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NOAA Technical Report NESDIS 11

Tropical Cyclone Intensity Analysis Using Satellite Data

Washington, D.C.
September 1984

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

NOAA TECHNICAL REPORTS

National Environmental Satellite, Data, and Information Service

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Tropical Cyclone Intensity Analysis Using Satellite Data

Vernon F. Dvorak
Satellite Applications Laboratory

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TROPICAL CYCLONE INTENSITY ANALYSIS USING SATELLITE DATA

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ABSTRACT. New and improved techniques for determining tropical cyclone intensity from satellite data have been developed over the past several years. This paper contains descriptions of methods designed to be used with visible, enhanced infrared and digital infrared data. The analysis techniques all use cloud feature measurements and rules based on a model of tropical cyclone development to arrive at the current and future intensity of a tropical cyclone. The model describes tropical cyclone development in terms of day by day changes in the cloud pattern of the storm and its environment. It contains cloud pattern descriptions at each stage of development and information on how they change with time. The VIS and IR techniques differ mainly in the cloud features that are used in the analysis and the way in which they are measured. The procedures and rules are the same for both methods.

The enhanced and digital infrared techniques, when applied to storms of hurricane strength, rely almost entirely on measurements of the "eye" temperature and the temperature of the clouds around the eye for the intensity determination. The enhanced infrared technique requires the use of a new concept to deal with the common occurrence of a sudden spreading of cold clouds over the central features of the disturbance. This central cold cover (CCC), when it persists, is used in the technique to signal an interruption in the development of the storm.

When visual pictures, or infrared pictures of weaker disturbances, are used for the intensity analysis the cloud feature measurements are usually more subjective and more complex. The analysis involves the appearance of the clouds forming the cloud system center and those encircling the center as well as measurements of these features. This results in more reliance on rules and modeling principles then is necessary with the enhanced or digital infrared technique.

Methods used to forecast tropical cyclone development and weakening are also described in the paper. These include a recently developed technique that uses cloud feature indications of changes in the westerly jet stream to forecast changes in tropical cyclone intensity.

I. INTRODUCTION

Tropical meteorologists have been using satellite pictures for monitoring tropical storms for almost 25 years. One of the most important applications of the pictures is in determining the intensity of the storms. The first methods developed for this purpose were used operationally in the early 1960's when only one satellite picture a day of a tropical cyclone was available for the analysis (Timchalk et al., 1965; Fett, 1964). At that time, the intensity estimation was made from the appearance of a storm's eye, its banding, and the size of the cloud pattern. These methods were useful for approximating the intensity of tropical storms in most cases, but they had serious shortcomings when the cloud pattern of a storm was either unclear or when it was undergoing extreme short-period change.

By the late 1960's, meteorologists had observed many tropical cyclones during their entire life cycles using good quality satellite pictures. Nighttime views and short-interval daytime pictures were also coming into use at that time with the advent of infrared (IR) sensors and geostationary satellites. Experience with these data shed new light on the relationship between tropical cyclone development and the cloud patterns observed in satellite pictures. One of the most important observations made during these years was that the cloud patterns of tropical cyclones evolve through recognizable stages as the intensity of the cyclone changed. The cloud patterns in general showed that the dense (cold) clouds of the disturbance formed around the storm center in the shape of a curved band in the early stages of development. The band was observed to curve halfway around the center at the weak tropical storm stage and completely around the center forming an "eye" at the weak hurricane stage. Further intensification was indicated by increasing dense (cold) clouds around the eye or by the eye becoming more well-defined (warmer). The difficulty with following this pattern evolution, however, was that the form and clarity of the pattern often varied with time. Periods of cloud pattern distortion, cloud dissipation, or of the development of an obscurring central overcast made it difficult to follow the evolution of the curved band pattern.

Movies made in subsequent years with pictures taken at short intervals showed that the cloud pattern did not evolve continuously from stage to stage but appeared to form in surges. The center as defined by the cloud features would appear well-defined and easy to interpret during a surge of pattern growth; but following the surge, the cloud features often became poorly defined and difficult to understand. The variability in the cyclone's cloud pattern appeared to result from several causes. Some of the variability was due to short-period convective-scale activity, some was related to diurnal influences, while other longer period distortions were due to the effects of adjacent circulations impinging on the storm. Much of the difficulty with intensity analysis during the 1960's arose when the only picture available for analysis was taken during a period when the cloud pattern was undergoing considerable variability. It was becoming apparent through these years that analysis procedures and rules would be needed along with additional cloud pattern signatures to derive consistently reliable intensity estimates from satellite pictures.

Other important observations made during the late 1960's concerned the initial development, future development, and the weakening of tropical cyclones as viewed in satellite pictures. It was found that cloud patterns normally showed indications of cyclogenesis 36 hours before the storm reached tropical storm intensity. Indications of whether or not a storm would continue to develop once the developmental process was initiated were also observed in the cloud features of both the storm and its environment. And when a storm started weakening, the indications of weakening in the cloud features were observed to precede the weakening shown in central pressure measurements of the storm. These observations suggested the possibility of using the pictures to make intensity forecasts.

The recognition of these and other factors led to a new technique for intensity analysis and forecasting using satellite pictures (Dvorak, 1972 and 1975). The technique came into operational use early in the 1970's and has been gradually improved over the years. During recent years, methods using enhanced IR and digital IR data have been added to the technique. By providing temperature measurements that are used in place of subjective judgments, these data make the analysis simpler and more objective than it is when visible pictures are used. The concepts underlying the technique are explained in this paper. A detailed description of the technique for use with visible or enhanced infrared imagery is given in the appendix.

II. TROPICAL CYCLONE ANALYSIS IN GENERAL

It is the pattern formed by the clouds of a tropical cyclone that is related to the cyclone's intensity and not the amount of clouds in the pattern.* Certain characteristics or features of the pattern such as those which form the storm center and the overcast around the center have been used for years to estimate tropical cyclone intensity. When the features are clear-cut and when they evolve in a systematic manner, they can be used to obtain reliable intensity estimates. But these essential features do not always appear clear-cut and may take on a variety of appearances at each level of cyclone intensity. There are also periods in the life cycle of storms such as the pre-storm stage and the weakening stage when some cloud patterns are known to be unrepresentative of the intensity of the storm. The analysis technique deals with this complexity through the use of systematic procedures, cloud pattern descriptions, and rules. The cloud pattern descriptions include measurable features used for quantitative analysis as well as drawings of cloud patterns to be used for qualitative comparisons. The descriptions show the cloud features that are related to storm intensity on each successive day of storm development to help the analyst recognize the essential elements in patterns of considerable complexity. The rules of the technique are designed to guide the use of the cloud pattern descriptions when the cloud pattern being analyzed is unclear or is known to be unrepresentative of the storm's intensity.

*Arnold (1977) could find no significant difference in the amount of convective cloudiness between stages of tropical cyclone development.

The analysis procedure of the technique consists of two major parts. In the first part, an estimate of cyclone intensity is obtained directly from measurements of the cloud features that are related to intensity. In the second part, another intensity estimate is made by comparing the cloud features of the cyclone being analyzed and their changes in time with those expected to occur in the cloud pattern descriptions in the technique. This subjective comparison of the day-by-day changes in a storm's cloud pattern with those in the descriptions becomes crucial when poor quality visible or unenhanced IR pictures are used in the analysis. The second estimate is used in the final analysis whenever good measurements are not possible. It is also used to determine limits within which the measured estimate must fall when measurable features are available.

III. A SIMPLIFIED VIEW, OR MODEL, OF TROPICAL CYCLONE DEVELOPMENT

The cloud pattern descriptions contained in the technique coupled with information on how they change with time can be thought of as a model of tropical cyclone development as observed in satellite pictures. Figure 1 is an example of the model. It shows the "curved band" pattern which is the most common type of cloud pattern seen in satellite pictures. The pattern is shown from left to right changing at the typical daily rate of development. Most tropical cyclones exhibit cloud patterns of the curved band pattern type through much of their lifetimes. The curved band pattern indicates an increase in cyclone intensity by an increase in the distance the overcast cloud band coils around the center of the cloud system. The cyclone's intensity at any given time is related to the distance the curved band is wrapped (coiled) around the center. When the cloud system being analyzed shows a day-by-day increase in the coiling of its cloud band at the same rate as that depicted in Figure 1, the storm is developing at the typical rate. When the curved band coils at a faster or slower rate than shown in the model, then a rapid or slow rate of growth is indicated. Storms that attain greater intensity than the peak intensity shown in the model are those that either develop at a rapid rate or those that develop over a longer period than 5 days.

The straight diagonal line in the figure illustrates the typical long-term growth rate observed in tropical cyclones. The rate is defined as one "T-number" per day. The T (for tropical) number is defined by the cloud features of a cyclone that are related to its intensity. Rapid and slow rates of growth (not shown) are most often observed to occur at 1 1/2 and 1/2 T-numbers per day, respectively. The empirical relationship between the T-numbers and the wind speed and central pressure (Atlantic) measurements used in the technique is shown on the left side of Figure 1. This relationship is also used in the eastern and central Pacific Oceans at the present time. The relationship between the wind speed (T-number) and the central pressure is observed to be significantly different in tropical cyclones in the northwest Pacific Ocean. The relationship is shown in the appendix, step 9. Examples of tropical cyclone cloud patterns at each T-number stage of development are shown in figure 2.

When the curved band pattern as shown in Figure 1 is recognizable in a tropical cyclone's cloud system on each day of its development and the rate of its change (coiling) is observed to be within reasonable limits, the analysis is simple and straightforward. But the simple cloud pattern as drawn in the figure may become complex and difficult to interpret at any time during its evolution. The pattern may be deformed by strong winds aloft or it may at times become obscured by a large dense overcast cloud mass. When these conditions exist additional pattern discriptions and rules are used in the technique to determine the storm's intensity. Also, frequent short period, mainly diurnal, changes occur in the clouds comprising the pattern (Oliver, 1974), (Browner et al, 1977). The changes can alter the intensity estimation made from the pattern. These changes are illustrated, or modeled, in Figure 1 as the wavy line superimposed on the straight diagonal line. Note that the amplitude of the fluctuations in the line is largest during the pre-storm stages of development and that they become less noticeable as the storm intensifies. The analysis technique deals with this type of fluctuation by allowing for little deviation from the typical rate of intensification during the pre-storm stage of cyclone development. During the remaining stages of development, the maximum rate of change of T-numbers (intensity) allowed by the rules of the technique is based on the past history of cloud pattern evolution and on the climatological extremes in pressure changes observed in tropical cyclones.

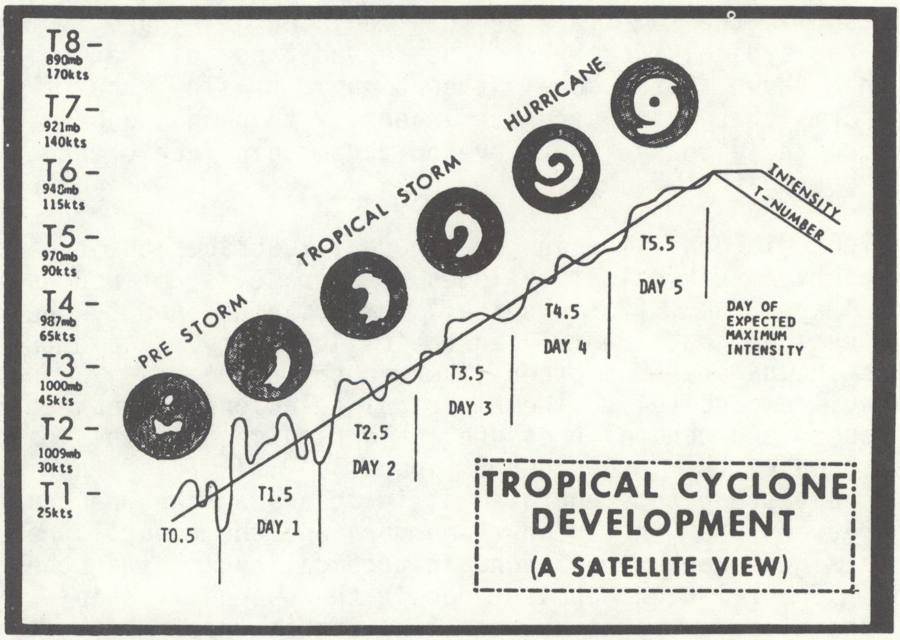


Fig. 1. Model of tropical cyclone development used in intensity analysis (curved band pattern type).

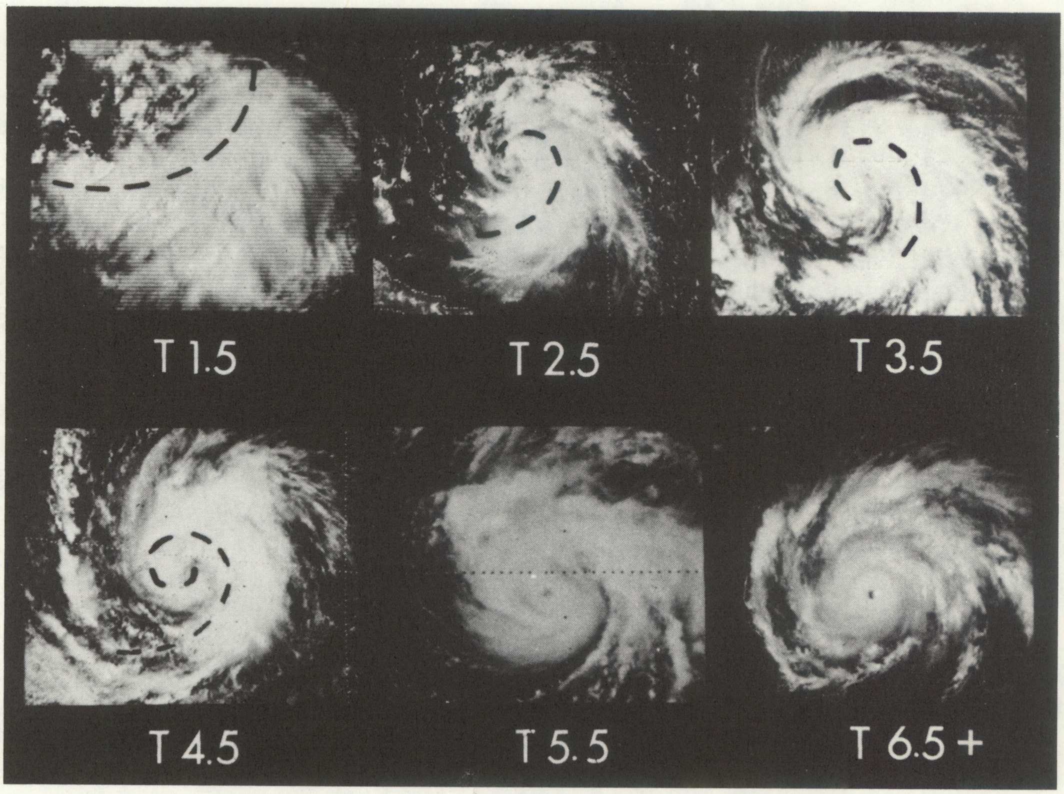


Fig. 2. Examples of tropical cyclone cloud patterns at each stage (T-number) of development. The dashed line follows the curved band axis.

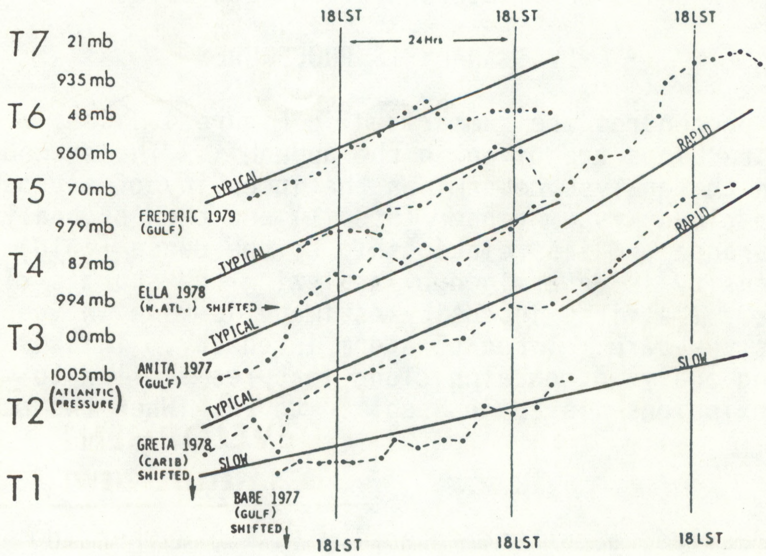


Figure 3. Plots of minimum central pressure for Atlantic hurricanes. Diagonal lines are modeled rates of intensity change used in analysis techniques.

The model in Figure 1 also includes a prediction of the day when a storm is likely to reach its maximum intensity. This is an estimate which is based on the direction of motion of the storm. A northwestward-moving storm is expected to "peak" 5 days after the T1 classification; westward moving storms, in 6 days; and northward-moving storms, in 4 days. The prediction is used in the model to alert analysts to the period when the subtle signs of peaking are likely to be observed. Note that after peaking, the T-number decreases more rapidly than does the intensity of the storm. This feature of the model is based on the observation that the indication of weakening in a storm's cloud pattern precedes the weakening of its pressure pattern (Lushine, 1977).*

Figure 3 shows how the central pressure changes in several hurricanes compare with the long-term developmental rates of change expected in the model used in the technique. Plots of all the hurricanes having frequent aircraft reconnaissance pressure data during the 1977, 1978, and 1979 seasons are shown. It can be seen that the average 24-hour change in pressure for most storms was approximated well by the typical curve used in the model (diagonal lines labeled "typical"). The typical one T-number a day rate of development occurs about 70 percent of the time in the Atlantic region. The later stages of Anita and Greta approximately follow the rapid curve of 1.5 T-number increase per day. Babe, at the bottom of the diagram, shows the slow rate of development (0.5 T-number per day). It is important to note that tropical storm growth as observed in changes in central pressure measurements, like that in cloud pattern changes, does not occur in a steady manner. The pressure falls are often observed to occur in surges followed by periods of little change or pressure rises. The pressure plots also suggest a tendency for a diurnal decrease in the growth rate of storms in general beginning near 1800 local standard time (LST). In the sample shown in Figure 3, the average pressure fall during the 6-hour period before 1800 LST is more than twice that observed after 1800 LST.

IV. ANALYSIS PROCEDURES

The analysis procedures are summarized in Figure 4. Complete analysis diagrams with instructions are given in the appendix. The procedures consist of ten steps in which the analyst determines the intensity of a tropical cyclone by first locating the cloud system center (Step 1) and then by analyzing the center's appearance and its relationship to the dense (cold) clouds of the pattern. The intensity is determined by analyzing the storm's cloud pattern in two different ways. The first intensity estimate is made in Step 2 by measuring the cloud features that are related to storm intensity. This is done when the cloud pattern being analyzed contains cloud features similar to those in the cloud pattern descriptions listed in Steps 2A to 2E. When the measurement

*In operational practice, a current intensity (C.I.) number, not the T-number, is used to describe the intensity of the storm. This is necessary because the actual intensity (C.I. number) remains higher than the T-number in weakening cyclones.

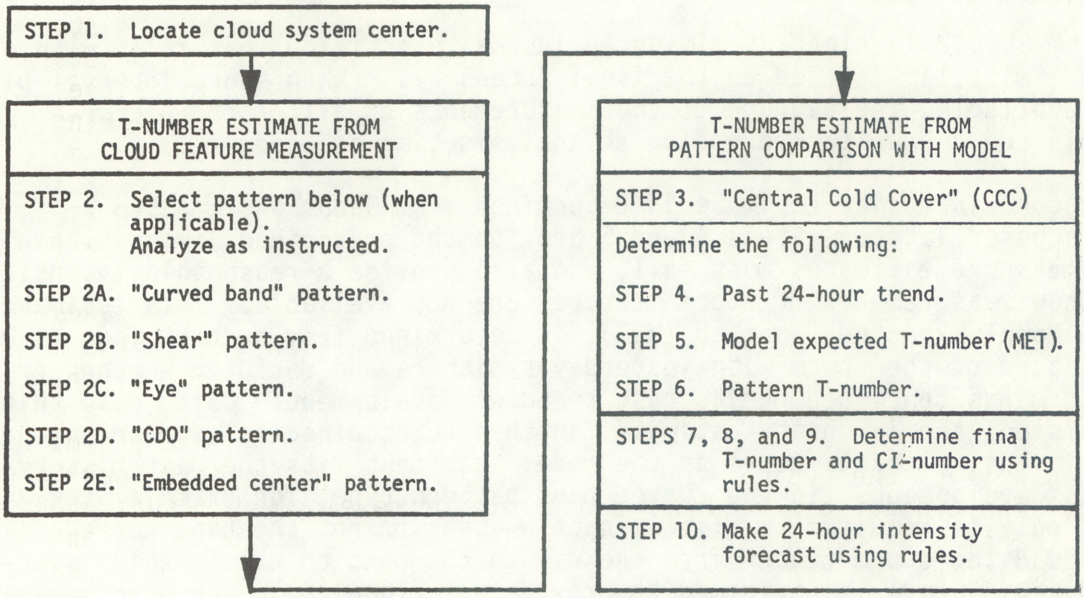


Fig. 4. Procedures for T-number determination.

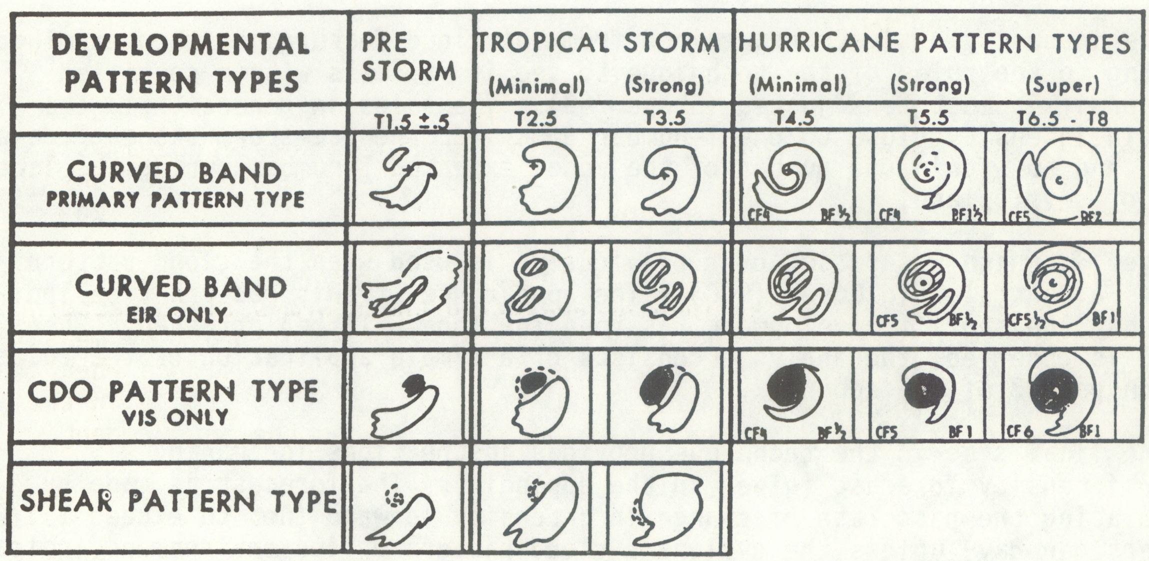


Fig. 5. Developmental cloud pattern types used in intensity analysis. Pattern changes from left to right are typical 24-hourly changes.

derived from Step 2 is clearcut giving an intensity estimate that falls within prescribed limits, it is used as the final intensity. (When short interval pictures are available, the average of the measurements of all of the pictures taken within the 3 hour period ending at analysis time is used.)

The second intensity estimate is determined from Steps 4-6. (Step 3 will be discussed later.) Steps 4 and 5 provide the prescribed limits within which the measured estimates must fall, and also provide a reasonable intensity estimate when measurements of storm features are not available. This estimate, called the Model Expected T-number (MET), is determined from a comparison of today's picture of the storm with yesterday's picture and deciding whether or not the storm has continued on its past trend of development. Using only this simple decision, the intensity estimate can then be obtained by extrapolation along the intensity change curve in the model that best fits the past history of the storm's development. In the curved band pattern type, for example, the analyst would only be required to discriminate whether or not the band curved farther around the storm center from one day to the next to obtain this intensity estimate. Step 6 is performed to provide a refinement to the Step 5 estimate of intensity. It is made by comparing the cloud pattern of the storm to patterns in the model that correspond to the stage of development indicated in Step 5. When the cloud pattern being analyzed appears to be obviously stronger or weaker than is expected from its past growth rate, the intensity estimate is adjusted up or down accordingly. This estimate of intensity is used whenever the cloud features related to storm intensity are distinguishable but not clearcut enough for measurement.

The intensity estimate determined from the cloud features is then examined according to the rules of the technique to see if it falls within specified limits or if it must be adjusted (Steps 7-9). The rules in general hold the change in intensity close to one T-number a day for the pre-storm stage of development and to within one number of the model expected T-number during the later stages of development.

Step 3, which was passed over previously, is used when the cloud pattern exhibits a Central Cold Cover (CCC). The appearance of this pattern type indicates that the storm's development has been (or soon will be) arrested. When the CCC is observed, the analysis consists of a simple application of the rules given on page 3 of the appendix.

The final step in the technique provides instructions for making a 24-hour intensity forecast (given in the appendix). The forecast is made by extrapolating the past rate of change in intensity forward (not to exceed 1 1/2 T-numbers per day) unless the cyclone's cloud pattern or its environment indicates that significant changes are occurring in the atmosphere. Strong favorable and unfavorable signs for future development are listed in the appendix along with rules for making the forecast.

V. CLOUD PATTERN DESCRIPTIONS USED WITH VISUAL PICTURES

The cloud pattern descriptions used in the technique are illustrated in Figure 5. The curved band pattern type (first row) is the primary developmental pattern type used in the technique. It is the most commonly observed pattern in both visible and IR pictures and is especially useful when low-resolution or unenhanced IR pictures are used. The pattern is observed when a storm is developing in an environment of average amounts of vertical shear and convection. For this pattern type, the storm intensity is determined from the extent to which a dense overcast cloud band encircles the storm center. At the minimal tropical storm stage, the band is observed to curve about halfway around the storm center. When the band has coiled completely around the storm center the hurricane stage has been attained if a required minimum length of time has elapsed during the coiling.* Continued strengthening of the hurricane or typhoon results either in continued coiling of the curved band or in the formation of a center or "eye" (cloud minimum) embedded in a dense overcast that appears central to the band curvature. When the eye is observed the intensity determination depends on the characteristics of the eye, the amount of dense overcast clouds surrounding it, and the amount of outer banding around these central features. The second row of pictures in Figure 5 shows the curved band pattern as it appears in enhanced IR pictures. The EIR pictures are discussed in the next section.

In some curved band patterns, the formation of a tightly curved "wall cloud" can also be used to tell when a disturbance has reached storm intensity. When visible, the wall cloud first appears at the concave edge of the curved band at the weak tropical storm stage (T2.5). Most often it appears as a cloud minimum area of about 1° latitude in diameter with deep-layer convective clouds forming about half the distance around the area. A forming wall cloud is visible in the T2.5 pattern shown in figure 2.

The Central Dense Overcast (CDO) pattern shown in the third row of Figure 5 is used in the analysis when a dense overcast cloud mass appears either over the curved cloud features that define the storm center or as a dense overcast surrounding the eye of the storm. The CDO can be thought of as a dense overcast mass of cloud that covers the most tightly curved inner coils of the curved band pattern. The CDO patterns are used only with visible pictures. In IR imagery, the thin cirrus clouds often appear cold enough to obscure the boundaries of the CDO making its size larger than the size observed in visible imagery. When the CDO pattern is observed, it is the size of the dense cloud

*Occasionally the coiling occurs more rapidly than pressure falls are known to occur. When this happens, the rules of the technique hold back the classification until the minimum length of time has passed.

mass that is used as a measure of intensity when no eye is observed. The size increases with increasing intensity. An eye usually becomes visible within the CDO before the T5 stage. When the CDO contains an eye, the distance the eye is embedded within the CDO is used in the intensity estimate. For cloud patterns containing CDO's and for most patterns of hurricane intensity, it is often necessary to make two measurements. The first is a measure of the central feature (CF), such as the CDO size or the embedded distance of the eye. The second is a measure of the banding feature (BF) , which is the amount of banding that coils around the central dense overcast. The banding features can be very important in the VIS analysis, adding as much as 2.5 T-numbers to the intensity estimate.

Examples of how the banding feature number (BF) increases with the amount of banding are shown in the hurricane patterns in Figure 5. Note also how the central feature number (CF) increases as the eye becomes more deeply embedded within the CDO. Another important factor in determining the T-number is knowing the vertical depth of the clouds involved in the central and banding features. An estimation of the vertical depth is made subjectively when using visible pictures. In the enhanced IR technique which is discussed in the next section, it will be seen that objective measures of the vertical depth (which are temperature measurements) of cloud features play the major role in the new method. When analysis rules are needed to adjust the intensity estimation, the equation for determining intensity can be written as:

T-Number = (CF + BF + Vert Depth) + Rules.

The "shear" pattern type in the fourth row of Figure 5 is used when vertical shear prevents the dense, upper-level clouds of the system from coiling around the storm center as they do in the curved band pattern. This results in the dense overcast clouds of the system appearing off to the side of the low cloud center of the disturbances. Figure 5 shows an example of relatively strong upper-level westerly flow causing the dense overcast clouds of the disturbance to be displaced to the east of the low-level center. When a shear pattern is observed, it is the curvature of the low cloud lines and their proximity to dense overcast clouds that are used to determine the intensity of the storm. When parallel, circularly curved lines form a cloud system center near the edge of a large dense cloud mass, minimal tropical storm intensity is indicated.

VI. INTENSITY ANALYSIS USING INFRARED AND ENHANCED INFRARED PICTURES

Infrared (IR) pictures are important in tropical cyclone analysis because they enable the analyst to monitor a storm's activity continuously night and day. The IR image of a tropical cyclone appears similar to that seen in a VIS picture of the same storm. In fact, the day by day changes in the cloud patterns shown in figure 1 can often be followed qualitatively in the IR picture in the same way they are in VIS imagery. However, there are two major differences between VIS and IR pictures as far as intensity analysis is concerned. The first is that the thin cirrus clouds which are normally transparent in the VIS pictures are often opaque in the IR; and when the cirrus covers the boundaries of cloud features used for measurement the IR image either provides no measurement or an erroneous one. This means that the CDO size and eye embedded distance measurements cannot be used in the analysis of unenhanced IR pictures.

The second difference between VIS and IR pictures is that the low cloud lines that are important in locating the storm center may not be visible in the IR picture. This problem is a serious one when unenhanced pictures are used but it can usually be solved by the enhancement procedures discussed below.

A technique using Enhanced InfraRed (EIR) pictures for determining tropical cyclone intensity was developed in 1978 (Dvorak and Wright). The method uses IR images that display the cloud features related to cyclone intensity in discreet gray shades representing known temperatures ranges. This enables the analyst to use the temperatures of the features as objective measures of intensity. The temperature of the eye and the temperature of the clouds surrounding the eye are of primary importance in the technique. These simple measurements replace several difficult subjective judgements required in the VIS technique to make an intensity estimate of the same storm.

During the early stages of cyclogenesis the EIR method is the same as the curved band analysis in the VIS technique. The intensity estimate is determined by the amount the curved band has coiled around the storm center. An example of how the amount of coiling is measured in opertional practice is shown in figure 6, (left side). A 10° log spiral is overlayed on the curved band axis of the storm's cloud pattern and then the number of tenths of the spiral covered by the cold portion of the band are counted. This spiral arc distance is empirically related to the storm's intensity. In the case shown an arc distance of 7/10 of a spiral represents a moderately strong tropical storm of T3 intensity.

When the curved band has coiled once around the storm center at the weak hurricane stage the EIR technique becomes much simpler and more objective than the VIS method. The analysis consists primarily of taking two simple measurements as shown in figure 6 (right side). The first measurement is the temperature of the coldest band (of a required minimum width) that completely surrounds the eye. The surrounding temperature or "surr temp" in the figure is displayed as a light gray shade. This temperature and the temperature of the eye contribute 5.0 and 0.5 respectively to the intensity estimate (T5.5) of the storm with the aid of empical relationships given on page two of the appendix. A simple version of this procedure is also used with digital IR data as shown in figure 9. A stronger hurricane than the one shown would exhibit either a colder surr temp or a warmer eye temp. The technique also allows for a small increase in the intensity estimate when a cold band is observed curved around the central cold area surrounding the eye. This addition is made only when the primary measurements result in a T-number that is lower than the model expected T-number.

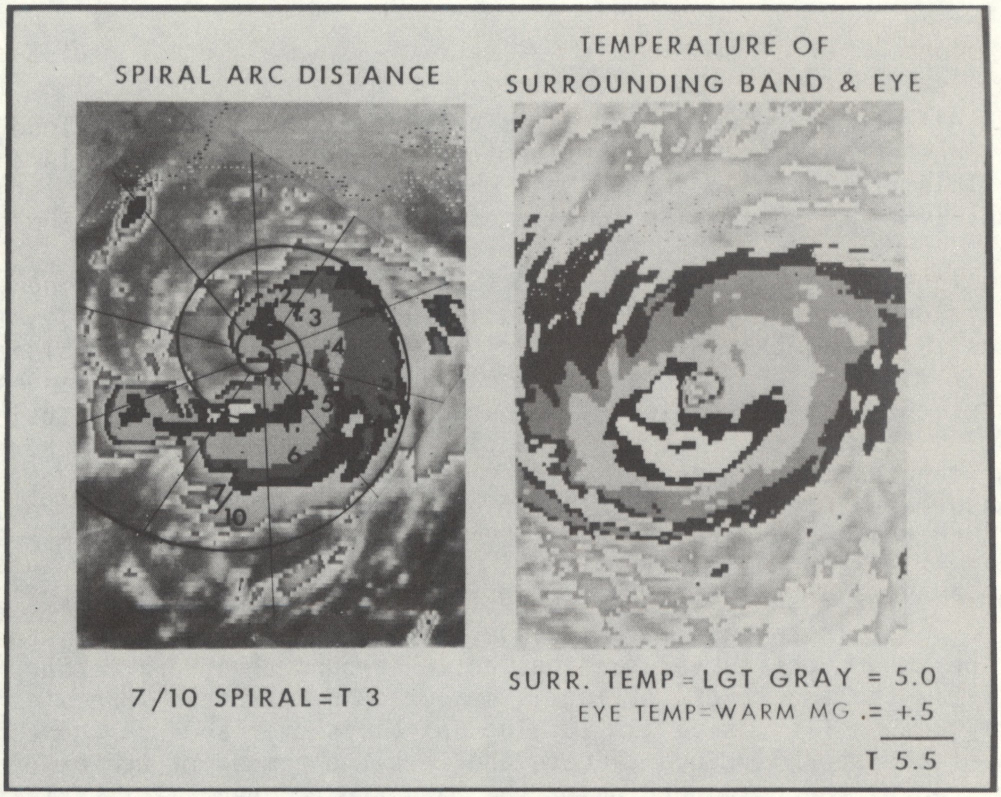


Fig 6. Enhanced IR pictures of a tropical storm (left) and a hurricane (right). Quantitative parameters used in intensity analysis are shown.

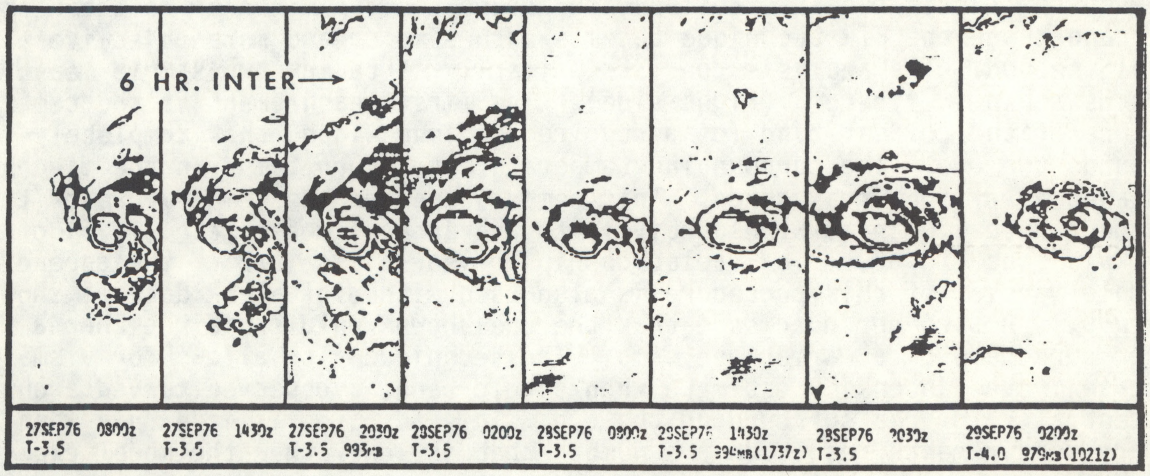


Fig. 7. Example of the life cycle of the Central Cold Cover (CCC). The central pressure of the storm stops falling when the CCC develops and the curved band begins to dissipate (Pictures at left). Pressure falls resume as the pattern redevelops (Pictures at right).

When short interval pictures are available, a more precise analysis can be made by using several pictures instead of the one at analysis time. This is done by using the average measurement of all of the pictures showing measureable features taken during the 3 hour period ending at analysis time. For pictures with eyes the average measurements can be used with the nomogram shown in figure 9 to obtain a T-number. For weaker disturbances the average curved band arc length can be converted into a T-number by using 2A on page 4 of the appendix.

The use of enhanced IR pictures in tropical cyclone analysis has resulted in the creation of a new concept, or pattern type, called the "central cold cover" (CCC). The CCC is observed as a round, cold overcast near the storm center that develops as the curved band pattern dissipates. These phenomena can occur at any stage of storm development and may last for several hours or for several days. When it persists, it is related to a stoppage of storm development. Figure 7 shows the life cycle of the central cold cover in pictures taken at 6-hourly intervals shown from left to right. The picture on the left shows the curved band pattern curving around the storm center at the strong tropical storm stage, approaching hurricane intensity. (The white and black shades follow the axis of the curved band.) Normal development would show the band curling farther around forming an eye within the next 12 hours (the next two pictures to the right). But in this case, the cold overcast near the storm center increases in size as the curved band of the pattern weakens. It is not until 36 hours later, in the next to the last picture on the right, that the curved band pattern reappears arched across the north side of the cloud system indicating that development is once more taking place. The central pressure of the storm resumed falling at about this time. The picture at the far right shows the warm-spot eye surrounded by a ring of cold clouds, indicating that the weak hurricane stage has finally been reached. Reconnaissance central pressure measurements taken during the occurrence of the central cold cover have shown that no significant change in storm intensity takes place during its occurrence. Consequently, the appearance of the cold central cover is used in the technique to signal an interruption in the development of a storm. The CCC pattern is also observed occasionally in visible pictures when the expanding cirrus is thick enough to obscure the storm pattern under it. When this occurs, the same rules apply.

For hurricane patterns exhibiting an eye, the enhanced IR pictures also provide a clearcut track of a storm. Figure 8 shows the tracks of hurricanes Anita and Frederic as they approach the coastline in the Gulf of Mexico. The temperature contour outlining the eye was traced directly from enhanced pictures produced operationally at 1- to 3-hour intervals. The eye positions of both storms indicate a loop as the eye first forms, and then show a clearly defined track as the storms intensify and move toward the coastline. Note that there is an oscillation in both of the tracks. The periods of the oscillations are not clearcut but appear to be about 10 to 12 hours in duration.

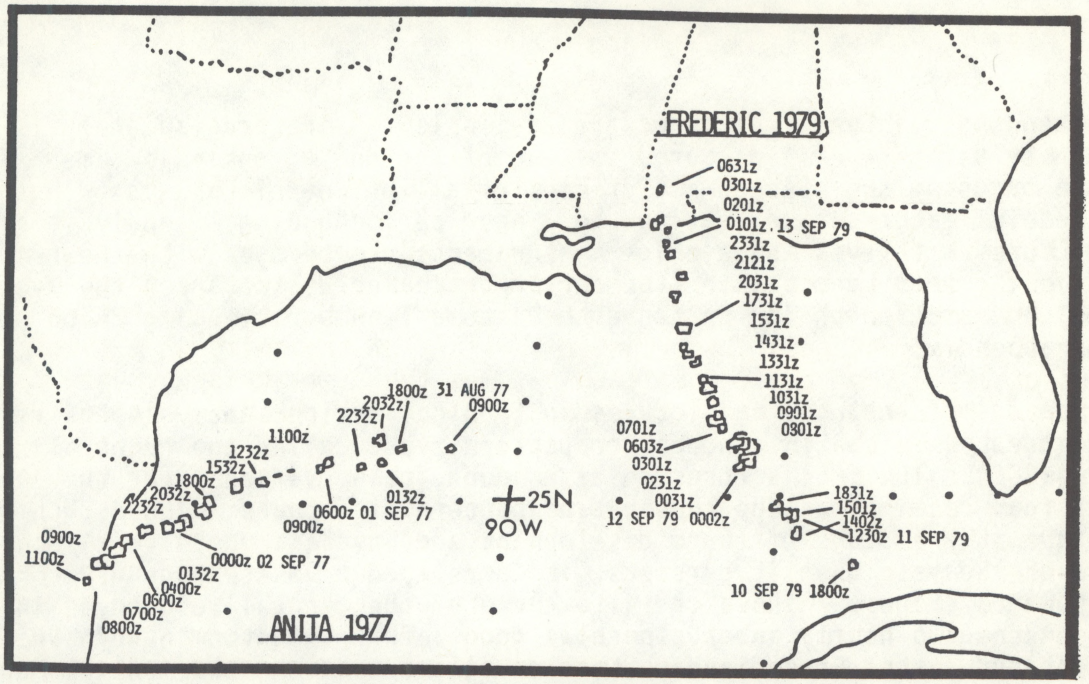


Figure 8. Tracks of hurricanes Anita and Frederic traced from the inner temperature contours of the eyes in enhanced IR pictures.

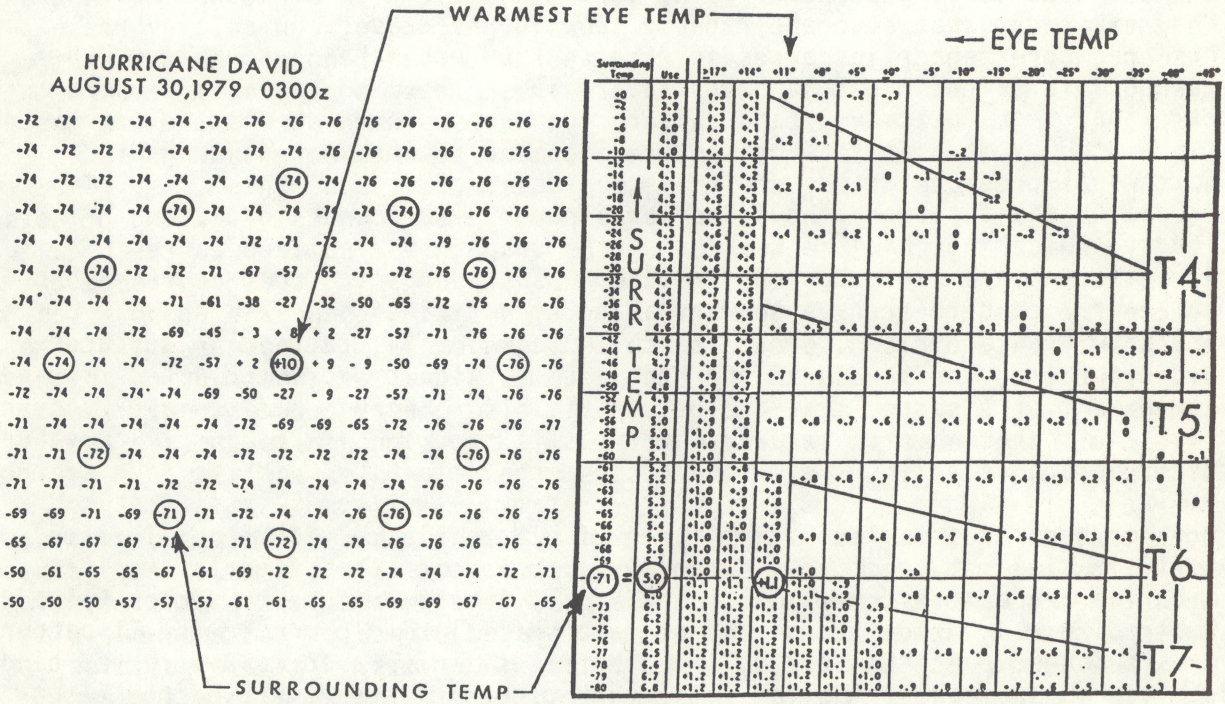


Fig. 9. Method for determining hurricane intensity from digital IR data. The digital printout on the left provides two temperature values which when entered in nomogram on the right result in an intensity estimate of T7. The surrounding temperature of -71°C contributes 5.9 while the relatively warm eye adds 1.1 to the T-number

VII. ANALYSIS USING DIGITAL IR DATA

The analysis technique has been simplified further by using digital print-outs of IR data in the analysis. By placing an overlay on a print-out of a storm, the analyst simply reads off two temperatures, the temperature of the center (the warmest point) and the temperature of the point on a circle with a radius of 30 nm from the center that defines the coldest surrounding temperature. By using the nomogram shown in Figure 9, these two values yield the intensity. When the intensities are calculated at short intervals and then averaged over 3-hourly periods, they produce intensities similar to those computed from reconnaissance dropsonde measurements. Figure 10 shows a plot of the intensity estimates from digital IR data of hurricanes Anita and Frederic. The 3-hourly mean satellite intensities are plotted as crosses connected by lines while the reconnaissance pressures are plotted as P's. The agreement between the two estimates is generally good. When the storm starts to weaken, however, as in the Frederic case, the satellite measurements indicate less intensity than the pressure shows. This phenomenon is typical in weakening storms and will be discussed in Section 8. To account for it, the rules of the technique hold the intensity of weakening storms at a higher intensity than that indicated by the cloud-top temperature measurements. In the Frederic case, the rules provide the intensity estimates indicated by the dashed line on the right side of the figure.

VIII. TROPICAL CYCLONE DEVELOPMENT ACCORDING TO THE MODEL

a. Initial tropical cyclone development (Day 1 in Figure 11)

The initial indications of development (T1) appear approximately 36 hours before the disturbance reaches tropical storm intensity. This is some 24 hours before significant pressure falls are normally observed in surface measurements. The T1 classification is made when curved cloud lines or bands indicate that a system center has been near to or within a deep-layer convective cloud system for a period of at least 12 hours. The radius of curvature of the lines, the center's proximity to deep convection, and the size of the overcast are all important factors for determining the T1 classification. Note that it is the close association of moderately curved cloud lines or bands and a sizable amount of deep-layer convection that signals tropical cyclogenesis. This means that either cloud line curvature or a convective cloud system by itself does not indicate initial development. The T1 pattern shown in Figure 11, Day 1 (15Z), is characterized by a formative curved band made up of dense (deep layer) convective clouds clustered around one cloud system center. By 21Z, the band is well formed and curves about one-fourth the distance around the center of the disturbance.

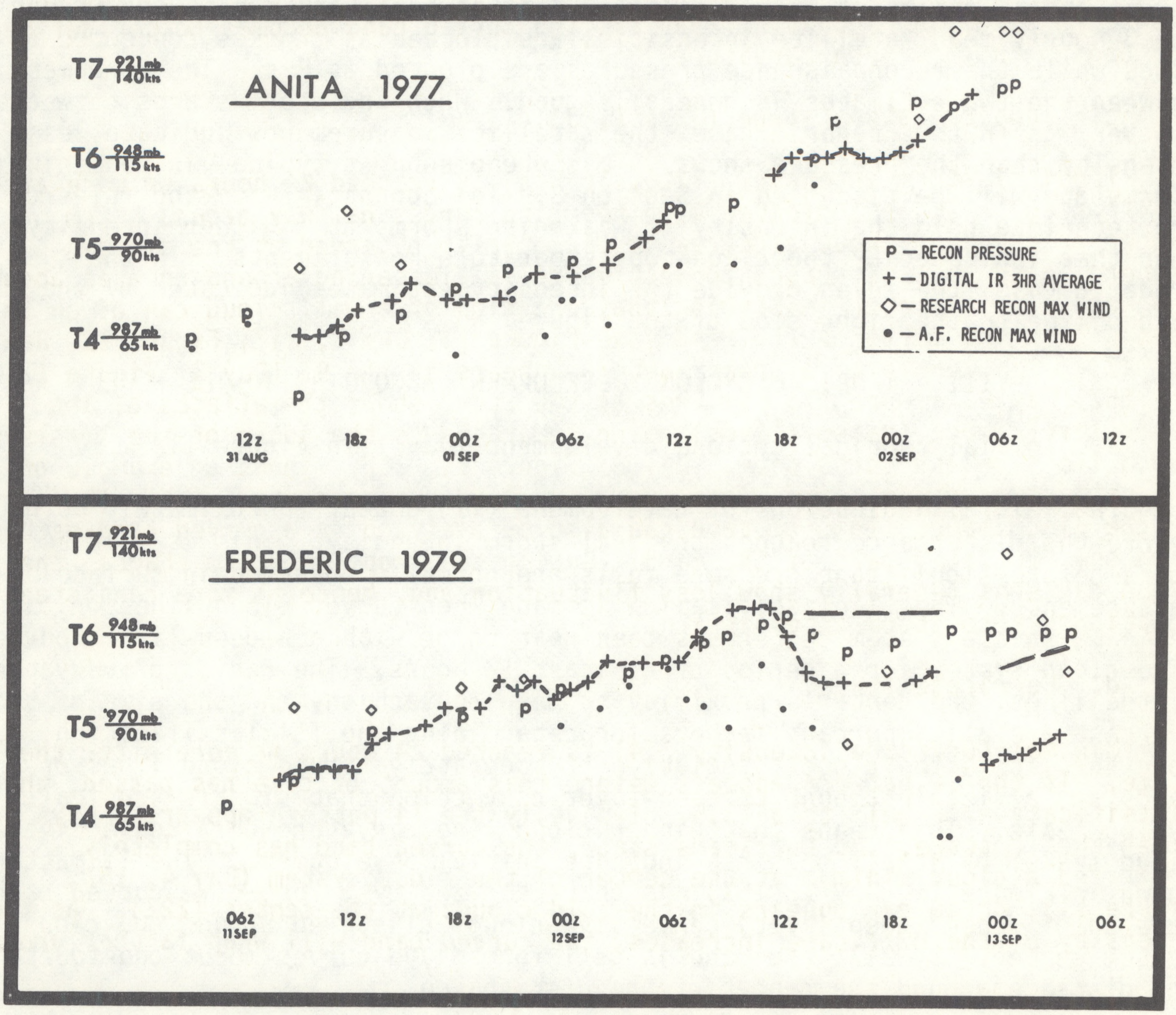


Fig. 10. Comparison of digital IR intensity estimates (+) with those from reconnaissance central pressure (P), and maximum winds.

b. Pre-storm stage (Days 1, 2).

Once a cloud system displays the signs of initial tropical cyclone development, intensification continues at a rate of one T-number a day unless otherwise indicated. That is, when a cloud system shows signs of development over a 24-hour interval and the changes in its pattern are similar to those shown in Figure 5, the disturbance is developing at the typical rate. During the pre-storm stage of development, the cloud pattern of a disturbance may indicate rapid short-period development that is known to be unrepresentative of surface cyclone development. For this reason, prestorm changes in T-numbers are constrained to one and 1/2 T-numbers per day no matter how strong the pattern may appear at the initial stage or 24 hours later.* The loss of clouds in the pattern at night may also be deceptive. This tendency requires a rule that prohibits the weakening of the pre-storm disturbances during nighttime hours. Note that much of the cloud cover comprising the storm pattern has dissipated during the nighttime hours on Day 2, 09Z, Figure 12. During the pre-storm stage in Figures, 11 and 12, the curved band becomes better defined and begins to show more curvature.

c. Tropical storm stage (Days 2, 3)

Tropical storm intensity (T2.5, 35 kts) is reached 24 hours or more after the T1 stage. It is indicated when the band curves halfway around storm center or a CDO of about a degree in diameter is observed at the system center. Also at this stage, convective cells clustering around an area about one degree in diameter indicating the formation of a wall cloud can often be seen within the curve of the band (see Figure 11, Day 2, 21Z; Figure 12, Day 3, 04Z). An example of a shear pattern appears in the 9Z (Day 3, Figure 12) and 15Z (Day 2, Figure 11) pictures as the storm shows the effects of its upper-level ridge (dense clouds) being separated to the south of the low-level cloud lines on its north side. Day 3, Figure 11, 20Z, shows an example of a CDO pattern as dense clouds form over the cloud system center within the curve of the cloud band. This pattern can also be analyzed as a curved band pattern with the CDO being part of the band. During the tropical storm stages, the cloud patterns generally show less fluctuation and, hence, a more consistent relationship to storm intensity.

d. Hurricane stage

Minimal hurricane intensity (T4) is reached 24 hours or more after the T2 stage. If the T4 pattern appears before this amount of time has passed, the classification is held to a T3.5. Typically the T4 pattern appears 2 days after the T2 stage. At hurricane stage, the curved band has completely encircled a cloud minimum at the center of the cloud system (Day 4, 15Z, Figure 11), or an eye appears in the cold clouds at the center (22Z). As the intensity of the hurricane increases, the curved band will wrap farther around

*There is a type of "subtropical" cyclogenesis, however, for which the rule does not apply. It is a very rapidly developing storm in the strong vorticity environment of a cutoff cold low or a cold low in the process of cutting off. This pattern evolution is described in a classification technique for subtropical cyclones (Hebert and Poteat, 1975).

Fig. 11. A 5-day sequence of pictures of hurricane Anita. Two VIS pictures taken about 6 hours apart are shown for each day with drawings illustrating the essential features of each picture. Details of the intensity analysis are listed below the pictures.

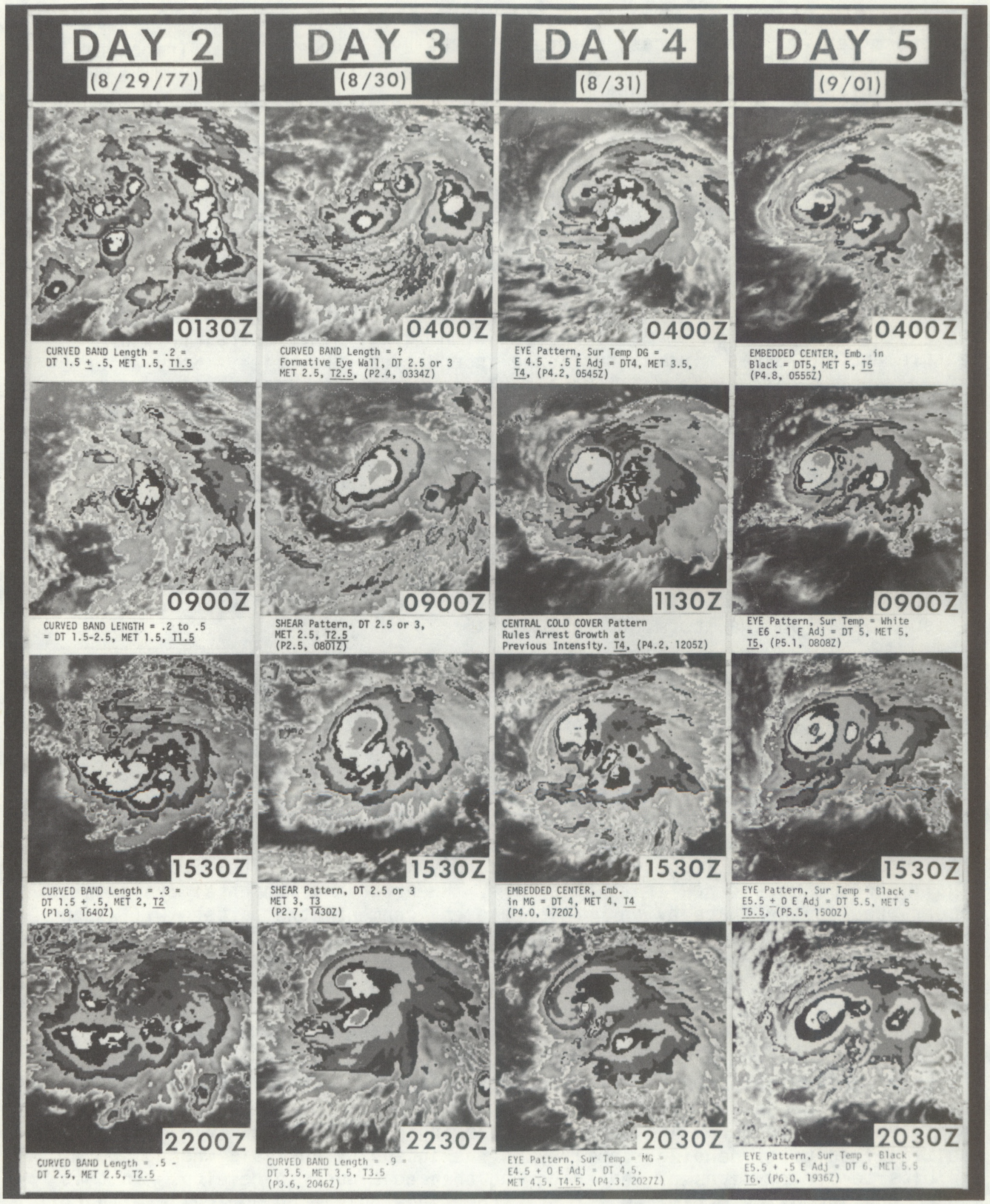


Fig. 12. Enhanced IR pictures taken at approximately 6-hour intervals are shown for 4 days in the life of hurricane Anita. The bottom two rows of pictures were taken at approximately the same time as the VIS pictures in Fig. 10.

the storm center, the overcast surrounding the eye becomes colder (smoother in appearance), or the eye of the storm will become either more deeply embedded in the overcast or warmer (more distinctly defined). In Figure 11, day 4 and 5 the eye of Anita becomes more sharply defined and more embedded in dense (smoother textured) clouds in time indicating continued development. In VIS imagery, an increase in the smoothness of the texture of the CDO containing an eye is also indicative of an increase of intensity. This is considered to be an increase in the vertical depth parameter.

Figure 12 shows the enhanced IR view of Anita's pattern evolution night and day at 6-hourly intervals. In these data, the curved band can be seen late on Day 3 to be curving strongly around the storm center and completely encircling a large cloud-free "eye" by 04Z on Day 4. The central pressure measurement indicates minimal hurricane intensity at that time. Soon after 04Z, a central cold cover develops (1130Z picture) arresting development until about 20Z when an eye (dark spot) first appears. The cloud pattern began to show signs of redevelopment (curvature in the white central clouds in 1530Z picture) some 6 hours before the pressure resumed falling. It is only when the pattern evolves beyond the stage commensurate with the current pressure (T4) that the pressure begins to fall. On Day 5, rapid development is observed as the center first appears embedded in the black temperature shade at 04Z, surrounded by white at 09Z, then warming rapidly for the rest of the day. The eye stopped warming at the time the lowest pressure was recorded in the storm. These temperature changes provide hour-by-hour moinitoring of the pressure falls in the storm.

e. Weakening stage (not shown in Figures 11 and 12)

The tropical cyclone is expected to reach its maximum intensity from 4 to 6 days after the T1 stage is observed if its environment remains favorable for that length of time. Northward-moving storms will "peak" in 4 days, northwestward-moving storms in 5 days, and westward-moving storms in 6 days. As the cloud pattern peaks in an environment of low or moderate vertical wind shear, it will begin to show less well-defined boundaries and less smoothness of its canopy in visible imagery (a warmer canopy in the IR). The pattern will usually become more circular at this time. When the developmental cycle is interrupted at any stage by an unfavorable environment, the pattern will show either the dense (cold) clouds separating from the low-level center, a non-diurnal lowering (warming) of the cloud tops, or a rapid expansion of dense (cold) clouds out from the storm center as the curved band dissipates.

When the storm begins to weaken, the indications of the weakening will be observed from 6 to 12 hours in advance of the weakening revealed by rises in the central pressure measurements of the storm (Lushine, 1977). For this reason, the rules of the technique hold the intensity of the storm higher than the cloud features indicate for weakening patterns. The rule has the additional value of lending stability to the intensity analysis when a storm exhibits temporary signs of weakening and then continues to develop. In this event, the intensity estimates for the storm show only a temporary leveling off in its trend rather than a yoyo effect. Because of the difference between a storm's intensity and its T-number, a current intensity (CI) number is used to describe the intensity of a storm, not the T-number. While the T-number and the CI-number are the same for developing storms, the CI-number is held higher than the T-number for weakening storms. (See weakening curve labeled "intensity" in Figure 1.)

IX. INTENSITY FORECASTING

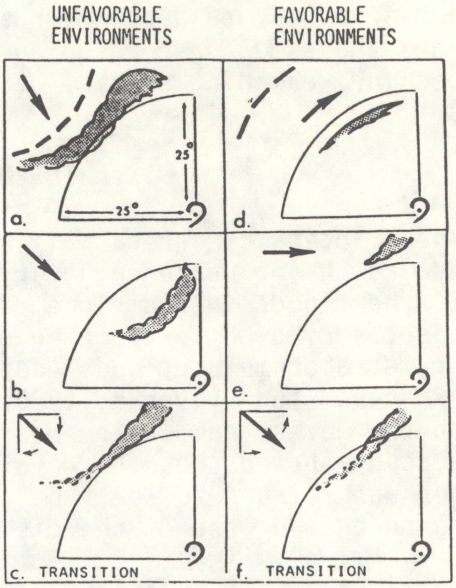
A 24-hour intensity forecast is made by first extrapolating forward along the modeled growth (or weakening) curve of the storm. The forecast is then modified if the clouds in the cloud pattern are changing significantly or when the storm is observed to be entering or leaving an environment of strong vertical shear, stratocumulus clouds (cold water), land, or southward-moving cirrus. A recent study (Dvorak, 1980) has also shown that cloud bands associated with the jet stream in the westerlies can be used to forecast development. The study showed that the development of westward-moving tropical disturbances was related to the type of banding visible within an area 25° latitude to the north and west of the disturbances.

Figure 13 is an illustration of the upstream environments that were unfavorable for future development (on the left) and those that were favorable (on the right). Unfavorable environments were those which had a strong (white in IR pictures), cyclonically curved band entering the area (a), or forming within the area (b and c). Favorable environments were characterized by anticyclonically curved bands (d), no banding (e), or weakening cyclonically curved bands (f) within the area. The strong cyclonically curved bands (unfavorable environments) appeared to be related to a southward directed jet in the westerly stream to the north of the band (arrows indicate the axis of the maximum wind on the 250-mb surface). Weldon (1979) has related such cloud band formation to frontogenesis and deformation in advance of the jet stream speed maximum. Anticyclonically curved bands, no banding, or weakening cyclonically curved bands appear to be related to a jet that was either directed over (to the north of) the environment of the disturbance or was too far upstream to affect the environment. Figures (c) and (f) at the bottom of the figure illustrate the transition states. In (c), the band forms southwestward as the jet turns more southward, and in (f) where the band weakens to the north as the jet turns more northward.

In cases where both cyclonically and anticyclonically curved bands are observed in the upstream environment of the disturbance, it is the broadscale curve of the current in which the shortwave systems are embedded that is important. When the current appears to be undergoing rapid change, it is the curvature of the more northerly (or upstream) banding that usually provides the best forecast. In general, the curved band rule does not apply to disturbances that turn to a near northerly direction or for those that stop moving westward. It is best used for westward or northwestward moving disturbance whose cloud patterns have begun to show the effects of the environmental change.

A study of cyclogenesis in the Atlantic region during the 1978 season (Dvorak, 1979) showed a similar relationship of tropical cyclone development to changes in the westerly current except for one curious difference. That study

Fig. 13. Illustrations of environments that are unfavorable (left), favorable (right) for continued development of westward-moving tropical disturbances.



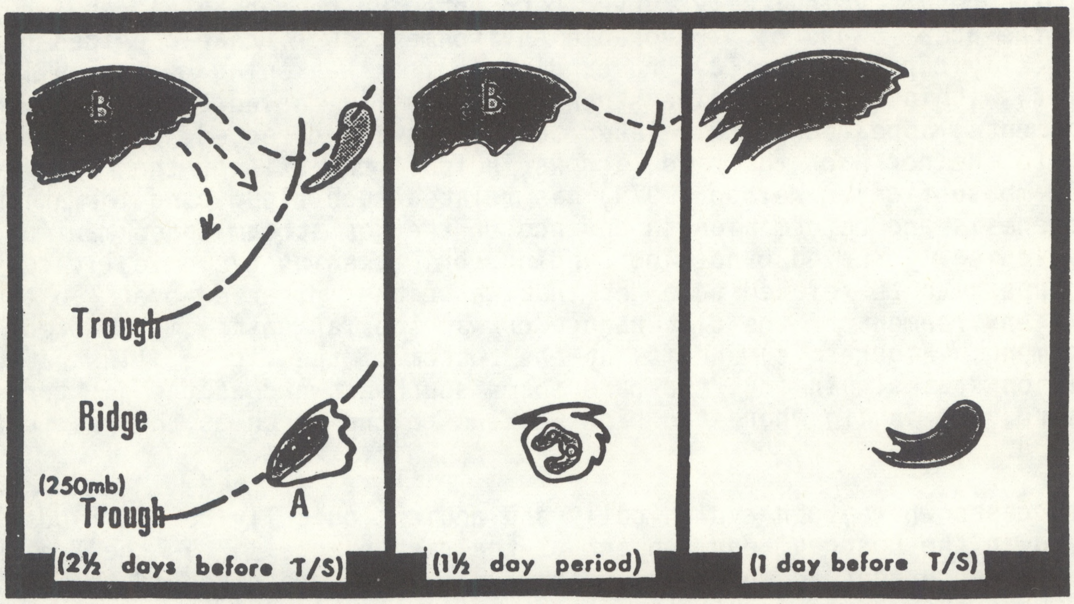


Fig. 14. Sequence of events associated with tropical cyclogenesis observed in most 1978 Atlantic storms. Cloud cluster is distorted by trough passages in left panel, then takes on a more circular pattern after trough passage (center), developing the curved band pattern about one day before tropical storm intensity is reached. After the trough passage, development is associated with anticyclonically curved banding or no banding to the northwest of the disturbance.

showed that most initial developments (T1) that year were preceded by a straightening of the northern edge of the cloud clusters just prior to the onset of cyclogenesis (see the left panel of figure 14). The straightening of the edge appeared to be related to the passage of a trough in the westerlies with the disturbances appearing at position A relative to the upper level troughs at the time of initiation. The occurrence appeared to play a role in the initiation of the cyclone development. The disturbances were probably involved with the transitional environment pictured in Figure 13f. During the subsequent development of most of the disturbances that year, an eastward moving anticyclonically curved band appeared northwestward of the disturbances as would be expected from the previously mentioned study. (See the curved bands at the top of the panels in figure 14.) Throughout the period shown in the figure the cloud pattern of the disturbance undergoing cyclogenesis exhibits a persistent cloud cluster that contains curved lines which define a cloud system center near dense overcast clouds. These features along with size requirements are used in the technique to forecast cyclogenesis.

X. ACCURACY OF INTENSITY ESTIMATES

The accuracy of tropical cyclone intensity estimates determined by satellite methods, or for that matter any method, is difficult to evaluate. This point is illustrated by the reconnaissance verification data shown in Figure 10. The regular U.S. Air Force reconnaissance maximum wind measurements are often found to be lower than the true wind speed of the storm since the maximum wind area is not usually intersected by the aircraft (see black dots). On the other hand, research aircraft in recent years have been reporting unexpected high winds for short periods in storms (see diamonds for Anita). The problems with using the extremely variable wind data from reconnaissance aircraft have led to a heavy reliance on an average maximum wind estimate that is inferred from reconnaissance pressure measurements when these are available. The post-season "best track" analyses of storm intensities also relies heavily on the empirically derived central pressure--maximum wind relationship. The satellite intensity estimates using methods developed from best-track data relate best with the central pressure measurements. Figure 15 shows the relationship between maximum wind speed measurements, central pressure estimates, and satellite intensity estimates of tropical cyclone Gert in 1981. The wind and pressure measurements were made by NOAA research aircraft. Each wind speed (W) indicated in the figure is the maximum observed four consecutive eyewall penetrations in about 1 hour's time. The pressure estimate was computed from the flight level height while flying at 850 mb. Reducing the smoothed maximum wind curve by 20 percent as recommended by Powell (1980) brings it into good agreement with the central pressure curve. It can also be seen that the operational satellite estimates agree well with the smoothed central pressure curve. The smooth curves represent an average maximum wind or minimum pressure over periods of about 6 hours. Tropical storm Gert at the time of these observations was recurving northward into a strong westerly current and probably shows a greater than average variability in its wind and pressure fields as a consequence.

Early studies by Erickson (1972) and Sheets (1975) compared satellite estimates of storm intensities with best-track data. The estimates were made from once-a-day visible pictures of varying quality by a selected group of analysts with experience in satellite picture interpretation. The results of the studies showed an average difference between the satellite estimates and the best-track intensity data of approximately 11 kts. The two most-recent studies comparing operational satellite intensity estimates with best-track estimates (Shewchuck and Weir, 1980; Gaby et al., 1980), using better quality pictures and more than one observation a day, indicate an average difference from the best-track maximum winds of 3 knots in the West Pacific region and 7 knots in the Atlantic. Unfortunately these more recent results are biased, especially in the Pacific where the satellite data have become a significant input into the best track computations. Shewchuck and Weir also found that "the mean error for the satellite forecasts was superior to the official JTWC 24-hour intensity forecasts" for the West Pacific region.

Enhanced IR pictures have been in operational use for only 3 years. Gaby et al. (1980) found after the first year of use that no significant difference in accuracy was evident between the EIR method and the visible. They also state that most meteorologists preferred the technique over the visible because of its 24-hour availability and its increased objectivity. The digital IR method discussed in the text has not been tested operationally at this time.

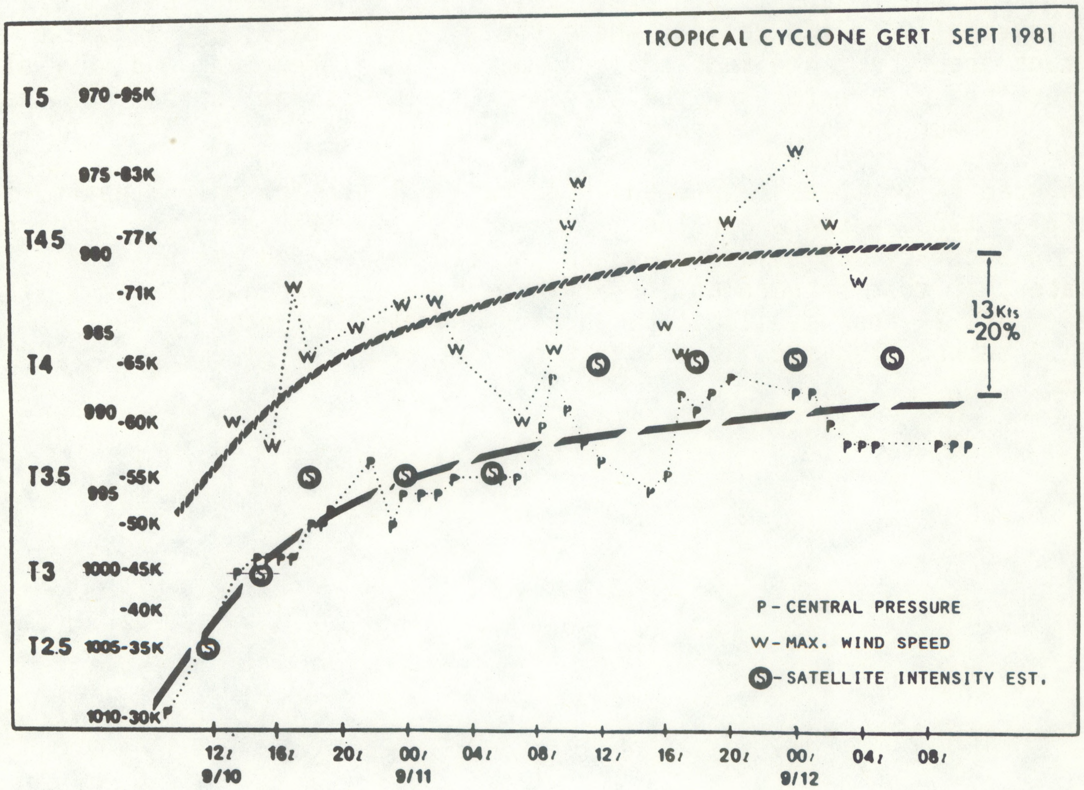


Fig. 15. A comparison of estimations of the intensity of tropical cyclone Gert, 1981. The maximum wind speed (W) and central pressure (P) estimates are from measurements taken on NOAA research aircraft. The satellite estimates (S) were made operationally at the Miami Satellite Field Services Station from EIR imagery.

XI. APPENDIX (The Intensity Analysis Technique in Detail)

Figures 1-4 on pages 2-5 are diagrams that outline the steps used for analyzing both EIR pictures (Figures 1 and 2) and VIS pictures (Figures 3 and 4). Figure 5, page 6, is a worksheet to be used for the analysis. The figures are followed by detailed instructions for each step of the technique.

'EIR' ANALYSIS DIAGRAM

Vernon F. Dvorak (April 1984)

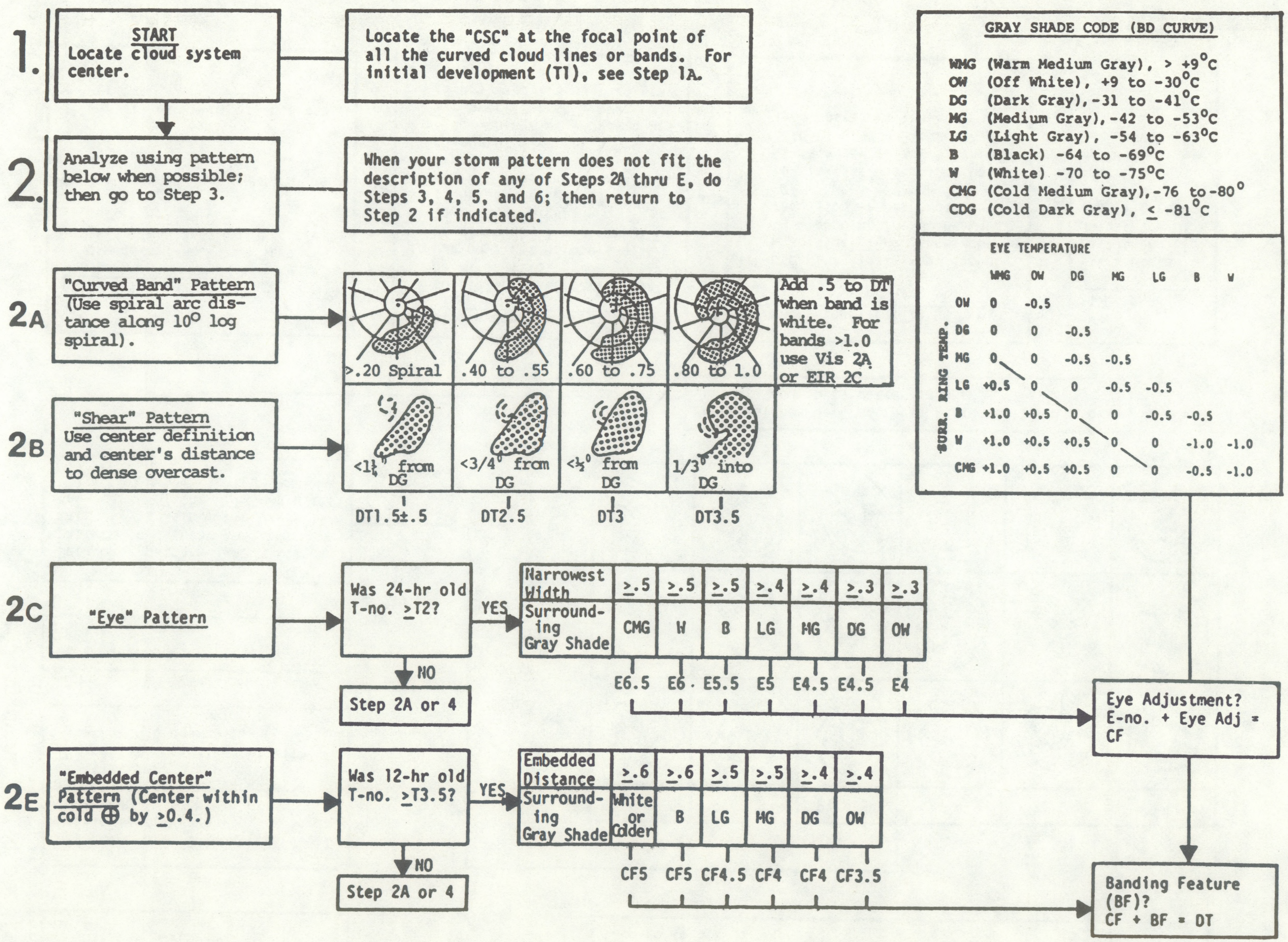


Figure 1. EIR Analysis Diagram, Part 1.

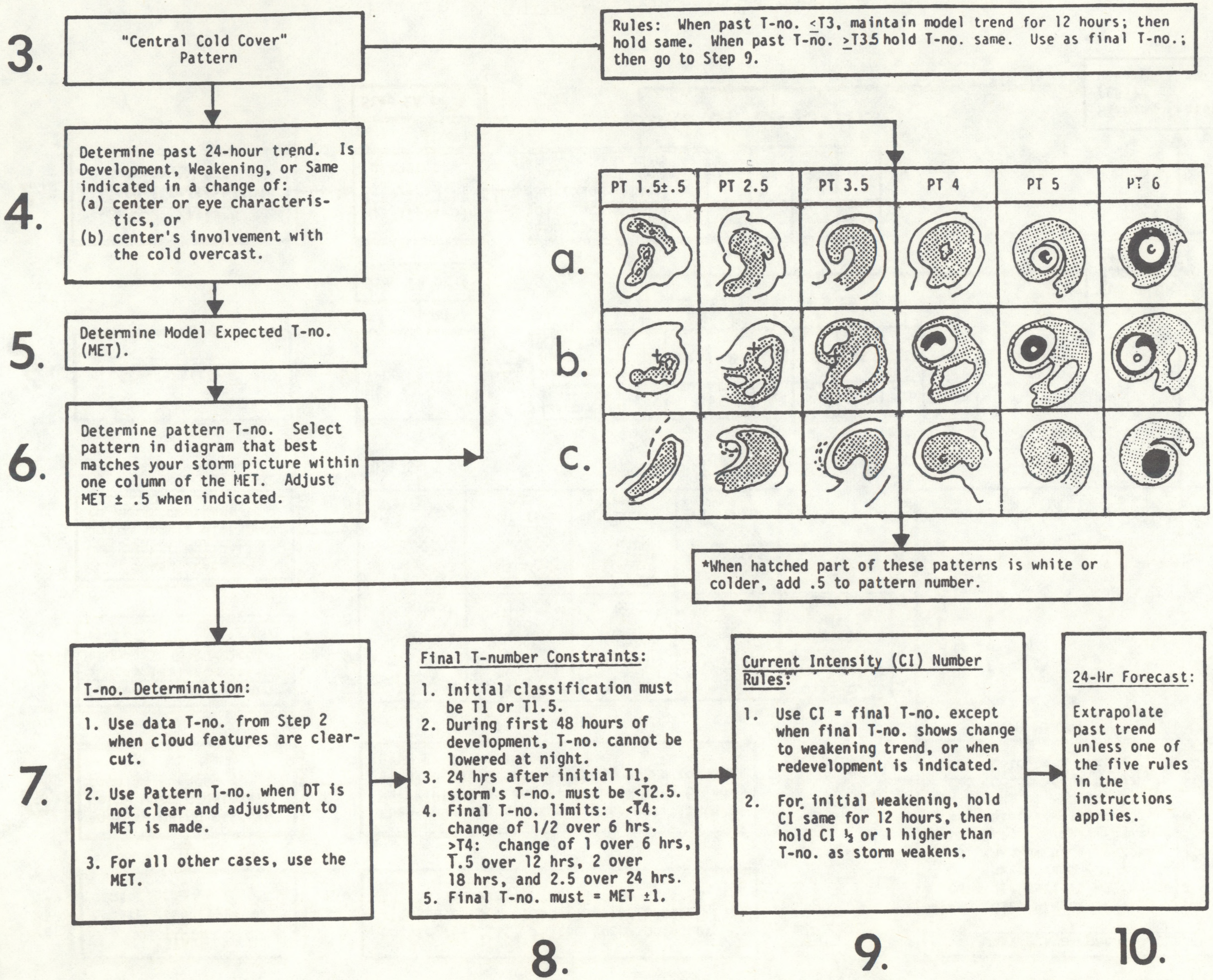


Figure 2. EIR Analysis Diagram, Part 2.

'VIS' ANALYSIS DIAGRAM

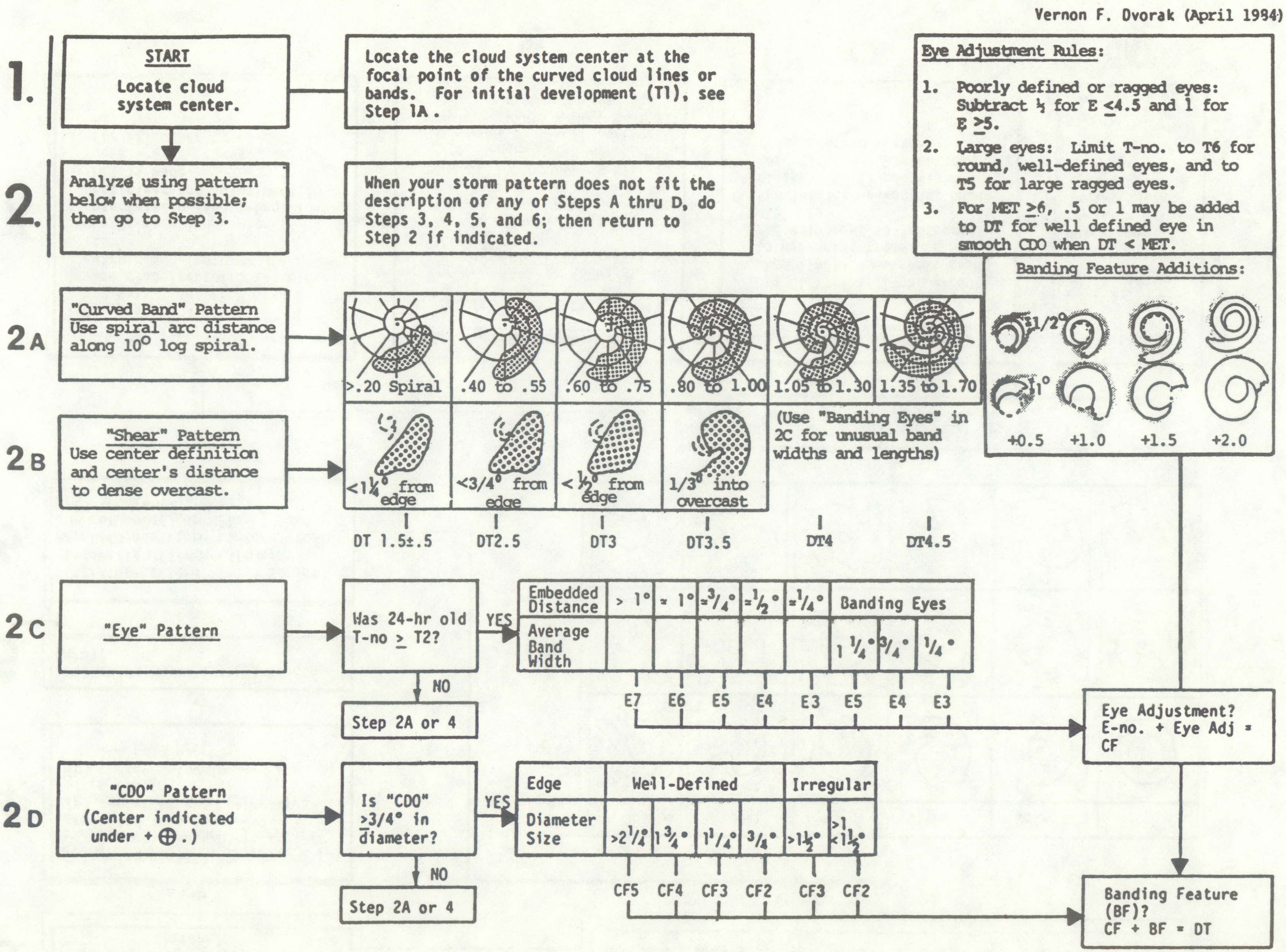


Figure 3. VIS Analysis Diagram, Part 1.

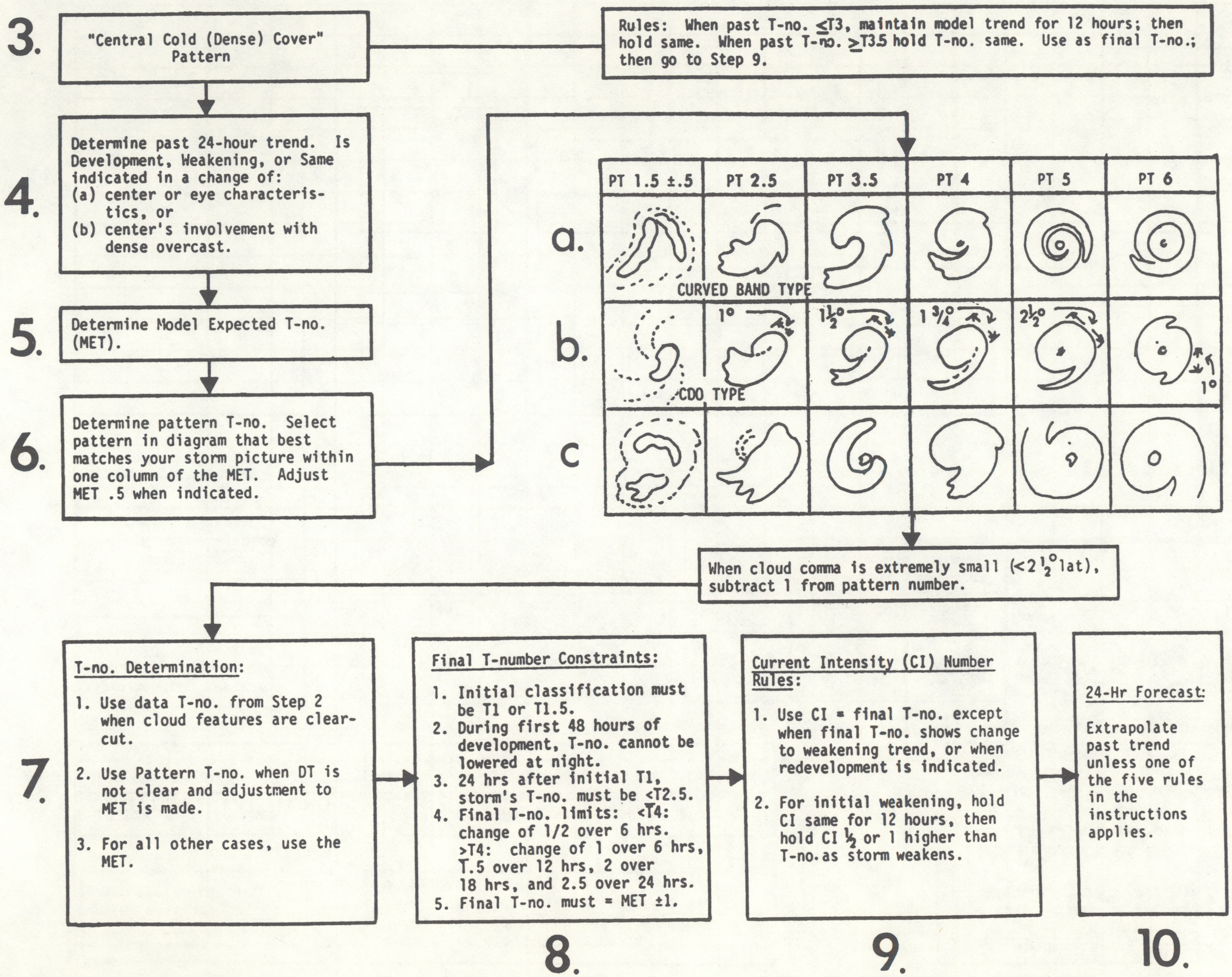


Figure 4. VIS Analysis Diagram, Part 2.

TROPICAL CYCLONE ANALYSIS WORKSHEET

Vernon F. Dvorak
June 1983

	T-NUMBER ESTIMATE FROM MEASUREMENTS FOR DATA T-NUMBER (DT) COMPUTATION															T-NUMBER ESTIMATE FROM MODEL (AND DT CONSTRAINTS)								
STEP →	1		2A,B				2C				2D	2E	Data T-Number Computation			3	4	5	6	7,8	9	10		INITIALS
DESCRIPTION →	Location		Curved Band or Shear				Eye		$E_{No}+E_{Adj}=CF$		CDO	Emb. Centr.				CCC	Trend	MET	PAT	FT	CI	24-Hr. Fcst.		
RULES →	Locate Cloud System Center at focal point of cloud curvature		Use Spiral Arc Length								Use Size		CF+BF=DT			Use Rules	24-Hr change			Use Rules		Adj. Model Fcst. if nec.		
DATE/TIME	LAT	LONG	DT1.5	DT2.5	DT3.5	DT4.5	(VIS) Use Embedded Distance	(EIR) Use Surrounding Temperature	From Rules E_{No}	Eye Definition E_{Adj}	Central Dense Overcast	(EIR) Use Surrounding Temperature	CF	BF	DT	Central Cold Cover	D-developing W-weakening S-same	Model Expected T-Number	Pattern T-Number	Final T-Number	Current Intensity Number	List Rule Used	Forecast Intensity Number	

Figure 5. Analysis Worksheet

INTENSITY ANALYSIS PROCEDURES AND RULES

STEP 1. LOCATE THE CLOUD SYSTEM CENTER (CSC)

The cloud system center is defined as the focal point of all the curved lines or bands of the cloud system. It can also be thought of as the point toward which the curved lines merge or spiral.
Procedure:

(1) The CSC is located at the center of the eye or at the center of curvature of a partial eye wall when one of these features is observed.

(2) When the CSC is not obvious, locate the model expected CSC. Draw a line along the "curved band axis" through the most dense (coldest) portion of the band. The axis should roughly parallel the concave (inner) overcast boundary of the band. Locate the model expected center location in relation to the curved band. (See plus symbols in diagram in Step 2A.) The center is located near the inner (concave) edge of the band on the counterclockwise end (comma head) portion of the band. Locate tightly curved lines, merging lines, or CDO near the point where the center is expected to fall. The CSC is located at the center of curvature, near the point of mergence or at the center of the CDO (for CDO of $\leq$ 1 1/2° latitude in size). For large CDO's, the center is sometimes defined by an arc of overshooting cloud tops or in an isolated cluster of convective tops. When not visible, use (3) below.

(3) When features are not visible at the expected CSC, or when the curved band is not apparent, use the circle method. The method consists of first drawing lines following the cloud line curvature or curved boundaries that fall within the curve of the curved band axis, and then fitting circles to the lines with tightest curvature. The CSC is located at the center of the area common to the circles. For relatively circular embedded center patterns of >T3.5 intensity, fit a log 10° spiral overlay to the curved band axis to locate center.

(4) When a cloud minimum wedge is visible on the concave side of the band near its middle, the CSC is located at the midpoint of a line drawn between the deepest cloud minimum incursion of the wedge and the counterclockwise extremity of the curved band axis. This method is frequently used with EIR pictures. In EIR pictures, the center is often located in the tight gradient near the coldest part of the pattern.

(5) When the location of the CSC is unclear, or could be placed at different locations, use all the methods above along with an extrapolation from the past track positions in making the final decision.

(6) When more than one well-defined CSC is apparent, use the one defined by the strongest appearing, lowest level cloud lines that best fits the past track of the storm. When strong vertical shear is apparent, remember that the upperlevel (dense) clouds will not be centered directly over the low-level center, but will be displaced with the CSC on the tight temperature gradient (sharp boundary) side of the dense cloud pattern.

Step 1A. Initial Development

The earliest signs of tropical cyclone development are observed about 1 1/2 days before a disturbance reaches tropical storm strength. At this time, the disturbance is classified a T1. A T1 is first used when a cluster of deeplayer convective clouds showing line or band curvature has the following three properties.

(1) It has persisted for 12 hours or more.

(2) It has a cloud system center defined within an area having a diameter of 2 1/2° latitude or less which has persisted for 6 hours.

(3) It has an area of dense, cold (DG or colder) overcast* of >1 1/2° in extent that appears less than 2° from the center. The overcast may also appear in cumulonimbus lines the curve around the center.

The cloud system center will be defined in one of the following ways:

(1) Curved band, a dense (DG or colder) overcast band that shows some curvature around a relatively warm (cloud minimum) area. It should curve at least one-fifth the distance around a 10° log spiral. Cirrus, when visible, will indicate anticyclonic shear across the expected CSC. (See diagrams, Step 6, PT 1.5 pattern types.)

(2) Curved cirrus lines indicating a center of curvature within or near a dense, cold (DG or colder) overcast. (See Figure 4, Step 6, PT 1.5b.)

(3) Curved low cloud lines showing a center of curvature within 2° of a cold (DG or colder) cloud mass. (See diagrams, Step 2B, DT 1.5 pattern.)

In many cloud clusters that eventually develop, the northern boundaries shows a straightening about 1 1/2 days prior to the T1 classifications. During the organizing stage of the T1 pattern, there may be extreme variability in the cloud pattern. In most developments at the T1 stage, strong upper-level horizontal anticyclonic shear will be indicated across the disturbance center when curved cirrus lines are present to reveal the shear. These upper-level clouds may indicate patterns far more advanced than T1 at the time of the initial classification. These patterns do not involve deep tropospheric circulations at this time and will be short lived. This means that the Day-2 data T-number may at times be less than Day-1's, but still development is indicated as long as the DT is 2 or more. There may also be times during the first two days of dvelopment when cirrus or convective clouds are almost absent, showing little pattern during the nighttime hours. This usually does not mean the storm is weakening. The rule is to never lower the T-number at night during the first 24 hours of development. A flat boundary rotating clockwise across the north side of the pattern throughout the period is a good sign of development. Note that a classification of T1 forecasts tropical storm

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*The amount of cold overcast may decrease during the subsequent nighttime hours making it crucial that the analyst watch for the required amount of overcast when it occurs.

intensity (T2.5) 36 hours after the T1 observation only when the environment is expected to remain favorable. A minus symbol is used after the T1 to indicate a T1 pattern that is not expected to develop. (See step 11.)

STEP 2. DETERMINE THE PATTERN TYPE THAT BEST DESCRIBES YOUR DISTURBANCE AND MEASURE CLOUD FEATURES AS INDICATED

The manner in which the cloud system center is defined determines the pattern type to be analyzed. The pattern types listed below are described on the following pages. When the cloud pattern being analyzed does not resemble one of the patterns, proceed to Step 3.

Step 2A. "Curved Band" Pattern
Step 2B. "Shear" Pattern
Step 2C. "Eye" Pattern
Step 2D. Central Dense Overcast (CDO) Pattern
Step 2E. Embedded Center Pattern

General Analysis Rules:

1. When short-interval pictures are available, use the average measurement of all of the pictures with well-defined features taken within the 3 hour period ending at analysis time.

2. When two or more T-number estimates are made from the same picture, use the estimate closest to the MET.

3. When in doubt concerning ambiguous features, bias the analysis toward the MET.

Step 2A. Curved Band Pattern

The intensity estimate determined from this pattern type is derived by measuring the arc length of the curved band fitted to a 10° logarithm spiral overlay. (A circle will give the same answer most of the time.) The intensity values that relate to the curved band length are given in the analysis diagrams, Figures 1,3. Curved band measurements may be used with both VIS and EIR pictures until an intensity of DT 4.5 is reached. For EIR patterns greater than DT3.5 use measurements from VIS diagram.

The spiral overlay is fitted to the curvature of the dense (cold) band by first drawing a line along the "curved band axis" and then fitting the spiral curve to the line drawn. The curved band axis is defined as the axis of the coldest overcast gray shade (most dense clouds) within the cloud band. The line should roughly parallel the overcast edge on the concave side of the band. When the band indicates two possible axes, use the one with tightest curvature. Cellular cold globs that do not fall in line with the curve of the comma band are ignored when drawing the line. Fit the spiral to the line drawn on the picture and measure the spiral arc length of dense (cold) band that follows the spiral curve.

In EIR patterns (like those in Figure 2, Step 6, Row b), the cold comma band will often show warm breaks through its middle. These breaks will appear to be almost clear in the VIS picture. When this occurs, draw the comma axis as though it were continuous through the breaks paralleling the edge of the cloud minimum incursion into the concave side of the band. As the curved band pattern evolves it will usually be defined by the dark gray shade of the BD curve, but may at times appear defined in warmer or colder shades of gray. At times the boundaries of the band must be interpreted from its form in previous pictures.

During the first 2 days of development (T1 to T2), the amount of overall band curvature may change excessively, very little, or even decrease somewhat for short periods even though typical development is occurring. For this reason, the tendency should be to raise the T-number by one during the first 24 hours of development as long as the band remains curved enough for T2 and clear signs of weakening or rapid development are not apparent. It is also important to allow at least 24 hours to pass between a T2 and a T4 classification. Even though the coiling process has been observed to be faster than this at times, the surface pressure does not fall accordingly.

During the T2.5 or T3 stage, a tightly curved band $\leq$ 1 1/4° diameter of curvature observed within the curve of the broad curved band can also be used as an indicator of tropical storm intensity. This is evidence that the wall cloud is forming. This tight curvature at weak tropical storm intensity is often ragged in appearance but will have deep-layer convective cloudiness on nearly opposite sides of a system center.

Step 2B. Shear Patterns

Shear patterns appear in pre-hurricane stages of development when vertical shear prevents the cold clouds from bending around the cloud system center as they do in the curved band patterns. The pattern may also appear after the hurricane stage has weakened to a pre-hurricane pattern because of increasing vertical shear.

The intensity estimate determined from this pattern type is derived by (1) the way in which the cloud system center is defined and (2) the distance between the low cloud center and the dense, cold overcast. For shear patterns associated with tropical storm intensity (T2.5 to T3.5), the center will be defined by parallel, circularly curved low cloud lines with a diameter of about 1.5° latitude or less. They indicate a center either near the edge or under the edge of a dense, cold (DG or colder) overcast cloud mass (see patterns in Step 2B, Figures 1,3). During the weaker stages of development (T1.5 $\pm$ .5), the low cloud center will either be poorly defined in spiral lines within 1.25° of the cold overcast, circularly defined but some distance ($>$1.25° latitude) from the cold overcast clouds, or circularly defined near a small amount ($<$1 1/2° diameter) of dense overcast.

Step 2C. Eye Pattern

Eye patterns are analyzed in this step only when the eye falls near the point of the expected cloud system center, and after a T2 or greater pattern has been observed 24 hours prior to the current observation.

The eye is defined as one of the following:

(1) A warm (dark) spot in a dense, cold (OW or colder) overcast. (When more than one dark spot appears near the CSC, use the center closest to the expected center location.)

(2) A point in a dense, cold (OW or colder) overcast centered within the curvature of a colder (denser) band that curves at least halfway around the point with a diameter of curvature of 1 1/2° latitude or less.

(3) A spiral band wrapped around a relative warm (dark) spot with a diameter of curvature of 1 1/2° latitude or less. The band must curve at least 1.0 the distance around the 10° log spiral curve. (See pattern labeled DT 4 in figure 3, 2A.

The analysis of the eye pattern involves three computations: The eye number (E), the eye adjustment factor (Eye Adj), and the banding feature (BF) number. The equation is: CF + BF = DT (data T-number), where CF = E no. + Eye Adj.

1. EIR only (See 2. for VIS)

a. E (eye) number. To get the E or eye number, first determine the coldest gray shade that surrounds the relatively warm spot. Make certain that the minimum width of this gray shade meets the "narrowest width" requirement shown in the diagram. When a spiral eye is defined, use the average width of the spiral band to determine the narrowest width criteria.

b. Eye Adjustment Factor. The eye adjustment factor is determined by using the graph in Figure 6. The graph is a plot of eye temperatures versus the temperature of the coldest ring or spiral that completely encircles the eye. This provides an adjustment of ± 0.5, ± 1, or 0 to the "E" number. No plus adjustment can be made for large eyes ($\geq$ 3/4° diameter within the surrounding gray shade) or elongated eyes. When no previous subtraction was made, .5 is subtracted for elongated eyes having E numbers of ≥ 4.5. Elongated eyes are defined as those having a short axis of $<2/3$ the long axis within the surrounding gray shade.

c. Banding Feature (BF). The BF addition is used with EIR pictures only when the T-number estimate without the BF is lower than the model expected T-number. It is defined only for patterns of CF4 or more that contain a clear-cut comma tail band that:

(1) curves 1/4 or more of the distance around the central features or comma head,

(2) is cold (MG or colder), and

(3) has a warm wedge (DG or warmer) between the tail and the central features that cuts at least halfway through the pattern for patterns a and b, Figure 7, and at least 2/3 the way for pattern c.

2. VIS only (See 1 above for EIR)

a. The E (eye) number is obtained by measuring the distance the eye is embedded in dense overcast clouds. The embedded distance of the eye is measured outward from the center of the eye to the nearest outside edge of the dense overcast for small (<30 nm) eyes. For large eyes, measure outward from the inner wall of the eye. When a banding-type eye is indicated, the arc length of the band around the eye and the average width of the band surrounding the eye are important to the intensity determination, as indicated in the diagram. See analysis diagram (Figure 3, 2C) for the relationships between E-number and embedded distance (eye in CDO), and for band width (banding eye).

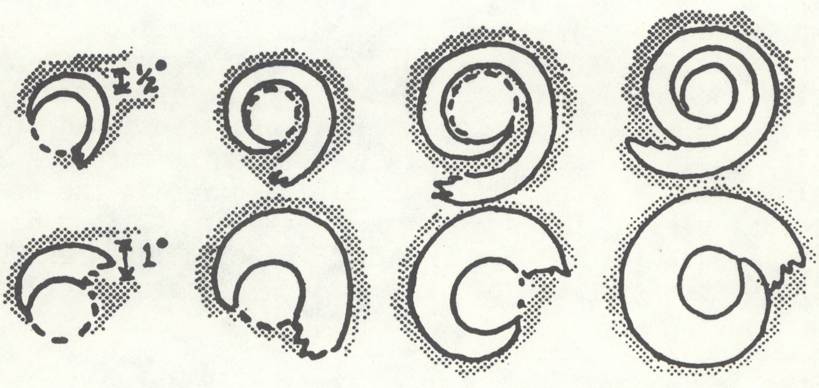
EYE TEMPERATURE

SURR. RING TEMP.	WMG	OW	DG	MG	LG	B	W
OW	0	-0.5					
DG	0	0	-0.5				
MG	0	0	-0.5	-0.5			
LG	+0.5	0	0	-0.5	-0.5		
B	+1.0	+0.5	0	0	-0.5	-0.5	
W	+1.0	+0.5	+0.5	0	0	-1.0	-1.0
CMG	+1.0	+0.5	+0.5	0	0	-0.5	-1.0

Figure 6. Eye Adjustment Graph. Rules: (1) For large or elongated eyes, use values to the right of the diagonal line only; (2) for elongated eye patterns $\geq$4.5, subtract .5 when no other subtraction was made.

a. Add 1/2 no. b. Add 1/2 no. c. Add 1 no.

Figure 7. EIR Banding Features. Add to the CF only when the data T-no. is lower than the MET.



BF = 1/2 BF = 1 BF = 1 1/2 BF = 2

Figure 8. VIS Banding Features.

b. The eye adjustment factor is determined by the definition, shape, and size of the eye. The eye is well-defined by either its blackness or by a well-defined boundary. To be well-defined, the eye should be dark or black. Remember that a very high or very low sun angle may reduce the eye definition unrealistically, and that high-resolution pictures may show a poorly defined eye that would not appear in the low-resolution pictures for which the technique was designed. A poorly defined eye is one that is barely visible. A ragged eye is one with a very uneven boundary with little circularity. VIS eye adjustment rules are as follows. (1) For poorly defined or ragged eyes, subtract 1/2 number for E numbers of $\leq$ 4.5 and subtract 1 number when E $\geq$ 5. When analyzing patterns with poorly defined eyes especially in high-resolution pictures, also check the CDO size. Use the estimate which is most consistent with the MET. (2) For large eyes, limit the maximum T-number to T6 for round, well-defined eye patterns, and to T5 or lower for all other large-eyed patterns. And, (3) the E-number may also be adjusted upward by either .5 or 1.0 when the eye is well-defined, circular and embedded in a very smooth, very dense appearing canopy. The addition is made only when the data T-number is lower than the MET and the storm's past history gives an expected T-number of T6 or more. The general rule for the eye adjustment factor is: When an adjustment is not clearcut, use the guidance of the MET to make the final decision.

c. The BF adjustment is often an important factor when VIS pictures are used. It is defined as a dense, mostly overcast band that curves quasi-circularly at least 1/4 the distance around the central feature. Bands that curve evenly around an inner BF may also be counted. The amount of the BF term ranges from .5 to 2.5. It depends on the width of the band and the amount the band curves evenly around the central features, as shown in Figure 8. A BF term is not used for pre-hurricane patterns when the curved dense band concept in Step 2A is used. However, it is still needed for CDO patterns and all hurricane patterns when indicated. For banding eye patterns use the central coil (once around the eye) as the CF and add the BF as indicated. This pattern type is rarely used for DT of greater than 4.5.

Step 2D. CDO Patterns (VIS only)

CDO patterns are defined when a dense, solid-looking mass of clouds covers the cloud system center and lies within the curve of the system's comma band. Both its size and the sharpness of its boundary are important to the analysis. A well-defined CDO has an abrupt edge on at least one side of the cloud mass. An irregular CDO appears within the curve of the comma band but has ragged boundaries and uneven texture. Generally, well-defined CDO's that measure about 1° latitude in their narrowest width are associated with tropical storm intensities while those measuring 2° latitude or more are associated with hurricanes. The size-CF number relationship is given in the analysis diagram, Figure 3. Examples of CDO's are shown in Figure 4, Step 6b. For CDO patterns, the analysis equation is CF + BF = DT. Banding features (BF) are usually added to the CF term for CDO patterns. The BF's are described above in 2C,2c.

Step 2E. Embedded Center Patterns (EIR only)

Embedded center patterns are analyzed when the storm has had a previous history of a T3.5 or greater intensity and when the CSC is clearly indicated to be within a cold overcast (OW or colder). Curved cloud lines or bands within the cold overcast as well as the outer curved bands will indicate the location of the CSC within the overcast. A 10° logarithmic spiral can often be fitted to the system's pattern to help locate the CSC in patterns of hurricane intensity. (See Step 2A for fitting spiral.)

The analysis of this pattern is similar to the eye pattern analysis except that no eye adjustment factor is added. Determine the coldest overcast in which the CSC is embedded the required distance. This yields the central feature number (CF). Then add a banding feature (BF) adjustment when indicated. The equation being CF + BF = DT.

STEP 3. CENTRAL COLD COVER (CCC) PATTERN

The CCC pattern is defined when a more or less round, cold overcast mass of clouds covers the storm center or comma head obscuring the expected signs of pattern evolution. The outer curved bands and lines usually weaken with the onset of CCC. When using VIS pictures, substitute the word "dense" for "cold." It is only rarely that the CCC pattern is used with VIS pictures since the CDO or curved lines are usually visible through the thin cirrus clouds. When the CCC persists (see rules in diagram, Step 3), development has been arrested until signs of development or weakening once again appear in the cloud features. Care should be exercised under the following conditions:

(1) Do not confuse a CCC pattern with a very cold comma pattern. A very cold (usually white) pattern is indicated by a very cold (very smooth texture) comma tail and head with some indication of a wedge in between. Curved cirrus lines or boundaries usually appear around the cold pattern and not around the CCC pattern. The very cold pattern for T-numbers of T3 or less warrant an additional 1/2 number in intensity estimate and often indicates rapid growth.

(2) Do not assume weakening in a CCC pattern when the comma tail begins to decrease in size. It is common to observe the tail decreasing in size at the onset of the CCC. Also the CCC often warms as the eye of the T4 pattern begins to be carved out by a warm incursion into the side of the cold overcast. This signals the resumption of pattern evolution (intensification) even though some warming is evident.

STEP 4. DETERMINE THE TREND OF THE PAST 24-HOUR INTENSITY CHANGE

The trend of the past 24-hour intensity change is determined qualitatively by comparing the cloud features of the current picture with those in the 24-hour old picture of the storm. In general, a disturbance has developed when its center appears better defined with no change in the relation to the dense clouds of the disturbance or is more involved with dense overcast clouds. More precise definitions for development, weakening or steady state changes are given below.

The storm has developed (D):

(1) Curved band pattern: Curved band coils farther around the CSC.

(2) CDO pattern: CDO becomes larger or an increase in banding features is noted.

(3) Shear pattern: CSC becomes more tightly defined in curved cloud lines or appears closer to the dense overcast.

(4) Eye pattern: Eye is more embedded, more distinct (warmer), less ragged, or is surrounded by colder (smoother textured) clouds, or more banding features.

(5) No significant warming (darkening) of the cloud system is noted. By significant, it is meant that a change that is not diurnal (near sunset), which lasts for more than 3 hours, and is great enough to lower the T-number.)

The storm has weakened (W):

(1) The storm has weakened when its cloud pattern indicates a persistent trend opposite to those listed in (1)-(5) above. Watch in particular for patterns that become sheared out (elongated with time) or for patterns undergoing nondiurnal warming (lowering) of their cloud tops.

The storm has become steady state (S):

(1) When a central cold cover appears in a T3.5 or greater storm or has persisted for more than 12 hours in a weaker storm; or

(2) When the CSC's relationship to the cold clouds has not changed significantly; or

(3) When there are conflicting indications of both development and weakening.

STEP 5. THE MODEL EXPECTED T-NUMBER (MET).

The MET is determined by using the 24-hour old T-number, the D, S, or W decision in Step 4, and the past amount of intensity change of the storm. When the growth rate has not been established in the case of new developments or reversals in trend, assume a past rate of change of one T-number per day. Equations for determining the MET are given below.

MET = 24-hour old T-number + (.5 to 1.5) when D was determined.
MET = 24-hour old T-number - (.5 to 1.5) when W was determined.
MET = 24-hour old T-number when S was determined.

Rapid or slow past rates of change are established when two consecutive analyses showing rapid or slow pattern evolution are obsrved at 6-hour or more intervals, or when one observation accompanied by signs of strong intensification or weakening is observed (see Step 10).

STEP 6. THE PATTERN T-NUMBER (PT).

The pattern T-number is used primarily as an adjustment to the MET when an adjustment is indicated. The PT-number is determined by choosing the pattern that best matches your storm picture from either the model expected T-number column or the column on either side of it. When the pattern being analyzed looks more like the pattern in the column to the right or left of the MET column, then raise or lower the MET .5 to determine the PT.

STEP 7. RULES FOR DETERMINING THE T-NUMBER

Use the data T-number (DT) when the cloud feature measurements are clear-cut. Use the pattern T-number (PT) when the DT is not clear and the pattern is understandable. When neither the DT or the PT is clear, use the Model Expected T-number (MET).

Step 8. FINAL T-NUMBER

This step provides the constraints within which the final T-number must fall. In other words, when the T-number gotten from Step 7 does not fall within the stated limits, it must be adjusted to the limits. The constraints hold the final T-number change to 1.5 during the first 24 hours of development; to 2 numbers in 24 hours for T-numbers T2 to T4 (i.e. 1/2 number over a six hour period); and to 2.5 numbers over a 24 hour period for changes in storms of T4 or greater intensity (i.e. 1 number over a six hour period, 1 1/2 numbers in 12 hours, 2 in 18 hours, and 2.5 in 24 hours). In general for storms of hurricane intensity, the final T-number must be within one number of the model expected T-number (MET). The constraints are listed in the diagram. The rules also prohibit the lowering of the T-number at night during the first 48 hours of development because the diurnal changes in clouds often give deceptive indications of weakening at this time.

STEP 9. CURRENT INTENSITY (CI) NUMBER

The CI number relates directly to the intensity of the storm. The empirical relationship between the CI number and the storm's wind speed is shown in figure 9.

CI Number	MWS (Knots)	MSLP (Atlantic)	MSLP (NW Pacific)
1	25 K		
1.5	25 K		
2	30 K	1009 mb	1000 mb
2.5	35 K	1005 mb	997 mb
3	45 K	1000 mb	991 mb
3.5	55 K	994 mb	984 mb
4	65 K	987 mb	976 mb
4.5	77 K	979 mb	966 mb
5	90 K	970 mb	954 mb
5.5	102 K	960 mb	941 mb
6	115 K	948 mb	927 mb
6.5	127 K	935 mb	914 mb
7	140 K	921 mb	898 mb
7.5	155 K	906 mb	879 mb
8	170 K	890 mb	858 mb

Figure 9. The empirical relationship between the current intensity number (CI), the maximum mean wind speed (MWS), and the minimum sea level pressure (MSLP) in tropical cyclones. The MSLP values for the NW Pacific were recommended in Shewchuck and Weir (1980).

After each intensity analysis, the previous analyses of the storm should be reviewed in the light of the current data. When an error was made in the previous day's analysis, correct the T-number to provide a more accurate model-expected intensity. The correction may at times alter the current intensity analysis.

The CI number is the same as the T-number during the development stages of a tropical cyclone but is held higher than the T-number while a cyclone is weakening. This is done because a lag is observed between the time a storm pattern indicates weakening has begun and the time when the storm's intensity decreases. In practice, the CI number is not lowered until the T-number has shown weakening for 12 hours or more. The CI number is then held one higher than the T-number as the storm weakens. (Hold the CI number 1/2 number higher when the T-number shows a 24 hour decrease of 1/2 number.) When redevelopment occurs, the CI number is not lowered even if the T-number is lower than the CI number. In this case, let the CI number remain the same until the T-number increases to the value of the CI number.

STEP 10. THE 24-HOUR INTENSITY FORECAST (FI)

The Forecast intensity (FI) is an extrapolation forward of the past 24 hr change in T-number (not to exceed 1 1/2 T-number per day) unless the cyclone's cloud pattern or its environment indicates a change in one of the following. Remember that the FI number is similar to a forecast CI number in that for a forecast of weakening the FI number is held one or 1/2 number higher than the forecast T-number.

Step 10A. Strong Unfavorable Signs for Future Development Within the Cloud Pattern

(1) Persistent warming of cloud pattern for more than 12 hours even though other features may indicate intensification.

(2) A central cold cover that persists for more than 3 hours.

(3) The storm's convective clouds are becoming involved with a field of stratocumulus clouds in the path of the storm.

(4) The cirrus cloud lines of the storm indicate less curvature because of increasing strong unidirectional flow aloft across the storm.

(5) The cloud pattern is undergoing increasing elongation (deformation) with time.

Rule 10A. When strong unfavorable signs are observed, forecast (either) no further development or reduce the past development rate of the storm by half. The changes in the environment listed in 10B should play a role in this judgment.

Step 10B. Strong Unfavorable Signs For Future Development Within the Environment

The disturbance is entering an unfavorable environment such that the storm will soon become involved with the following:

(1) Stratocumulus clouds.

(2) Land.

(3) Southward-moving cirrus appearing less than 10° latitude to the north or west of the storm.

(4) Increasing unidirectional flow across the storm pattern.

(5) A southward surge of the westerlies in the upstream environment of a disturbance. The surge is observed as either jet stream cirrus pointing southward northwest or north of the disturbance or as curved cloud lines or bands bowed toward the disturbance moving southward becoming more convective or remaining convective with time. Watch for areas of increasing convection. The band structure may be very weak at first. The environment is considered unfavorable when a broadscale cyclonically curved cloud band is within 25° latitude of a westward-moving disturbance. When the clouds of the disturbance indicate signs of upper-level westerly shear the probability of arrested growth is increased.

Rule 10B. When the storm is entering an unfavorable environment, forecast slow development (1/2 T-number per day) for developing disturbances; or when signs are strong in both the disturbance (10A) and the environment, forecast no development.

Step 10C. Strong Favorable Signs For Future Development Within The Cloud Pattern

(1) Two successive observations of 24-hour changes that indicate rapid development. (The observations should be at least 6 hours apart.)

(2) One observation of rapid development and either (a) a cold pattern (white or colder); (b) cold (dense) comma tail pattern such as those shown in Figure 2, Step 6b; (c) or signs of two or three strong outflow channels. That is, cirrus bands extending some distance out from the disturbance. This is also observed as a fanning out of the cirrus to the south or east of rapidly developing storms.

Rule 10C. When strong favorable signs are observed, forecast rapid development in a developing disturbance of $\leq$ T5.5 that is not expected to peak or enter one of the environments listed in Step 10B. Never forecast an intensity greater that in T7.

Step 10D. Favorable Signs For Future Development Within the Environment

The disturbance is moving away from the conditions described in Step 10B. A disturbance leaving an unfavorable environment as described in 10B (5) is indicated by jet stream cirrus pointing more northward than previously or as curved cloud bands in the broadscale environment to the north of the storm bowing more away from the disturbance or dissipating in time.

Rule 10D. When a storm is leaving an unfavorable environment and it had weakened as a consequence of the unfavorble environment, forecast rapid development until the storm reaches its previous intensity and then forecast the previous rate of change. If the rate of development had decreased because of the unfavorable environment, forecast a resumption of the previous rate of development. When a storm had originally been developing in an unfavorable environment, forecast an increase to one T-number/day in the rate of development as the storm moves into the more favorable environment.

Step 10E. Signs of "Peaking"

Most storms reach their maximum intensity 4 to 6 days after the T1 classification has been made. The day of peaking often depends on the direction of motion of the storm; northward moving in 4 days, westward moving in 6 days, and all others in 5 days. The signs of peaking observed in a storm's cloud pattern are a general warming of the cloud tops (less smoothness in texture), or a more or less circular pattern having an absence of peripheral convective clouds or bands.

Rule 10E. If the signs of peaking are observed at or after the time of expected peaking, forecast no change in intensity.

STEP 11 (Optional)

Encode the intensity estimate using the code in Figure 10 below. The code is self-explanatory except for the PLUS and MINUS (indications of ongoing change). These are used only when the cloud pattern of a disturbance or its environment indicates a change in trend will occur during the succeeding 24-hour period, or when rapid change is forecast. The PLUS is used either to forecast development when a past trend of W or S is indicated in the code or to forecast rapid development when a D was shown. A MINUS is used in the code either to forecast weakening when a past trend of D or S is indicated in the code or to forecast rapid weakening when a W was shown. When the past trend as indicated by D, S, or W is expected to continue for the next 24 hours, the space is left blank.

Figure 10. Code to be used for communicating satellite intensity estimations and forecast.

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