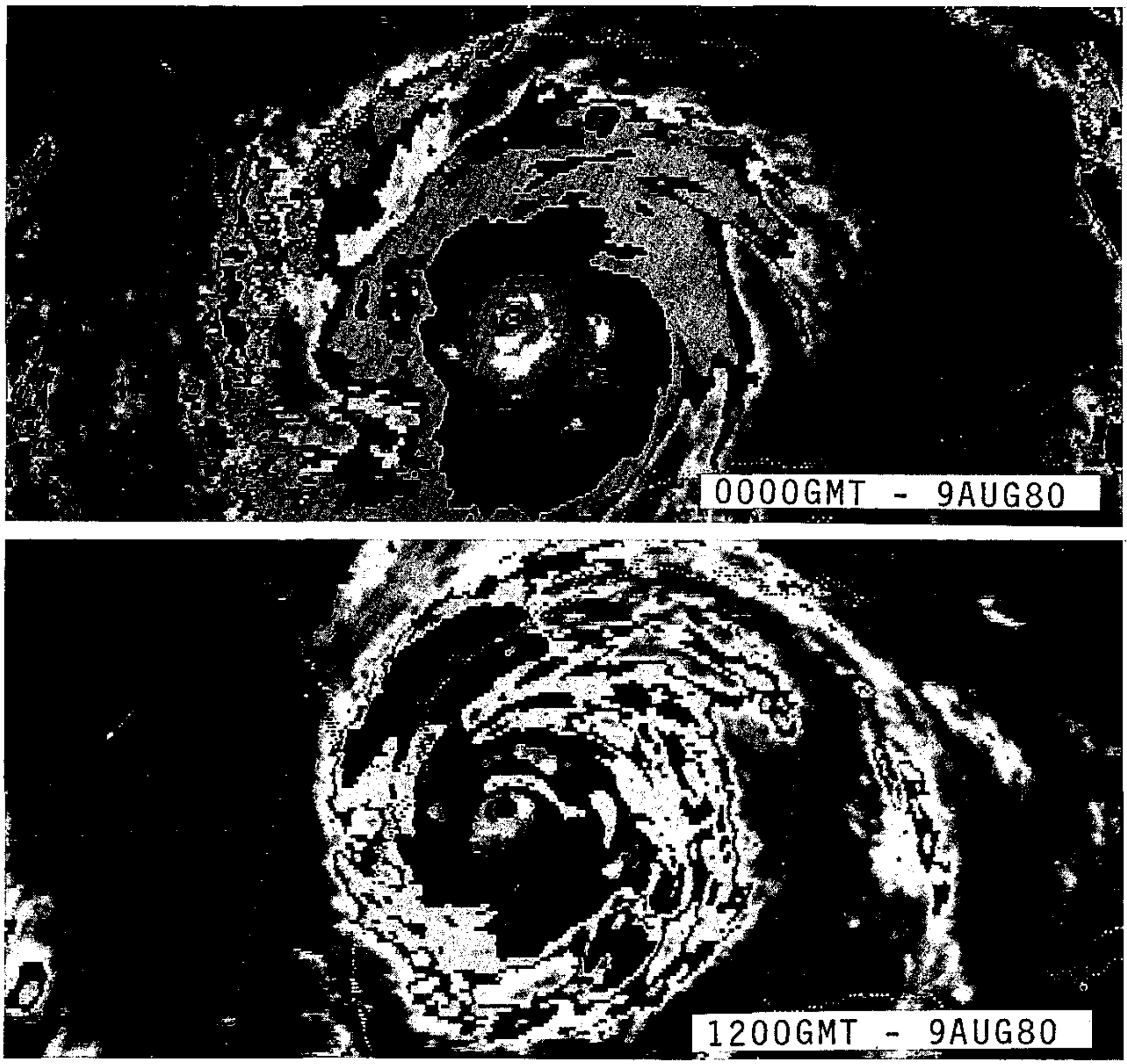

Figure 23a. *Enhanced IR images (Mb curve) of hurricane Allen at 0000 GMT and 1200 GMT on August 9, 1980.*

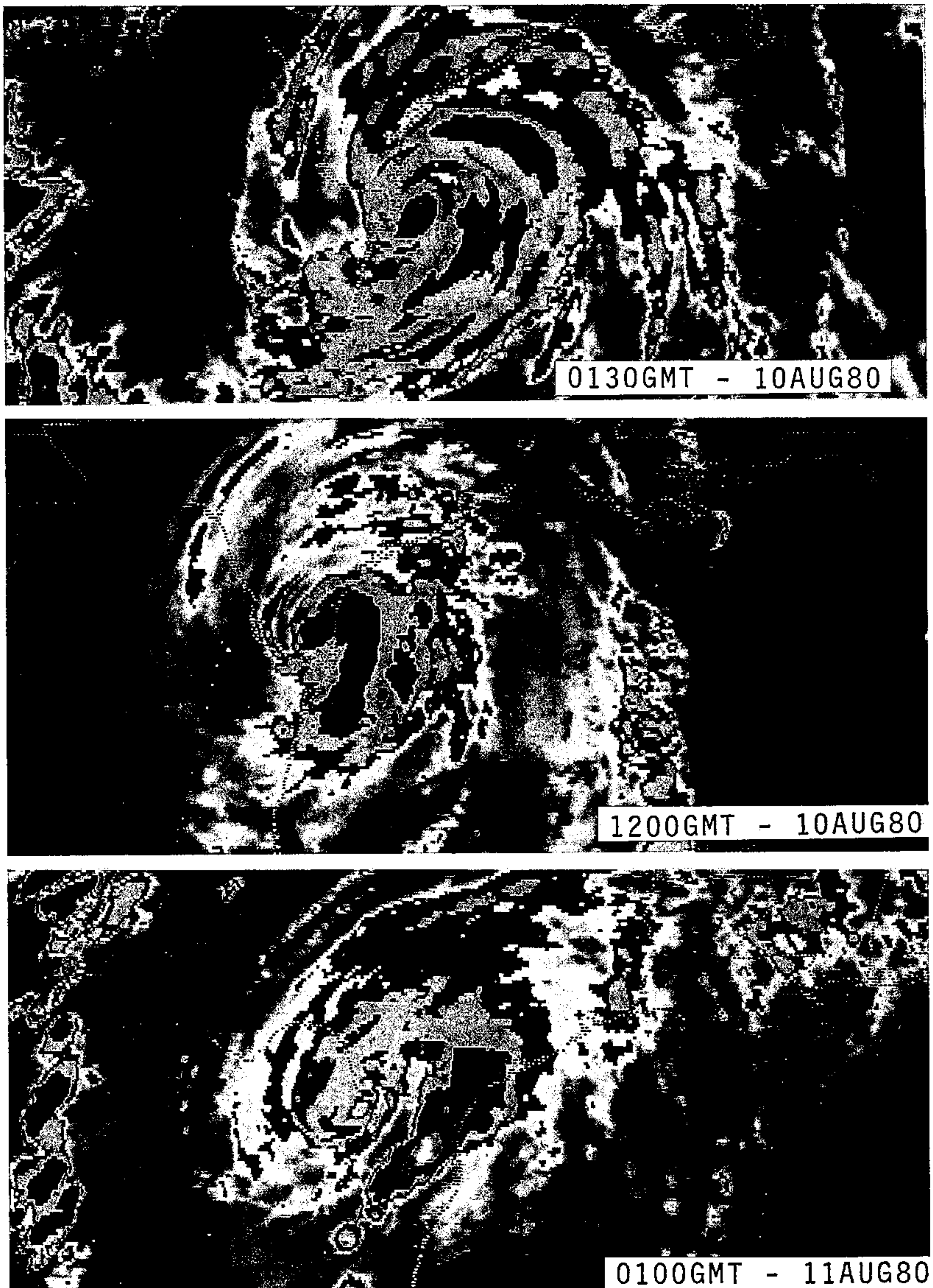

Figure 23b. *Enhanced IR images (Mb curve) of hurricane Allen at 0130 GMT and 1200 GMT on August 10 and 0100 GMT on August 11, 1980.*

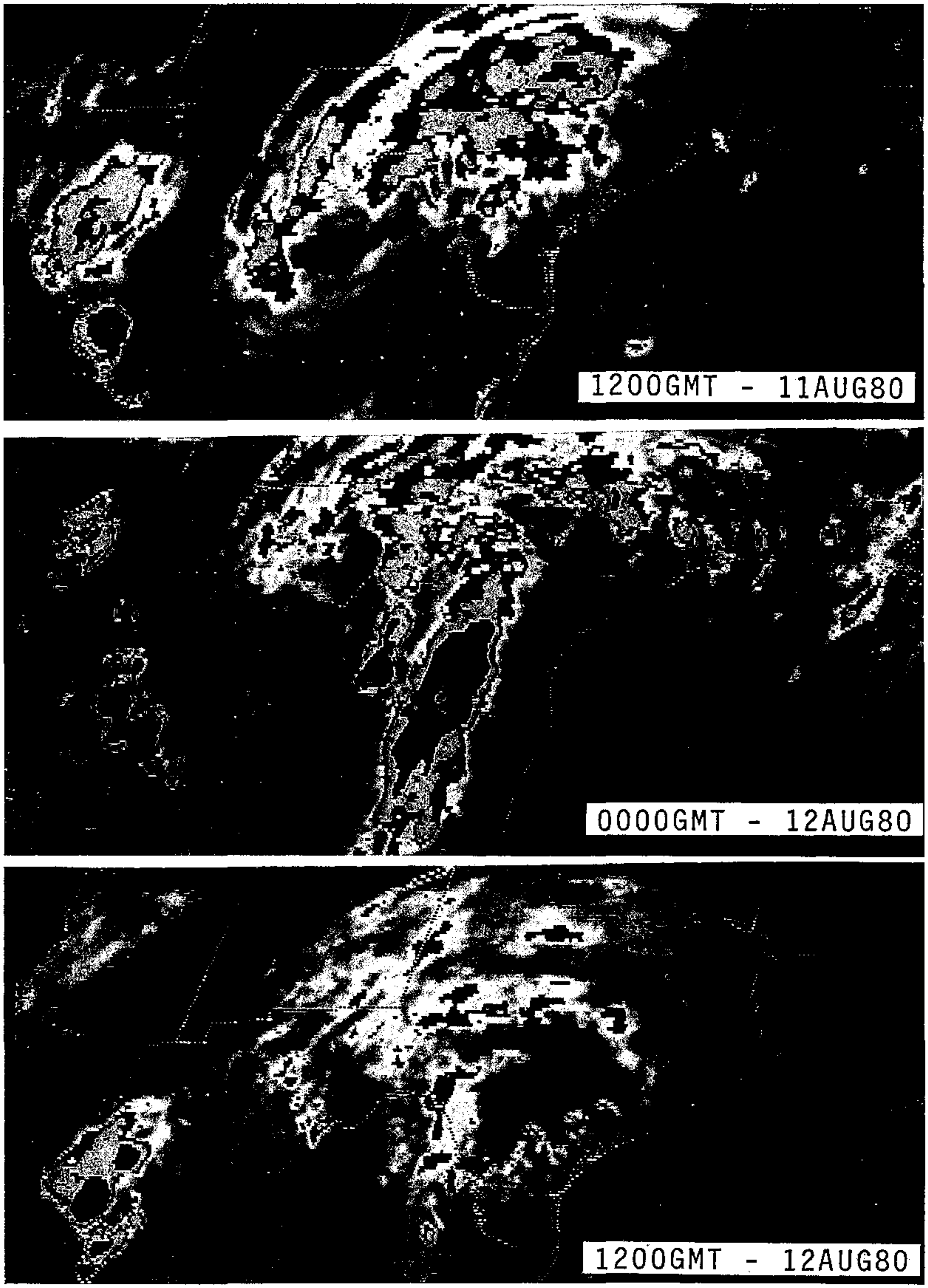

Figure 23c. *Enhanced IR images (Mb curve) of hurricane Allen at 1200 GMT on August 11 and 0000 GMT and 1200 GMT on August 12, 1980.*

RAINFALL POTENTIAL OF HURRICANE ALLEN

0000 GMT AUGUST 9:	R (inches/hour)	D (degrees latitude)
CDO	1.5	0.8
WC	2.0	0.7
	3.0	0.3
OBA	0.3	1.0
ECT (30% Coverage)	2.0	0.3

V = 0.2° latitude/hour (12 Knots)

1200 GMT AUGUST 9:	R (inches/hour)	D (degrees latitude)
CDO	1.0	0.5
WC	2.0	0.4
	3.0	0.2
OBA	0.3	0.5
	1.0	0.4
ECT (0% Coverage)	---	---
(25% Coverage)	2.0	0.1

V = 0.13° latitude/hour (8 knots)

0130 GMT AUGUST 10:	R (inches/hour)	D (degrees latitude)
CDO	0.5	0.5
WC	1.0	0.5
OBA	0.2	0.5
	1.0	0.5
ECT (20% Coverage)	2.0	0.1
(40% Coverage)	0.4	0.2

V = 0.07° latitude/hour (4 knots)

$$\frac{R_{CDO} D_{CDO} + R_{WC} D_{WC}}{V} + \frac{R_{OBA} D_{OBA} + R_{ECT} D_{ECT}}{V}$$

= 22.0 inches at 0000 GMT, August 9
= 20.4 inches at 1200 GMT, August 9
= 23.3 inches at 0130 GMT, August 10

Figure 24. *A calculation of the rainfall potential of hurricane Allen at 0000 GMT and 1200 GMT August 9 and 0130 GMT, August 10, 1980.*

Operational half-hourly rainfall estimates using the Scofield/Oliver convective technique were computed for over 75 consecutive hours in real-time and sent to the WSFO's in Texas for evaluating the flood potential and for issuing flash flood warnings. The period of heaviest rainfall occurred during the 24 hour period ending at 1200 GMT, August 11, 1980, and the operationally produced rainfall estimates are shown in Figure 25. The half-hourly estimates were graphically added to produce 6-hourly totals and telecopied to the Dallas-Fort Worth River Forecast Center for use in river flow forecasts. Rainfall estimates were computed using the tropical cyclone technique and 6-hourly interval imagery (Figure 26). Figure 27 shows the 24-hour observed precipitation in Texas. Note that both the operational estimates and the tropical cyclone technique estimates correspond accurately to the maximum rainfall and the axis of maximum rainfall in extreme southern Texas during this 24-hour period. The maximum rainfall during and after landfall of hurricane Allen was over 21 inches near the track of the eye about 40 miles inland at Faysville, Texas. This observed storm total amount corresponds favorably to the rainfall potential of the hurricane calculated before landfall.

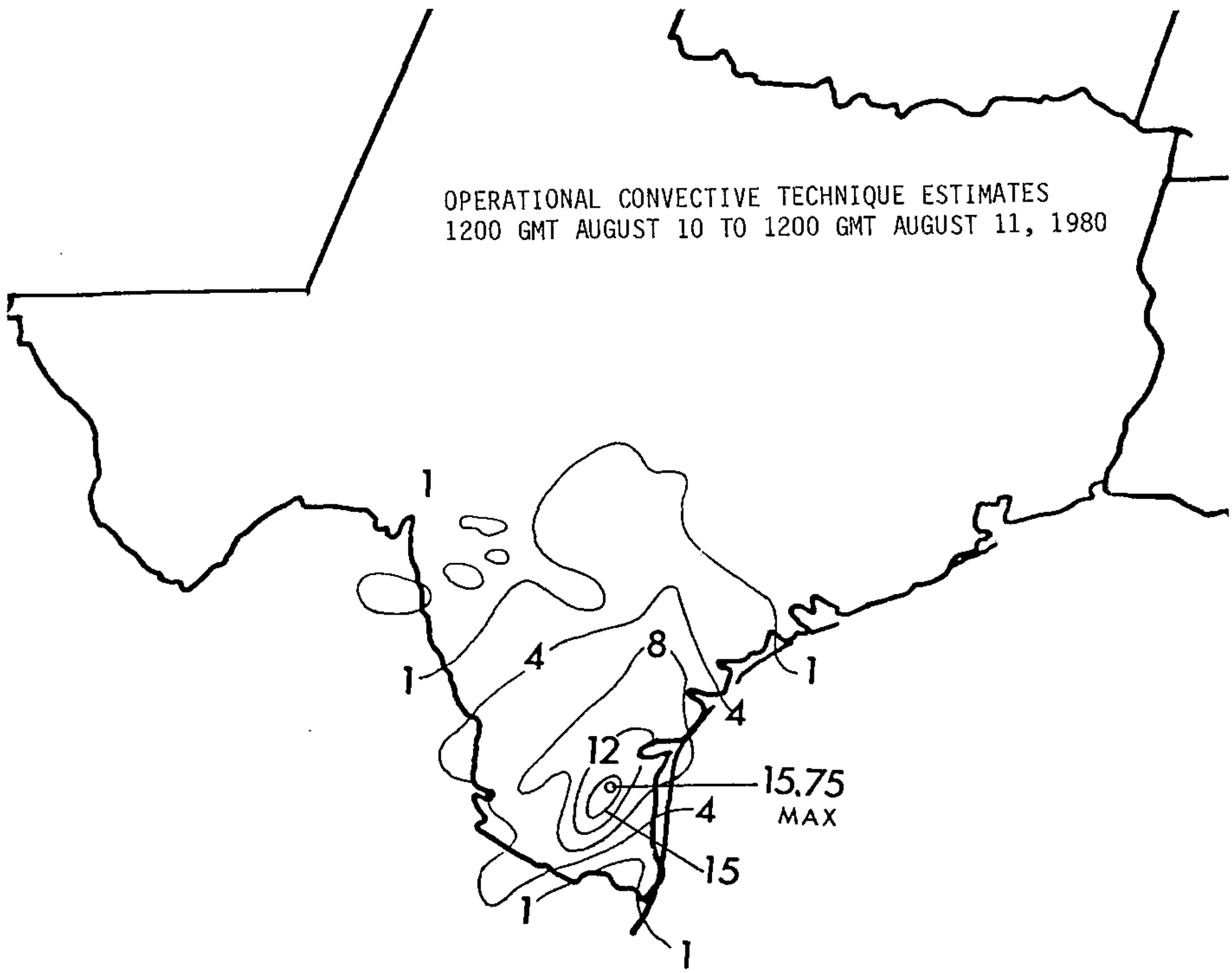

Figure 25. *Operationally produced rainfall estimates in inches from the Scofield/Oliver convective technique for hurricane Allen for the 24 hour period ending at 1200 GMT, August 11, 1980.*

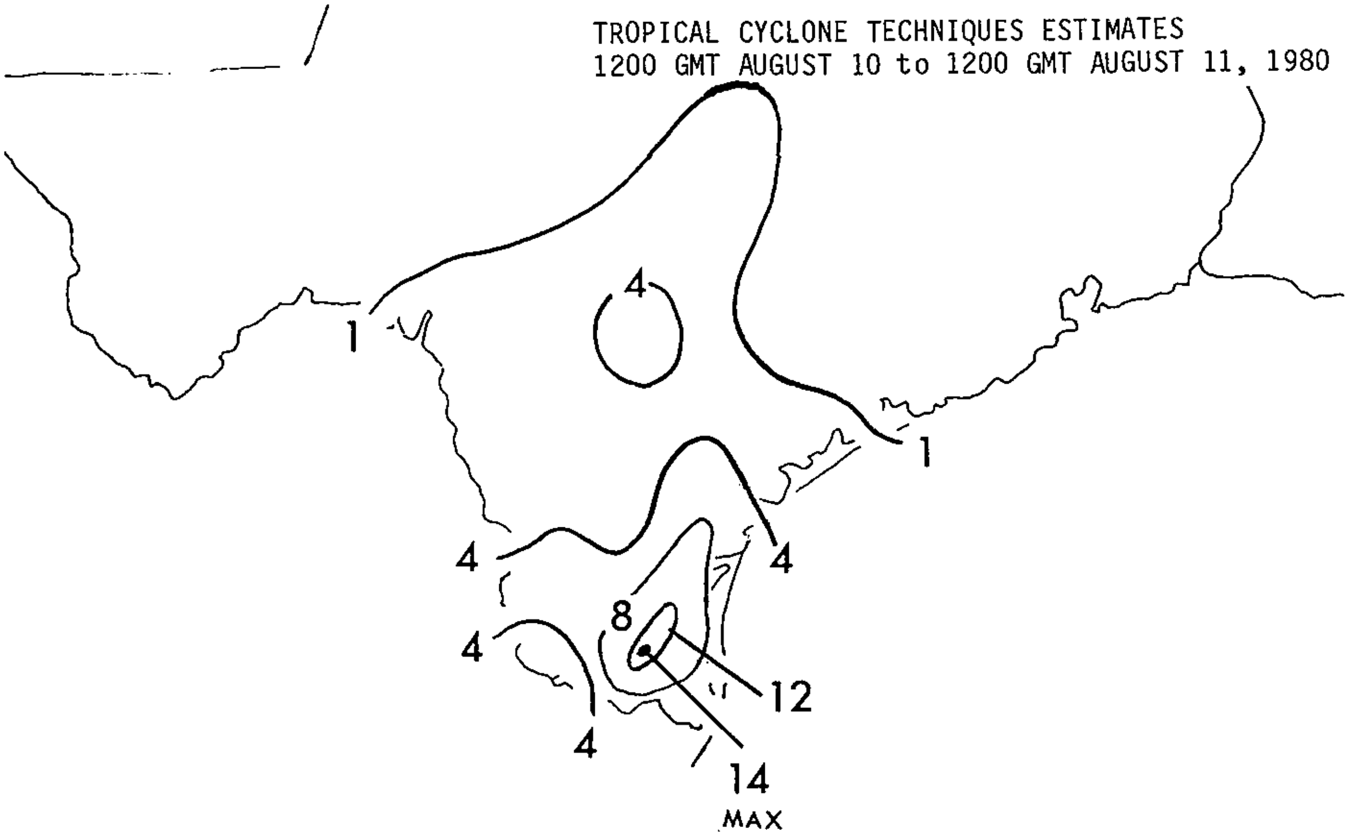

Figure 26. *Tropical Cyclone technique rainfall estimates in inches using 6 hourly interval imagery for hurricane Allen for the 24 hour period ending at 1200 GMT, August 11, 1980.*

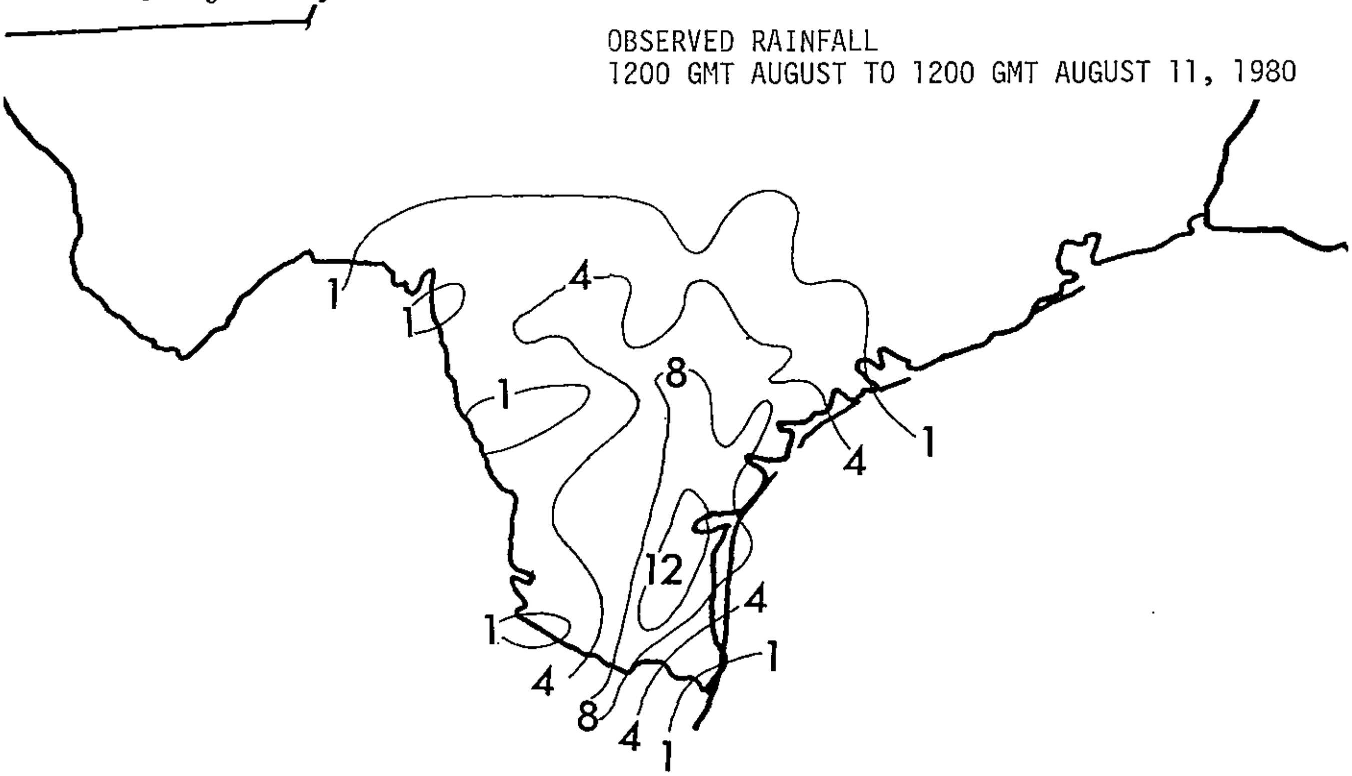

Figure 27. *An isohyetal analysis of the observed rainfall in inches for hurricane Allen for the 24 hour period ending at 1200 GMT, August 11, 1980.*

VII. CONCLUSIONS

This memorandum presented an experimental technique for estimating precipitation from tropical cyclones using visible and IR geostationary satellite data. This technique offers meteorologists around the world a simple tool for forecasting and analyzing heavy rainfall from tropical cyclones with existing resources. These heavy rainfall analyses and forecasts offer another tool for field forecasters to use in evaluating the flood potential and in issuing flash flood watches and warnings. Initial results indicate that this technique may be easier to use and better for tropical cyclones than the convective technique. The tropical cyclone technique produces an acceptable predicted maximum rainfall while the cyclone is still over the open waters. This technique will be tested and evaluated operationally in the 1984 hurricane season by NESDIS and NWS satellite meteorologists. Results from operational application of this technique will be used to modify the tropical cyclone methodology.

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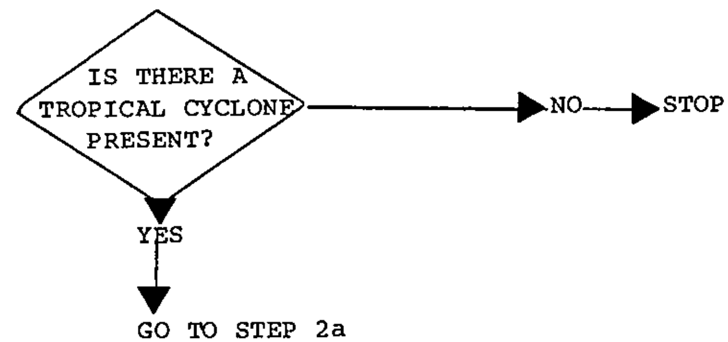
APPENDIX A

A TROPICAL CYCLONE PRECIPITATION ESTIMATION TECHNIQUE USING GEOSTATIONARY SATELLITE DATA

STEP 1. Tropical Cyclone Identification:

- A sharply defined comma configuration with cyclonically spiraling cloud bands encircling the eye or the cloud system center.
- An anticyclonic outflow of cirrus may be seen at the periphery of the cyclone.

STEP 1



This technique estimates hourly areal rainfall amounts from tropical cyclones over land or water. This technique uses unenhanced or enhanced infrared satellite data and visible satellite data. The technique can be adjusted to compute rainfall from images available every 3 or 6 hours.

STEP 2.

The Central Dense Overcast (CDO) area is the dense overcast mass which is part of the comma head that appears cradled within the curvature or the comma cloud band. Included within the CDO is the wall cloud which encircles the eye or the cloud system center and is often associated with very cold temperatures in the IR and very bright areas in the VIS. The CDO often appears to be oval in shape during the early stages of the cyclone and usually becomes larger, rounder, and brighter in the VIS and colder in the IR as the cyclone intensifies. Heavy rain in the CDO occurs in a 50 n mile radius either side of the cyclone. The coldest temperatures in the IR or brightest and most textured areas in the VIS help to locate the heavy rainfall areas within the CDO. These features should be used to modify the location and magnitude of the heavy rain in the 50 n mile radius. The heaviest rainfall occurs in the wall cloud (20n mile radius from the cloud system center). Cloud tops within the heavy rain portion of the CDO and wall cloud that become warmer should have lower rainfall estimates. Little or no rain occurs at the outer edge of the CDO.

STEP 2a

Identify and locate the following cloud features in the tropical cyclone:

- Eye (or cloud system center)
- Wall cloud (20 n miles either side of the eye or the cloud system center)
- Central Dense Overcast (CDO) area
- Outer Banding Area (OBA)
- Area of embedded cold convective cloud tops (ECT) in the OBA area

GO TO STEP 2b

The Outer Banding Area (OBA) is that part of the comma cloud band that is generally overcast and curves evenly around the CDO. Several bands are often seen curving evenly around the CDO separated by relatively cloud-free areas. Part of the OBA is composed of an anticyclonic outflow of cirrus--this part of OBA has no rain. Moderate-to-heavy rain occurs in that part of the OBA which is composed of cyclonically spiraling convective cloud bands; these bands often have embedded cold convective tops. Occasionally a pronounced convective cloud line encircling the CDO and merging with the CDO is observed; this cloud line is called the Primary Comma Band. The most important features are areas of cold convective cloud tops embedded in the OBA--these tops are active, growing thunderstorm clusters producing heavy rainfall in a saturated environment. These convective tops are best resolve in the enhanced IR and high-resolution visible pictures.

STEP 2b

From comparing two consecutive pictures, draw isolines in the second picture around the following:

- o Wall cloud (approximately 20 n miles either side of the eye or the cloud system center).
- o A 50 n mile radius either side of the cloud system center within the CDO; heavy rain often occurs within this radius. Use IR and VIS to help modify the size and location of the isoline. Within this isoline, coldest and brightest areas should also be analyzed; these areas often locate the heaviest rainfall within the CDO.
- o Bands in the OBA that are convective.
- o Within the OBA, areas of embedded cold convective cloud tops in the convective cloud bands.

↓

GO TO STEP 3

STEP 3.

- Estimate the rainfall as a function of the cloud feature, i.e.,
  - -- Wall cloud
  - -- CDO
  - -- OBA
  - -- Areas of cold convective cloud tops embedded in the OBA.
- Estimates may need to be displayed to take into account the strong winds associated with the tropical cyclone circulation.

STEP 3

From comparing two consecutive pictures, compute rainfall estimates for the isolines drawn above; the underlined rainfall accumulation is normally the value used in the estimate.

Estimates for the CDO Area and Wall Cloud	Rainfall Accumulations [1] (inches per hour)
CDO (a 50 n mile radius either side of the cloud system center; this radius can be modified by the IR and VIS.)	[3]0.50-1.00-2.00[2]
Outer edge of the CDO.	0.01-0.05-0.10
Wall cloud (20 n miles either side of the eye or cloud system center)	[3]1.00-2.00-3.00

1. The colder the canopy temperature in the IR and the brighter and more textured the canopy is in the VIS, the higher the rainfall estimate.

2. Colder and brighter features analyzed within the CDO should be given higher rainfall estimates.

3. Cloud tops that are becoming warmer should have lower rainfall estimates.

- Cloud features over coasts and located in areas of onshore flow should be given higher rainfall estimates as compared to those features over coasts and located in areas of offshore flow.

- If the IR pictures are enhanced by an Mb-type of enhancement curve, the following rules are applied for the area of cold convective cloud tops embedded in the convective cloud bands.

  (1) "Decreasing in area" includes those cloud features that warm from white to repeat gray or within the repeat gray.

  (2) "Becoming warmer" refers to those cloud features that become warmer by one or more shades of gray.

STEP 3 (Continued)

Estimates for the OBA	Rainfall Accumulations[1] (inches per hour)
Outer Banding Area	0.10-0.30-0.50
The first band from the CDO located in the onshore flow.[2]	0.50-1.00-2.00
Area of cold convective cloud tops embedded in the convective cloud bands.[3]	
Growing, becoming colder, or remaining the same.[4]	0.25-1.00-4.00[5]
Decreasing in area.[4]	0.10-0.50-1.00
Becoming warmer.[4]	0.05-0.20-0.50

1. The colder the canopy temperature in the IR and and the brighter and more textured the canopy is in the VIS, the higher the rainfall estimate.

2. Only considered when the OBA is moving onshore.

3. These estimates are obtained from the convective technique for estimating rainfall from convective systems.

4. These categories are determined from the changes observed in the thunderstorm anvil in two consecutive pictures.

5. The more rapid the convective cloud tops grow and/or become colder, the higher the estimate.

GO TO STEP 4

STEP 4.

The Rainfall Potential can be computed and used to predict the maximum rainfall accumulations over coastal areas while the cyclone is still over the open waters.

STEP 4

Compute the Rainfall Potential along the tropical cyclone track before landfall.

Rainfall Potential =

$$\frac{R_{CDO}\,D_{CDO} + R_{WC}\,D_{WC}}{V} + \frac{R_{OBA}\,D_{OBA} + R_{ECT}\,D_{ECT}}{V}$$

Where,

R_{CDO}, R_{WC}, R_{OBA}, and R_{ECT}: Rainfall rates (R) of the CDO, wall cloud (WC) area, significant bands in the OBA, and embedded cold convective tops (ECT), respectively

D_{CDO}, D_{WC}, D_{OBA}, and D_{ECT}: Diameter (D) of the rainfall rates in the direction of motion

V: Speed of the tropical cyclone

APPENDIX B

CONVECTIVE STORM TECHNIQUE

STEP 1

RAINFALL IS COMPUTED ONLY FOR THE ACTIVE PORTION OF THE THUNDERSTORM SYSTEM:

THE FOLLOWING ARE CLUES FOR HELPING TO MAKE THIS DECISION.

- IR TEMPERATURE GRADIENT IS TIGHTEST AROUND STATION END OF ANVIL FOR A THUNDERSTORM SYSTEM WITH VERTICAL WIND SHEAR (IR).
- STATION IS LOCATED NEAR THE CENTER OF THE ANVIL WITH A TIGHT, UNIFORM IR TEMPERATURE GRADIENT AROUND ENTIRE ANVIL FOR A THUNDERSTORM SYSTEM WITH NO VERTICAL WIND SHEAR (IR).
- AN OVERSHOOTING TOP IS OVER THE STATION (VIS AND IR).
- ANVIL IS BRIGHTER AND/OR MORE TEXTURED (VIS).
- FROM COMPARING LAST TWO PICTURES: STATION IS UNDER HALF OF ANVIL BOUNDED BY EDGE WHICH MOVES LEAST (IR).
- STATION IS NEAR 300-MB UPWIND END OF ANVIL (IR, SKIP THIS CLUE IF NO UPPER AIR DATA AVAILABLE).
- STATION IS NEAR THE AREA OF LOW-LEVEL INFLOW (VIS).
- STATION IS LOCATED UNDER A RADAR ECHO.

STEP 2

HALF-HOURLY RAINFALL ESTIMATES IN INCHES ARE COMPUTED FROM THE FOLLOWING FACTORS:

FACTOR 1

CLOUD-TOP TEMPERATURE AND CLOUD GROWTH FACTOR [IR].
DETERMINE AMOUNT THAT THE COLDEST CLOUD TOPS INCREASED WITHIN HALF-HOUR.

	>2/3° LAT	>1/3° ≤2/3° LAT	≤1/3° LAT OR SAME	AREAL DECREASE OF SHADE OR WARMING FROM WHITE TO RPT GRAY OR WITHIN THE RPT GRAY	COLDEST TOPS 1 OR MORE SHADES WARMER
MED GRAY (-32 TO 41°)	0.25	0.15	0.10	0.05	T
LT GRAY (-41 TO -52°)	0.50	0.30	0.15	0.10	↓
DK GRAY (-52 TO -58°)	0.75	0.40	0.20	0.15	↓
BLACK (-58 TO -62°)	1.00	0.60	0.30	0.20	↓
RPT GRAY*(-62 TO -80°)	1-2.00	0.60-1.00	0.30-0.60	0.30	↓
WHITE (BELOW -80°)	2.00	1.00	0.60	0.40	0.10

*COLDER REPEAT GRAY SHADES SHOULD BE GIVEN HIGHER RAINFALL ESTIMATES.

OR

DIVERGENCE ALOFT FACTOR* [IR AND 200-MB ANALYSIS].

MED GRAY	LT GRAY	DK GRAY	BLACK	RPT GRAY	WHITE
0.15	0.30	0.40	0.60	0.60-1.00	1.00

*IR IMAGERY SHOWS EDGES OF THUNDERSTORM ANVIL ALONG THE UPWIND END FORMING A LARGE ANGLE OF BETWEEN 50-90 DEGREES POINTING INTO THE WIND; 200-MB ANALYSIS OFTEN SHOWS THESE STORMS JUST DOWNWIND FROM WHERE THE POLAR JET AND SUBTROPICAL JET SEPARATE.

GO TO FACTOR 2

FROM FACTOR 1

FACTOR 2

OVERSHOOTING TOP FACTOR [VIS, IR]. ADD TO THE OVERSHOOTING TOPS*:

MED GRAY	LT GRAY	DK GRAY	BLACK	RPT GRAY	WHITE
0.50	0.45	0.40	0.30	0.30	0.30

*HIGH-RESOLUTION VISIBLE IMAGERY IS THE BEST DATA FOR DETERMINING THIS FACTOR.

FACTOR 3

THUNDERSTORM OR CONVECTIVE CLOUD LINE MERGER FACTOR [IR, VIS]. ADD 0.50 TO THE COLDER TOPS IN THE AREA OF THE MERGER.

FACTOR 4

SATURATED ENVIRONMENT FACTOR [IR, VIS]. ADD TO THE COLDER TOPS STATIONARY FOR A GIVEN AMOUNT OF TIME:

	MED GRAY	LT GRAY	DK GRAY	BLACK	RPT GRAY	WHITE
≥1 HOUR BUT <2 HOURS	0.20	0.20	0.20	0.20	0.30	0.30
≥2 HOURS	0.40	0.40	0.40	0.40	0.50	0.50

FACTOR 5

MOISTURE CORRECTION FACTOR = PRECIPITABLE WATER (SFC-500MB) • RELATIVE HUMIDITY (SFC -500 MB)

STEP 3

FACTORS ARE SUMMED AND MULTIPLIED BY MOISTURE CORRECTION FACTOR:

TOTAL HALF-HOURLY CONVECTIVE RAINFALL ESTIMATES (IN INCHES) =

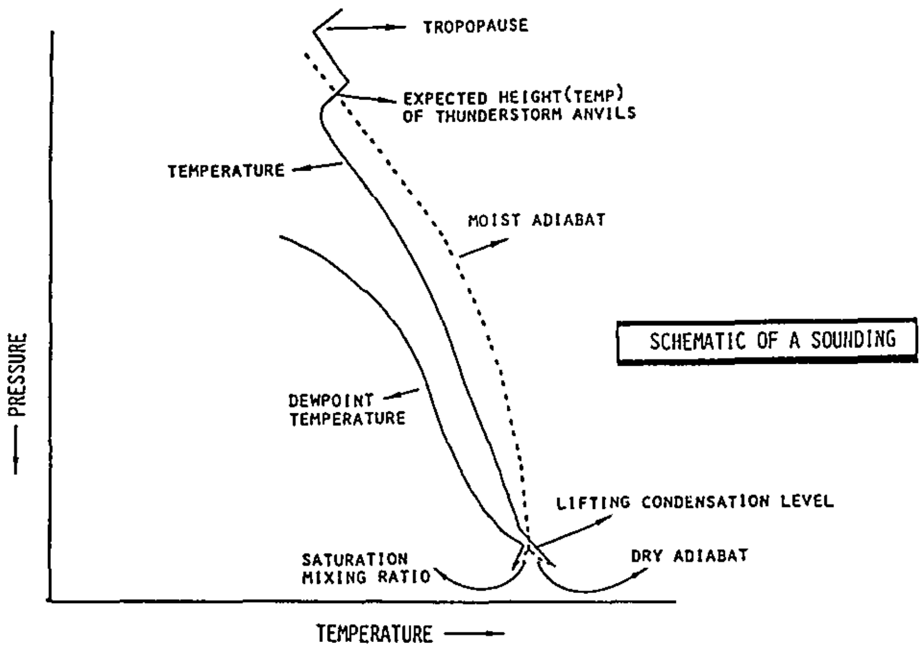
[(CLOUD-TOP TEMEPERATURE AND CLOUD GROWTH FACTOR OR DIVERGENCE ALOFT FACTOR)[1] + OVERSHOOTING TOP FACTOR[2] + MERGER FACTOR[3] + SATURATED ENVIRONMENT FACTOR[4]] • MOISTURE CORRECTION FACTOR[5]

END OF TECHNIQUE

APPENDIX C

CONVECTIVE STORM TECHNIQUE
WARM-TOP MODIFICATION

STEP 1. COMPUTE THE EXPECTED TEMPERATURE (EQUILIBRIUM LEVEL) OF CONVECTIVE TOPS FROM THE SOUNDINGS.



STEP 2. USE THIS TEMPERATURE AS THE SPREADING ANVIL LEVEL AND ASSIGN IT THE RAINFALL RATE OF THE WARMEST REPEAT GRAY LEVEL (BETWEEN -62 TO -67°C).

GO TO STEP 3

FROM STEP 2

STEP 3. COMPARE THE ANVIL TEMPERATURE WITH THE COMPUTED TEMPERATURE. FOR ANVIL TEMPERATURES COLDER THAN THE COMPUTED EXPECTED TEMPERATURES, USE AN APPROPRIATELY HIGHER ESTIMATED AMOUNT. FOR ANVIL TEMPERATURES WARMER THAN THE COMPUTED, ADJUST THE ESTIMATES UPWARD THE SAME RELATIVE AMOUNT.

STEP 4. USE THE ADJUSTED CLOUD-TOP TEMPERATURE TO CHANGE THE OTHER FACTORS, WHERE APPLICABLE.

USE THE ADJUSTED FACTORS OBTAINED IN THE ABOVE STEPS TO COMPUTE THE RAINFALL IN THE CONVECTIVE STORM TECHNIQUE.

TOTAL HALF-HOURLY CONVECTIVE RAINFALL ESTIMATES (IN INCHES) =

[CLOUD-TOP TEMPERATURE AND CLOUD GROWTH FACTOR OR DIVERGENCE ALOFT FACTOR + OVERSHOOTING TOP FACTOR + MERGER FACTOR + SATURATED ENVIRONMENT FACTOR]

X

[MOISTURE CORRECTION FACTOR]

END OF TECHNIQUE