Tropical Cyclone Intensity Analysis and Forecasting from Satellite Imagery

VERNON F. DVORAK

Applications Group, National Environmental Satellite Service, NOAA, Washington, D. C. 20233

(Manuscript received 12 July 1974; in revised form 20 January 1975)

ABSTRACT

A technique for using satellite pictures to analyze and forecast tropical cyclone intensities is described. The cloud features used to estimate the cyclone's intensity and its future change of intensity are described. Procedures for interpreting cloud characteristics and their day-by-day changes within the guidance and constraints of an empirical model of tropical cyclone changes are outlined.

1. Introduction

The meteorological satellite is uniquely suited to the task of tropical cyclone surveillance. During the past decade, hundreds of storms have been observed throughout their life cycles providing meteorologists with a wealth of new data.

Early in the meteorological satellite program, the feasibility of using satellite pictures for tropical cyclone analysis was recognized (Sadler, 1964). Methods were devised for estimating the intensity of the tropical cyclone by associating certain cloud features with conventional estimates of its strength (Fett, 1966; Fritz *et al.*, 1966). During recent years, systematic procedures for both the analysis and forecasting of tropical cyclone intensity were developed (Dvorak, 1973). These procedures were designed to improve both the reliability and the consistency of intensity estimates made from satellite imagery. The procedures have been used and tested under operational conditions during the past three years at centers responsible for tropical storm surveillance. This paper describes the methods currently in use with refinements based on these years of field testing.

2. The technique in general

The goal of the technique is to provide good estimates of the current and future intensity of tropical cyclones using satellite imagery. To reach this goal, the technique outlines procedures and rules which combine meteorological analysis of satellite imagery with a model of tropical cyclone development. The model consists of a set of curves depicting tropical cyclone intensity change with time and cloud feature descriptions of the cyclone at intervals along the curves. The curves show the intensity changes of a typical cyclone during its life cycle with departures from this sequence for rapidly and slowly developing cyclones (Fig. 1). The cloud feature descriptions contained in the model describe the characteristics of the cyclone that are used to estimate both its present and its future intensity. The cloud features used to estimate cyclone intensity at the time of a satellite picture are described in Fig. 4 as "central features" and "outer banding features." These features are analyzed in a three stage procedure that assigns a T-number to a disturbance by using both the qualitative description of intensity shown in Fig. 2 and the quantitative description of Fig. 4. The T (for tropical) numbers, which range from one to eight, describe tropical (and subtropical) disturbances ranging from those exhibiting minimal but significant signs of tropical cyclone intensity (T1) to those characteristic of the maximum possible intensity (T8). The successive T-numbers determined for a cyclone are used to fit the cyclone to one of the three curves of the model or to show departures from a particular curve. The cloud features associated with the cyclone's future intensification are then examined to determine whether the cyclone is likely to remain on its modeled curve during the next 24 hours. The features used in this step provide inferences about the ongoing change of intensity within the cyclone at the time of the satellite picture and also about environmental changes that will affect the cyclone's future growth.

The procedures and rules of the technique give guidance to, and place constraints on, the intensity analysis and forecast. A cyclone's progress throughout its life cycle is analyzed by continually comparing its cloud features and cloud feature changes to those expected from model considerations based on the cyclone's past history. Once the initiation of tropical cyclone development is observed, the procedures place the disturbance on the typical curve of the model until its cloud features indicate a departure from typical. The typical disturbance is recognized at its initial stage by a specified combination of cloud features about 36 hours before it attains tropical storm intensity. When development is not interrupted by a radical

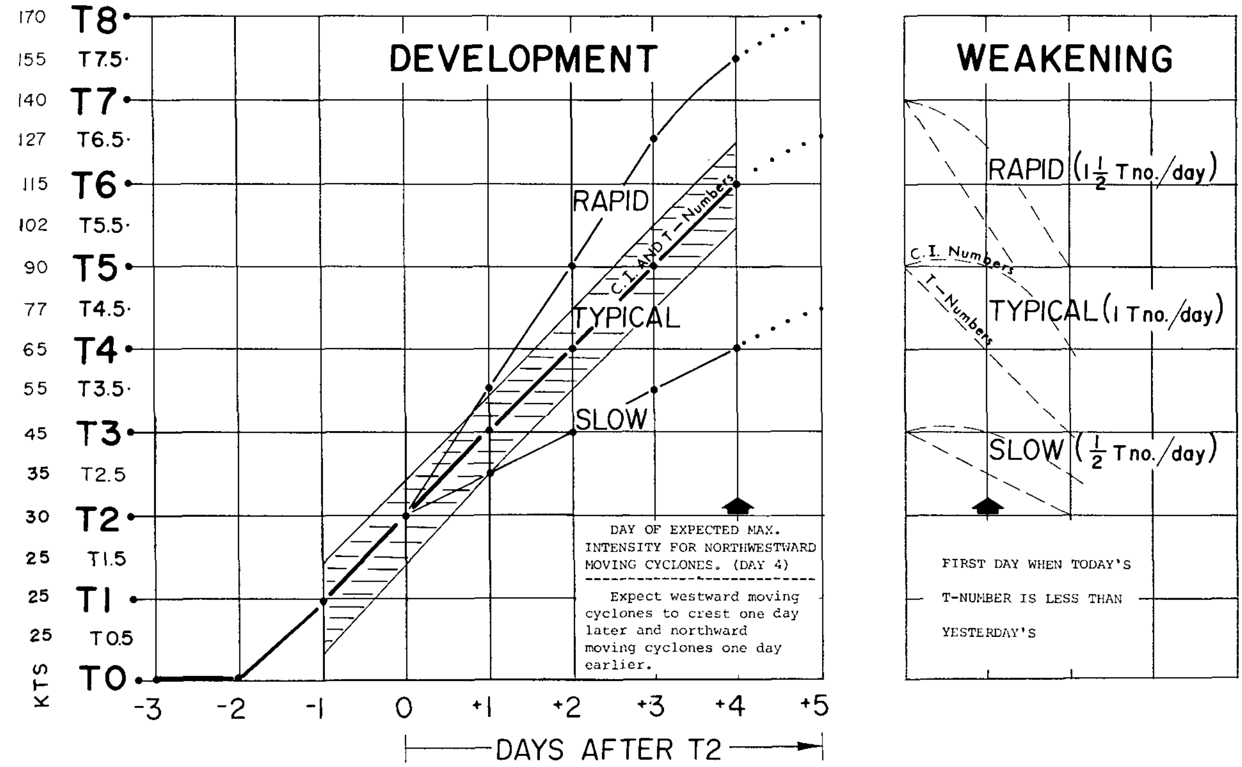

FIG. 1. Intensity change curves of the model. The shaded area surrounding the typical curve is used to represent "intensity" as a zone one T-number wide. The figure is discussed in Section 4.

change of environment, the typical cyclone is expected to develop steadily displaying the modeled amount of daily cloud feature change. It is also expected to reach maximum intensity after a period of time determined by its direction of motion. Note that in addition to the typical rate of development, the technique accounts for rapid and slow rates of change as well as for interruptions in the cyclone's growth rate; the cases in which the cyclone's growth rate departs from the typical curve of the model. The atypical developments are viewed in the procedures as resulting from either a cyclone developing in an unusual environment or a cyclone undergoing a significant change of environment. Atypical development is detected by means of the absence of, or changes in, those cloud features associated with typical cyclone growth and decay.

3. The analysis of cloud features

The cloud features of the tropical cyclone are divided into two sets; one set is used to estimate its current intensity and the other its future intensity. The features are described as they appear in satellite pictures taken during daylight hours from reflected light. Motion picture displays and data from other sensors, however, may also be used as aids to the analysis. At this time we have too short a period of reliable IR data to make detailed classification decisions from it alone. However, some of the more vigorous changes in intensity can be determined from IR data and, when clear-cut, these changes are used operationally to alter the trends established by the more reliable daytime indications.

a. Cloud features used to estimate cyclone intensity

Although the tropical cyclones viewed in satellite pictures appear in a great variety of patterns, most can be described as having a comma or a rotated comma configuration. The pattern of the comma usually consists of a combination of convective cloud lines that cluster and merge together, and cirrus clouds. The cirrus clouds may add to or detract from the organized appearance of the pattern. The merging end of the comma may appear either to hook inward or to curve broadly around a central core of clouds. These core clouds, which can be thought of as the head of the comma, may appear as curved cloud lines, another smaller comma configuration, or a dense overcast cloud mass. As the cyclone intensifies, the comma configuration is usually observed to become more circular with its central core clouds increasing in amount and density.

The cloud features related to cyclone intensity are described in Fig. 4 as central features (CF) and outer banding features (BF). The central features are those which appear within the broad curve of the comma band and either surround or cover the cloud system center.[1] The outer banding features refer to only that part of the comma cloud band that is overcast and curves evenly around the central features. These two parameters, the CF and BF, and an implied cloud depth parameter, taken together, comprise the T-number description of the cyclone.

The central features are defined in terms of both the characteristics of the innermost curved cloud line(s) and the characteristics of the CDO. This is necessary because a cloud system center may be cloud-free and located within the curve of a cloud line on one day and be obscured under a central dense overcast (CDO) on the next day. The CF portion of the intensity estimate depends on the size, shape, and definition of the central features as well as on the amount of dense overcast associated with them.

When the innermost cloud lines of the disturbance are visible, indications of cyclone intensity are inferred from cloud features showing the definition of the CSC and its association with deep-layer convection. That is, the distance between the low cloud center and an adjacent dense cloud mass, the pattern and depth of convection in the curved cloud lines defining the center, the radius of the curvature of the innermost deep layer convective cloud lines or bands, and in the characteristics of the eye and the banding encircling it.

When a central dense overcast covers the cyclone's central cloud lines, its characteristics are used in the intensity estimate. The CDO is the dense overcast mass or ball of clouds which is the part of the comma head that appears cradled within the curvature of the comma cloud band. The CDO often appears to be angular or oval in shape during the early stages of the cyclone, and usually becomes larger, rounder, and more smooth-textured as the cyclone intensifies. The characteristics of the CDO are illustrated in rows b and d of Fig. 2; examples of each pattern are shown in Fig. 3. At times the CDO appears, through thin cirrus, to be composed of thin, tightly coiled lines. A dense, curved, C-shaped narrow band is often observed to precede the formation of the CDO which forms after the T3 stage is reached (see Fig. 2, column T3, rows a, c, and e).

The cyclone eye is defined as either a banding type eye, or an eye imbedded within a CDO. In both cases the numerical value of the CF is increased when there is an increase in the amount of dense overcast surrounding the eye, and is decreased for ragged, large, or cirrus-covered eyes. Indications of the eye becoming more distinct, rounder or more central to the CDO, are used qualitatively as signs of intensification.

[1] The cloud system center (CSC) is located at the center of an eye or at the center indicated by a partial eye wall when one of these features is visible. Otherwise, the CSC is located by fitting circles to the inner curve of the comma band and the curved lines that appear within its broad curve. The CSC is considered to be the center of the area common to all the circles.

The outer banding features (BF) add to the intensity estimate of the cyclone in proportion to the amount and circularity of the dense overcast in band form that curves around the central features.

When the cloud features of a cyclone are poorly defined in the imagery, changes in the overall cloud pattern can be used to infer changes in cyclone intensity. The pattern will normally reveal an increase in cyclone intensity by showing an increase in the amount and circularity of the dense central features (CF), or by showing an increase in the amount and circularity of the outer banding (BF).

b. *Cloud features used to estimate the cyclone's future intensity*

Indications of the ongoing change in intensity within the cyclone at the time of the satellite observation provide clues concerning its future growth or decay. These indications are observed in cloud features that show the cyclone's vertical motions and its inflow/outflow characteristics. A cyclone undergoing typical or rapid development will normally appear as a bright, sharply defined comma configuration, indicating a pattern of strong vertical motions. Its central features will be composed of either deep-layer convective elements or a dense, solid appearing overcast showing some cirrus. The comma clouds and peripheral clouds equatorward of the cyclone and in its direction of motion will appear strongly convective. The cirrus clouds will appear to be spreading out from the central features in three or more quadrants. This outflow may appear either as clouds with fuzzy edges or as cirrus bands arcing out from the central features. (Caution should be exercised in drawing conclusions from cloud patterns observed early in the morning since signs of both intensification and intensity often appear weaker than expected at that time of day.)

A slowly developing or steady state cyclone will show a lack of one of the characteristics mentioned above or a weakness in several of them. A weakening cyclone will display little evidence of any of them. The possibility of rapid development is to be considered each time all of these characteristics are clearly indicated.

The cloud features related to cyclone intensification are observed to change with the cyclone's changing environment. Environmental changes that result in increasing the cyclone's involvement with land, stratocumulus, unidirectional flow aloft, or apparent "blocking" may affect the cyclone's growth for a short period or permanently. Increasing unidirectional flow aloft is observed as an increase in the cirrus flow across the cloud system. Apparent blocking is indicated when the cloud system is becoming elongated perpendicular to the cyclone's direction of motion. The convective clouds ahead of the cyclone usually appear suppressed when this occurs. The rules of the technique (Appendix) use

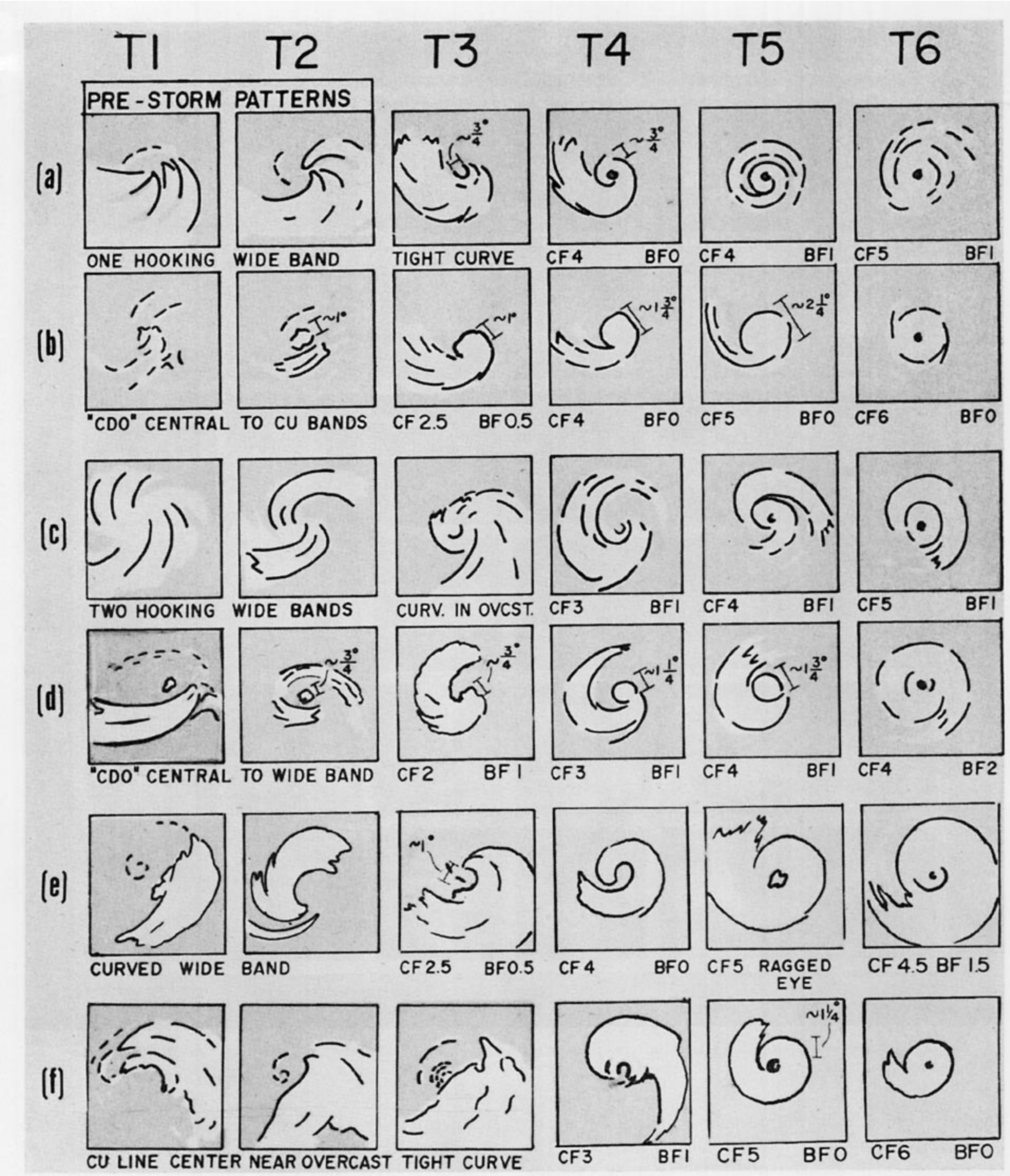

Fig. 2. Common tropical cyclone patterns and their corresponding T-numbers. The T-number shown must be adjusted for cloud systems displaying unusual size. The patterns may be rotated to fit a particular picture of a cyclone.

signs of increasing involvement of the CF with these influences to forecast a 24-hour interruption or slowing down of development. And, conversely, when the involvement is expected to decrease, development is forecast to resume.

As a tropical cyclone develops or weakens, it will also usually show corresponding increases or decreases in its CF, BF, or vertical depth parameters over a short period as well as over a 24-hour interval. Short-period changes in these cloud features, however, are often

FIG. 3. Examples of the tropical cyclone patterns illustrated in Fig. 2. The T-numbers shown are the "pattern" T-numbers; these may be adjusted for model considerations.

deceptive since they are usually small and can be masked by temporary fluctuations or surges in the cyclone's wind field. The rapidly developing cyclone, however, will exhibit large, short-period changes which override such effects.

c. *Initial tropical cyclone development*

The earliest signs of tropical cyclone development that have predictive value appear in typical disturbances about 36 hours before they develop to tropical storm intensity. The cloud features that first reveal the development are curved cloud lines associated with deep layer convective clouds or dense overcast which have persisted for 12 hours or more. The cloud system is normally organized over an area of at least four degrees of latitude in diameter that includes an area of convective overcast or cumulonimbus organization at least three degrees in extent. When lines of cumulonimbus are observed, they will appear to merge toward, hook at, or curve around one general area of less than $2\frac{1}{2}°$ diameter. When the cloud lines are made up of small-element low clouds which clearly define a center, the center must be less than $1\frac{1}{4}°$ from a dense overcast cloud mass. In both of these types of early development, the cloud system center is clearly defined in one small area and it is also associated with deep-layer convective cloudiness. When a combination of the two is observed, the distance from the CSC to the overcast may be larger.

Indications of intensification should also be in evidence to insure that continued development will take place over the succeeding 24-hour period. These indications, described in Section 3b, are especially important during the earliest stages of development. Of prime importance are the presence of deep-layer convective clouds near the system center and the absence of strong unidirectional flow at the cirrus level across the central features. In addition, when clouds appear near the cyclone in its direction of motion, they should appear convective.

The pattern of the disturbance on the day it first shows significant signs of development may occasionally appear stronger than its surface winds or central pressure indicate. For this reason, the rules prevent an estimate of greater than T1.5 on the first day of development. It appears that rapidly forming initial patterns may at times be reflecting winds that have not had time to reach the surface.

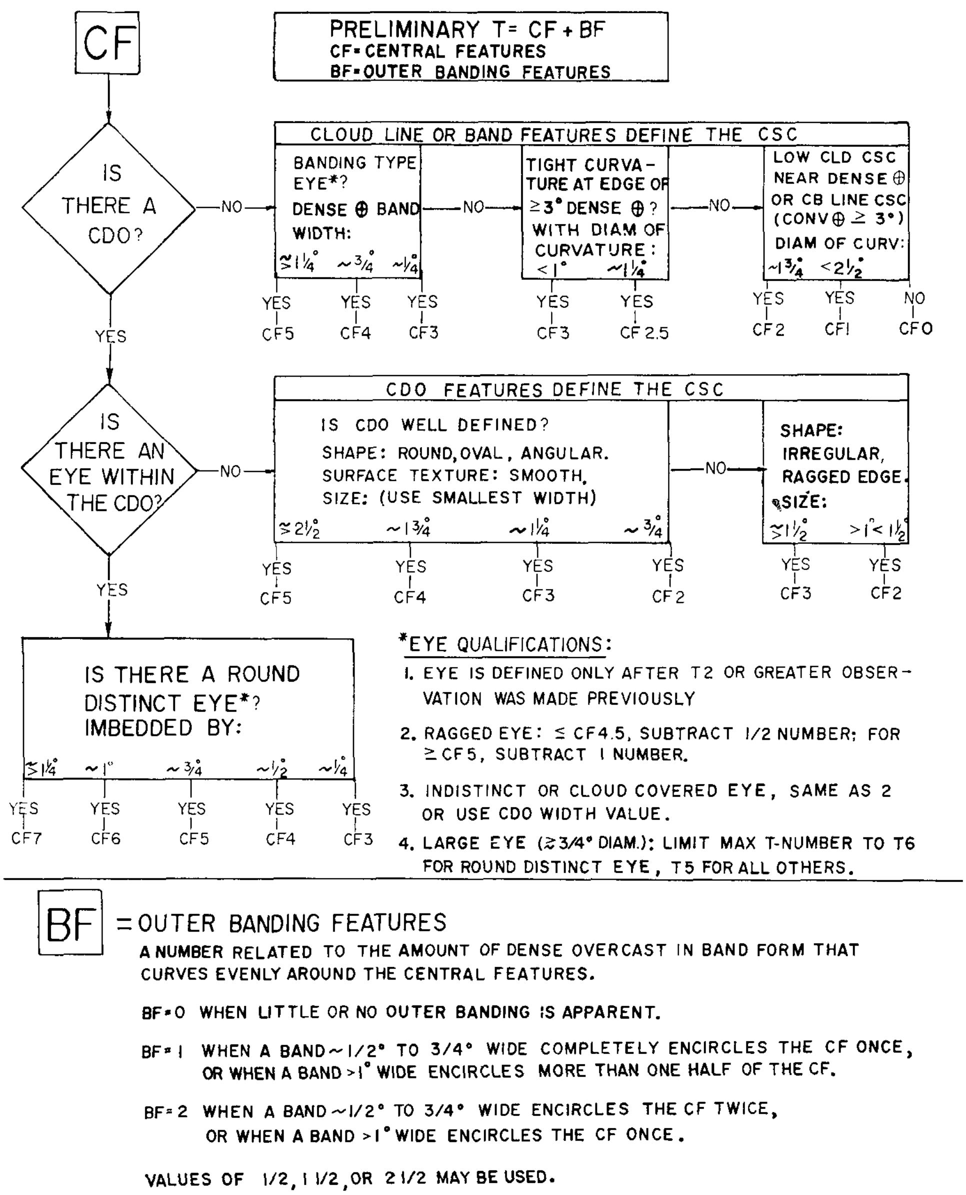

FIG. 4. A diagram for determining the preliminary T-number from cloud feature measurements.

d. Common tropical cyclone patterns

Types of tropical cyclone patterns commonly observed in satellite pictures are illustrated by sketches in Fig. 2; a photographic example of each pattern is shown in Fig. 3. In these figures, initial development is shown in the first column on the left (T1) with increasing intensities to the right. The typical cyclone pattern is expected to change by one T-number (one column) during a 24-hour period.

The cloud patterns observed in the T1 and T2 stages of development usually show deep layer convective elements in lines clustered together in one or two wide bands. When two bands are observed, they appear to be interlocking (or hooking together) as depicted in row (c) of Fig. 2. When one wide band is visible, it usually has organized lines of small element cumulus within its broad curvature as shown in rows (a), (d), and (e). Rows (a), (c), and (e) show patterns in which the cloud system center is defined by central band curvature which tightens or coils around the center as intensity increases. Rows (b) and (d) show the CDO type development with the CDO generally becoming more regular in shape and larger at the higher T-numbers. The figure also illustrates the complementary roles of the central features (CF) and outer banding features (BF) throughout the developmental process. The role of the CF term appears to dominate in the initial stages in rows (a) and (b), while the BF term contributes significantly to the patterns in rows (c) and (d).

The superstorm patterns (T7 and T8, not shown in Fig. 2) are similar in appearance to the T6 patterns but exhibit larger CF or BF quantities. A superstorm often has a very distinct eye centered in a round, smooth-textured CDO, or has a CDO which is completely surrounded by a wide, smooth-textured, banding feature. Other indications sometimes observed are an eye wall within a wider wall or an outer banding feature outside of the usual banding feature. Note that the curves in Fig. 1 indicate that superstorm intensities (greater than T6) occur either in tropical cyclones undergoing continuous development along the rapid curve, or in cyclones moving in a westerly direction during the later stages along the typical development curve.

4. Intensity change curves of the model

The intensity change curves (Fig. 1) used in the technique were derived empirically by relating satellite intensity estimates to those obtained from official storm histories and reconnaissance data. The curves depict tropical cyclone development and weakening as occurring along one of three paths which are plots of T-numbers with time. The typical daily change in a tropical cyclone is approximately one T-number a day; rapid and slow changes are one-half T-number per day greater than or less than typical. Although the occurrence of the three rates of growth varies somewhat according to season and to ocean, the typical change of T-numbers occurs about 70% of the time. The rapid and slow rates of growth occur approximately 10 and 20% of the time, respectively, in the North Atlantic; these percentages are reversed in the northwest Pacific Ocean. Figure 1 also includes the day of expected maximum intensity to provide guidance both for the analysis and for the long range intensity forecast.

The modeled guidance depicted in the figure applies only to cyclones developing or weakening in more-or-less homogeneous environments. When the cloud features of the cyclone or its downstream environment indicate a changing environment, the expectation implied by Fig. 1 must be modified accordingly.

Another feature of the technique is the current intensity (C.I.) number. It is the C.I. number that relates directly to the intensity (in terms of wind speed) of the cyclone for all cases. The C.I. number differs from the T-number to account for factors which are not directly related to cloud features. Two factors that affect the C.I. number are the observed delay in the reduction of the (official) maximum wind speed after the cloud features have indicated weakening, and the cresting of the cyclone's winds between satellite observations. Figure 5 shows the empirical relationship between C.I. numbers and maximum wind speeds (MWS), and the T-number's relation to the minimum sea-level pressures (MSLP).

5. The analysis procedure

The intensity analysis consists of three separate stages. The first stage requires a qualitative judgment as to how cloud features related to cyclone intensity have changed between yesterday's picture and today's. To do this, the CF, BF, and vertical depth parameters are examined separately to determine the recent trend of intensity change. This judgment, together with the T-number for the previous day and the modeled curve, provides an estimate of the present and future intensity of the cyclone. The estimate is modified up or down when an obvious change of environment has occurred during the past 24 hours.

In the second and third stages of analysis, the overall cloud pattern and its component features are examined to see if they agree with the modeled estimate of intensity arrived at during the first stage of the analysis. In the second stage of analysis, the pattern of the cyclone is compared to the generalized patterns in Fig. 2. A decision is made as to whether the pattern fits best in the column determined by the model estimate or in an adjacent column which may indicate a higher or lower intensity. The T-number that corresponds to the cyclone pattern is adjusted when cloud features displaying unusual size or depth are observed. Un-

C.I. Number	MWS (Knots)	T Number	MSLP (Atlantic)	MSLP (NW Pacific)
1	25K	1		
1.5	25K	1.5		
2	30K	2	1009 mb	1003 mb
2.5	35K	2.5	1005 mb	999 mb
3	45K	3	1000 mb	994 mb
3.5	55K	3.5	994 mb	988 mb
4	65K	4	987 mb	981 mb
4.5	77K	4.5	979 mb	973 mb
5	90K	5	970 mb	964 mb
5.5	102K	5.5	960 mb	954 mb
6	115K	6	948 mb	942 mb
6.5	127K	6.5	935 mb	929 mb
7	140K	7	921 mb	915 mb
7.5	155K	7.5	906 mb	900 mb
8	170K	8	890 mb	884 mb

Fig. 5. The empirical relationship between the current intensity (C.I.) number and the maximum wind speed (MWS), and the relationship between the T-number and the minimum sea level pressure (MSLP). The relationship between cloud features and the isotach pattern is described in Dvorak (1973).

usually large or small cloud systems increase or decrease the T-number by one, respectively.

In the third stage of analysis, a quantified analysis is made of those cloud features studied qualitatively in the first stage of analysis. This is accomplished by use of the flow diagram in Fig. 4.

The final estimate of cyclone intensity is a C.I. number based either on the T-number implied by the model or on a small (half) T-number adjustment to it. An adjustment is made when the results of the second or third stages of the analysis indicate a significant difference from the model T-number in the absence of conflicting evidence between them. A maximum adjustment of one T-number may occasionally be necessary when the model curve for the cyclone was chosen incorrectly or when the environment of the storm has changed radically. Once the intensity estimate has been made, the previous satellite pictures of the cyclone are reexamined in light of the new data. A smoothed curve of all data is then compared to the rapid, typical, and slow curves of the model to determine which will best represent the future history of the cyclone.

The analysis is accomplished most easily and reliably when a comparison is made between pairs of pictures taken by the same satellite system at 24-hour intervals. Such an analysis negates the problems resulting from the differing response characteristics of different satellite sensors and those resulting from diurnal variations in cloud characteristics or viewing conditions.

The transmission code shown in Fig. 6 is currently used to transmit the intensity estimates derived from satellite data. The analysis of intensity yields the T-number, the C.I. number, and the D, S, or W parts of the code.

6. The forecast procedure

The intensity forecast is made by using either the cyclone's model curve to obtain tomorrow's intensity or by adjusting the curve when an interruption due to landfall or the approach of some unfavorable circulation is indicated. Such changes are detected in a recent abnormal change of T-number or in recent changes in the cloud features related to cyclone intensification. The simple modeled forecast implied by the curves in Fig. 1 must be altered whenever one of three events is in evidence. The first is an obvious reversal in trend indicated by a significant past change of intensity. In this case, either a steady state condition or a reversal in trend may be forecast depending on the signs of ongoing change. The second event is that in which all signs of intensification appear opposed to the expected trend. In this case, no change in C.I. number will be forecast during the succeeding 24-hour period. The third event is the case in which the cyclone is entering or leaving an environment that will significantly effect its trend. When this occurs, it is both the cloud features signifying the event and the timing of its occurrence that determine the extent to which the expected trend should be modified.

The transmission code in Fig. 6 implies a forecast change of intensity of one number per day in the same sense as the past change (D, S, or W) unless a "PLUS," "MINUS," or remarks are used to modify

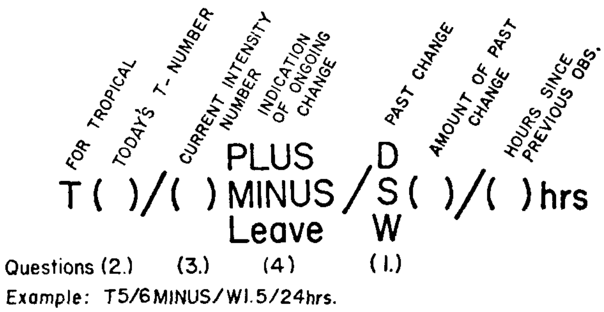

FIG. 6. The operational code used for transmitting cyclone intensity estimates derived from satellite data. When no PLUS or MINUS is added to the code the forecast is a persistence trend forecast of one C.I. number during the next 24 hours. The addition of a PLUS adds $\frac{1}{2}$ number to the forecast C.I. of a "D" or "S" cyclone during the next 24 hours, and 1 number to a "W" cyclone (or no change). The addition of a MINUS subtracts $\frac{1}{2}$ number from the C.I. of a "W" or "S" cyclone and 1 number from a "D" cyclone. A forecast of slow change must be indicated in the remarks.

the forecast. The current rules enable the analyst to account for forecasts of rapid and slow changes as well as no change for cyclones with "D" or "W" past change. In addition, the "S" cyclone may be forecast to change its C.I. number by $\frac{1}{2}$ number in a 24-hour period.

7. Performance

The technique has undergone considerable change and improvement since its inception almost four years ago. The earliest form of the technique was evaluated by Erickson (1972). His results showed good consistency between analysts with nine out of ten estimated T-numbers of the participants deviating from the instructor's analysis by one number or less. The average difference between the official intensity estimates and those of the instructor and the participants was approximately 12 kt for the instructor and 15 kt for the participants. The test, however, brought to light a consistent bias which resulted in a change in the empirical relationship between T-numbers and wind speeds. More recently, Arnold (1972) published verification statistics comparing operational T-number estimates using the technique with the official Joint Typhoon Warning Center estimates for west Pacific cyclones during the 1972 season. These data show a mean deviation of 8 kt from the official intensity estimates with a rmse of 12 kt and a 24-hour forecast mean deviation of 13 kt from the official post season estimates.

8. Summary

The technique is a systematic procedure for estimating tropical cyclone intensities using imagery from meteorological satellites. Two sets of cloud characterisitics are analyzed with guidance from a model of tropical cyclone change derived empirically from satellite data. One set of characteristics is used to estimate cyclone intensity. It is made up of three parameters: the central features which define the cloud system center and its relation to dense overcast clouds; the outer banding features which curve around the central features; and the vertical depth of the clouds comprising these features. Intensity is considered to be related to the sum of the three parameters. The assessment of intensity is made in three stages. The first stage yields a modeled estimate of the cyclone's intensity while the second and third stages use the cloud pattern and feature measurements to verify or adjust the modeled expectation.

The second set of cloud features is then analyzed to determine if an extrapolation along the cyclone's particular modeled curve is to be used for the 24-h intensity forecast. These features are related to the intensification processes within the cyclone and to environmental changes which may affect the cyclone during the forecast period.

The procedures and rules of the technique currently in use are given in the Appendix. They are used to guide the analyst in complex situations and to insure consistent estimates between analysts.

Acknowledgments. The technique described in this paper was developed with the generous assistance of many individuals. In particular I would like to thank Mr. V. J. Oliver, Mr. Lee Mace, and Mr. A. W. Johnson whose advice and encouragement at a time when skepticism prevailed made this work possible. Others who provided helpful suggestions were Dr. H. M. Johnson, Mr. S. Wright of NESS, and Capt. C. Arnold of JTWC, Guam. I am also indebted to the meteorologists of the Analysis Branch of NESS for their continued patience and support in the face of ever-changing rules of operation. Thanks are especially extended to Mr. T. Burtt and Mr. F. Smigeilski. In addition I would like to thank Mr. Paul Lehr for his generous assistance in making the text readable.

APPENDIX

An outline of rules and procedures currently in use (1/15/75). The analyst normally follows these rules in the sequence as listed.

1. *Locate the cloud system center* (*CSC*). Fit circles to the inside edge of the curved lines and bands. Fit a circle to the curve of the comma band first. The CSC is the center of the area common to all the circles.
2. *Recognize initial development.*
   a. Examine the definition of the cloud system center and its association with deep-layer convection. (See Section 3c in the text.)
   b. Regard all cloud systems as T0 or T0.5 until they develop T1 or greater characteristics.
   c. Tend to begin each development at the T1 stage on the typical curve in Fig. 1, making

certain that initial development was not overlooked on the previous day. (T1.5 may also be used when a pattern showing characteristics of greater than T2 is clearly indicated.) Prematurely developed patterns do sometimes occur at this early stage.

3. *Determine the past change of intensity* for disturbance by comparing yesterday's picture with today's. In general, compare pictures taken at 24-hour intervals. Examine changes in the CF, BF, and vertical depth parameters between the two pictures. Has the cyclone developed (D), weakened (W), or remained the same (S) since the previous observation?
   a. Maintain the expected trend when it is supported by a change in either the CF, BF, or vertical depth parameter without a significant compensation in the other parameters. When the signs of ongoing change are as expected, look for reasons to go with the expected trend. (Caution must be exercised in assuming the developmental trend of a very weak or very strong cyclone has prematurely ceased when the CF and BF parameters appear almost the same from one day to the next. In these instances, when signs of intensification are still in evidence, it is usually an increase of vertical depth that gives reason for maintaining the expected trend.)
   b. Use an S when the past change is opposed to the trend but by less than ½ number and the convection in CF supports the expected trend. (In this case the expected trend will be maintained by the addition of a PLUS or MINUS to the code.) Also use an S when today's T-number is the same as yesterday's and the signs of ongoing change do not support the trend.
   c. Reverse the model expected trend (change a D to a W or vice versa) *only* when the past change appears to be at least ½ number or more opposed to the modeled trend, or when both the signs of intensity and intensification appear opposed to the trend.
4. *Determine today's T-number as follows:*
   a. Take the model expected T-number from Fig. 1 using the recent trend determined from 3 above, yesterday's T-number, and the appropriate model curve. For a developing disturbance which has obviously been involved with an unfavorable environment during the past 24 hours, reduce the expectation ½ number.
   b. Take the cyclone's pattern T-number (with size adjustment) from Fig. 2.
   c. Determine the preliminary T-number using the flow diagram in Fig. 4. Rules: (1) When the CF can be determined from both line curvature and CDO characteristics, use the higher number. (2) The imbedded distance of the eye is measured outward from the center of the eye to the nearest edge of the CDO for small (<30 n mi) round eyes. For all others, measure outward from the inner wall of the eye. (3) Always measure the CDO of the cyclone even when it shows an eye. A CDO with indication of an eye must give a CF quantity as large or larger than the CDO measurement alone would give.
   d. The final T-number is the model expected T-number or a small (½ number) adjustment to it when the pattern or the preliminary T-number clearly indicates a need for an adjustment while not showing conflicting evidence between them. A maximum adjustment of one number from the model expectation may be made when clearly indicated.
   e. When a "D" or "W" is determined from 3 above, the change in final T-number of a typical or rapid cyclone must be at least ½ number.
5. *Determine the current intensity (CI) number* by using:
   a. the same number as the T-number for "D" changes
   b. a number either ½ or 1 higher for "W" changes when the past 24-hour T-number change has been ½ or 1 or more.
   c. the same number as the T-number for "S" changes except when a cyclone crests between two 24-hour observations. Use a C.I. number ½ number higher than the T-number when this occurs.
6. *Determine the cyclone's modeled curve* by plotting all the satellite derived intensity estimates for the cyclone and comparing its smoothed curve with the curves in Fig. 1.

Characterize the cyclone as typical, rapid, or slow. Change past estimates when indicated. Make the initial adjustment to the rapid or slow curves when two or more consecutive observations clearly indicate abnormal change. The change to the rapid curve should be expected for rapidly changing patterns or those moving into an area which is climatologically favorable for rapid development. Do not initiate a rapid curve poleward of 20° latitude. Watch for slow development in cold water areas and areas of strong upper level westerlies.

7. *Determine the forecast CI number* by using the forecast CI number expected by the cyclone's modeled curve unless one of the following is indicated:
   a. The past 24-hour change has been ½ number or more against the trend.
   b. All signs of ongoing intensification or weakening are inconsistent with the expected trend.

c. The cyclone is entering or leaving an environment which will inhibit, stop, or reverse its trend. These environments are observed as areas of land, stratocumulus, upper level unidirectional flow, or apparent "blocking."
   (1) When a developing cyclone's outer bands are adjacent to one of these features and the CF are expected to become involved, stop development for the next 24 hours. (Use a MINUS in the code.)
   (2) When the environment will only affect the developing cyclone marginally (i.e., the outer banding features), expect slow or typical development during the succeeding 24 hours.
   (3) When the cyclone is leaving one of these environments and a "W" or "S" was used in the code, use a PLUS to forecast development.

When the forecast is for a change other than one T-number per day, the code in Fig. 6 must be modified with symbols or remarks. The forecast of rapid change and no change is accomplished by placing a PLUS or MINUS, respectively, with a "D" cyclone and reversing the symbols for a "W" cyclone. The expected development or weakening of an "S" cyclone is indicated by using a PLUS or MINUS in the code. The expected change in this case is a change of $\frac{1}{2}$ number per day. The forecast of slow change for "D" or "W" cyclones must be indicated in the remarks of the code.

The analyst must be alert to the possible use of a MINUS (arrested development) under the following circumstances:

a. When a developing cyclone is near the expected "peak" intensity. The "peak" is expected to occur approximately four days after the T2 was observed. (At times, the isolation of a circular cloud pattern or recurvature may be the only indication that the cyclone has stopped developing at its expected "peak.")
b. When the disturbance is entering an area of strong flow aloft which will blow the cirrus or middle clouds unidirectionally across the disturbance center.
c. When the cyclone's cloud pattern is beginning to elongate perpendicularly across the cyclone track with suppressed convection downstream. The cyclone appears "blocked."
d. When recurvature is evident for a northwestward developing cyclone with a change to a near poleward direction of motion.
e. When the disturbance has entered a stratocumulus region and the stratoform clouds appear adjacent to the convective clouds of the disturbance.
f. When a disturbance is on the verge of moving over land.

The analyst must be on the lookout for the possible use of a PLUS (redevelopment) when:

a. the central features of a weakened disturbance show renewed deep-layer convective clouds or curved CB lines.
b. a weakened disturbance shows deep-layer convection in its CF after 24 hours of being within the influence of upper level unidirectional flow or an apparent block (even though the cloud pattern has lost much of its cirrus overcast).
c. a weakened disturbance shows a clearing of stratocumulus clouds ahead of the BF in the direction of cyclone motion.
d. a weakened disturbance is moving away from the influence of a land mass.

REFERENCES

Arnold, C. P., 1974: Tropical cyclone position and intensity analysis using satellite data. First Weather Wing Pamphlet, IWWP 105-10, Department of the Air Force, HQ 1st Weather Wing (MAC) APO San Francisco 96553, 97 pp.

Dvorak, V. F., 1973: A technique for the analysis and forecasting of tropical cyclone intensities from satellite pictures. NOAA Technical Memorandum NESS 45 (Revision of NOAA TM NESS 36). U. S. Dept. of Commerce, Suitland, Md., 19 pp.

Erickson, C. O., 1972: Evaluation of a technique for the analysis and forecasting of tropical cyclone intensities from satellite pictures, NOAA Technical Memorandum NESS 42. U. S. Dept. of Commerce, Suitland, Md., 28 pp.

Fett, R. W., 1966: Upper-level structure of the formative tropical cyclone. *Mon. Wea. Rev.*, **94**, 9–18.

Fritz, S., L. F. Hubert, and A. Timchalk, 1966: Some inferences from satellite pictures of tropical disturbances. *Mon. Wea. Rev.*, **94**, 231–236.

Sadler, J. C., 1964: Tropical cyclones of the Eastern North Pacific as revealed by TIROS observations. *J. Appl. Meteor.*, **3**, 347–366.