NOAA Technical Memorandum NWS NHC 3

INTENSIFICATION CRITERIA FOR TROPICAL DEPRESSIONS IN THE WESTERN NORTH ATLANTIC

National Hurricane Center
Miami, Florida
April 1977

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NWS NHC 3 Intensification Criteria for Tropical Depressions in the Western North Atlantic. Paul J. Hebert - April 1977

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DEPARTMENT OF COMMERCE
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INTENSIFICATION CRITERIA FOR TROPICAL DEPRESSIONS IN THE WESTERN NORTH ATLANTIC

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ABSTRACT

A study for the five-year period 1968-1972 evaluates several of the factors which have been generally considered favorable for the development of a tropical depression into a tropical storm or hurricane. The study considered all depressions in the western North Atlantic south of latitude 35 North and west of longitude 55 West.

The individual and cumulative importance of these factors as criteria for assessing the potential for development of a tropical depression into a tropical storm within 24 hours is discussed.

The results of the study have led to modifications of the criteria for operational use at the National Hurricane Center (NHC). The criteria currently used at NHC are presented together with a brief discussion of plans to obtain objectively a quantitative development potential index for all intensity stages of tropical cyclones.

INTRODUCTION

Significant advances in understanding the structure of the hurricane vortex became a reality with the advent of frequent aerial reconnaissance of tropical cyclones during the past two decades. In particular, research flights during the 1950's and 1960's led to numerous studies on individual and composite features of tropical storms and hurricanes. In turn, this led to a better understanding of the dynamics and energetics of the hurricane development process(es). The studies are too numerous to list here.

Numerical modelling of tropical cyclones by researchers such as Yamasaki (1968), Rosenthal (1970), Ooyama (1969), Anthes et al. (1971a, 1971b), and earlier theoretical work by Kuo (1965) have further increased this understanding. However, this work has been largely diagnostic in nature. Most of the applied research in tropical cyclone forecasting has been directed toward predicting the track, and in a few models the intensity (in terms of vorticity) is a byproduct, for example, Sanders and Burpee (1968). In the latter, however, the intensity can only decay with time since the model is barotropic. Miller (1969) has successfully achieved intensification of a tropical disturbance to the tropical storm stage using real data, but not on a real-time basis. His model has also successfully forecast a non-developing case (Miller, 1971). Currently, Hovermale (1976) is developing a numerical model at the National Meteorological Center (NMC) which forecasts both track and intensity changes of an existing hurricane. However, initial emphasis has been on the track forecast, as the problems involved in obtaining reliable intensity forecasts are formidable.

The primary function of the National Hurricane Center (NHC) is to monitor all weather disturbances which might eventually become a tropical (or subtropical) storm and/or hurricane, to determine the location and movement of all tropical (and subtropical) cyclones, and to forecast changes in their track and intensity for upwards of 72 hours and issue coastal warnings when required. While some progress has been made in objective hurricane track forecasting, little immediate hope is available for significant skill in objective forecasting of the intensity changes of tropical cyclones. This rather gloomy outlook stems from several factors: 1.) Incomplete understanding of the dynamical and physical processes involved, including the difficulties of handling interactions of various scales of motion; 2.) Insufficient data on both the synoptic scale and the meso/micro scale; 3.) In some instances, insufficiency of computer capabilities to make real-time forecasts with models as presently formulated.

In an attempt to fill the void in quantitative intensity forecasts, NHC initiated a series of decision ladders after Simpson (1971), which strived to make more objective decisions on determining the location, track forecast, and development potential of disturbances in the tropics and subtropics. The two decision ladders for development potential listed some of the criteria which are considered necessary for the development and maintenance of a tropical disturbance into a storm/hurricane. Many of these criteria are adaptations of factors which Gray (1968) has shown to be related both to favorable climatological areas for tropical storm development and also to be characteristic of composited individual disturbances which later became storms. Gray's work in turn summarized and evaluated mainly qualitative factors which Riehl (1954) and others had deemed as necessary conditions for tropical storm development.

A study in progress by the author to evaluate some of the criteria presented by Gray (1968) was modified to assess the original decision ladder criteria of Simpson (1971). This study for the period 1968-1970 by Hebert (1971) led to a revision of those criteria. Figures 1 and 2 show the revised decision ladders.

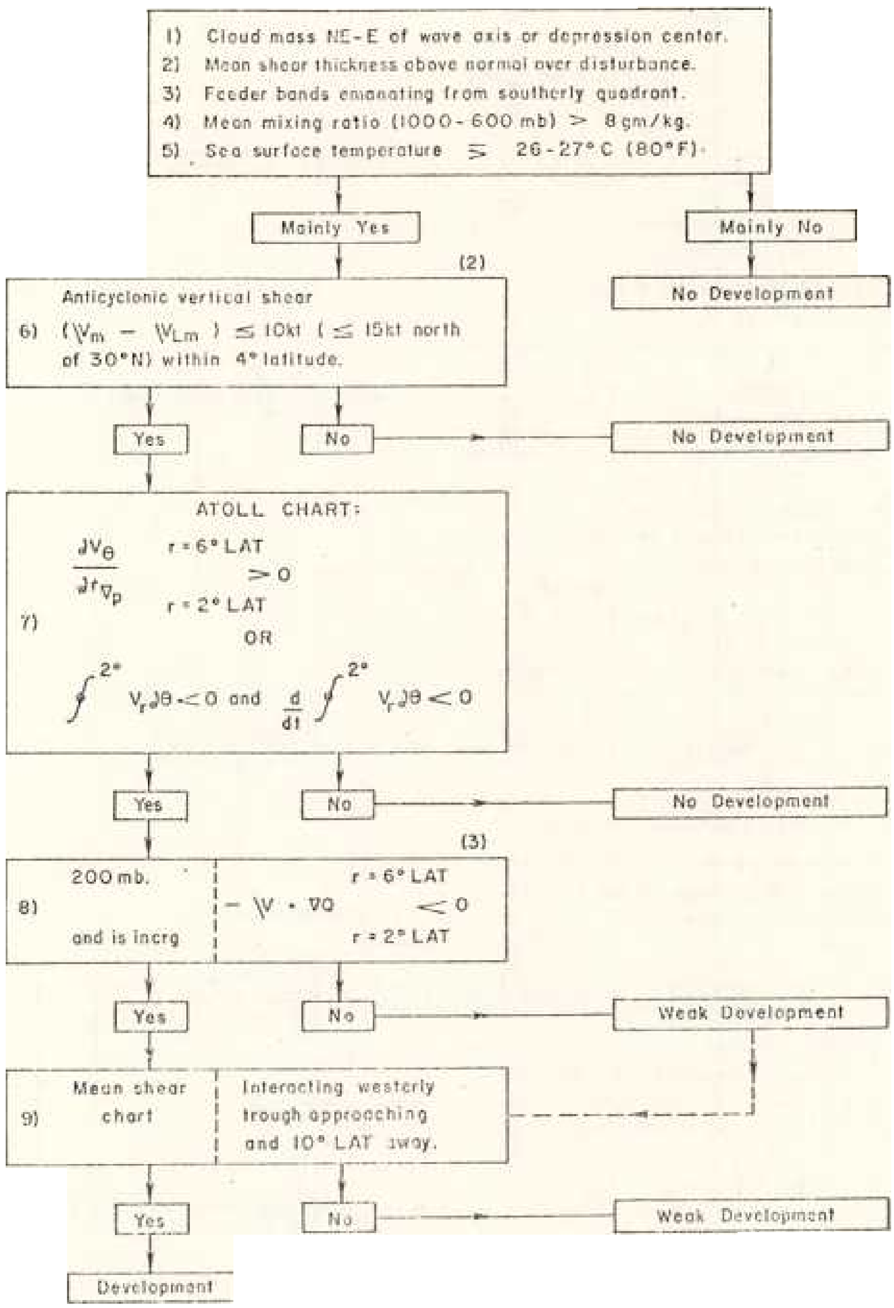
Mean thicknesses and vertical wind shears are obtained from the NHC mean layer charts for 600-200 millibars and 1000-600 millibars. Mean heights and pressure-weighted mean wind vectors are obtained for each layer. Grid point subtraction of the mean winds and mean geopotential of the 1000-600 mb layer from the 600-200 mb layer produces the NHC mean thickness and vertical wind shear chart from which developmental criteria are assessed. The interacting westerly trough is also reflected in the mean thickness analysis. Anomalies of mean thickness are obtained by comparing current data to appropriate monthly normals which have been derived by the same procedure. The NHC lower mean layer chart (1000-600 mb) also furnishes the mean mixing ratio which is obtained from radiosonde moisture values.

SEEDLING DEVELOPMENT POTENTIAL (1)

(Computations and factors apply to current through 24-hour conditions)

DECISION LADDER

Environmental Factors Favorable



(1) Tropical waves and weak depressions.

(2) Averaged over a circular area with a radius of 4°L

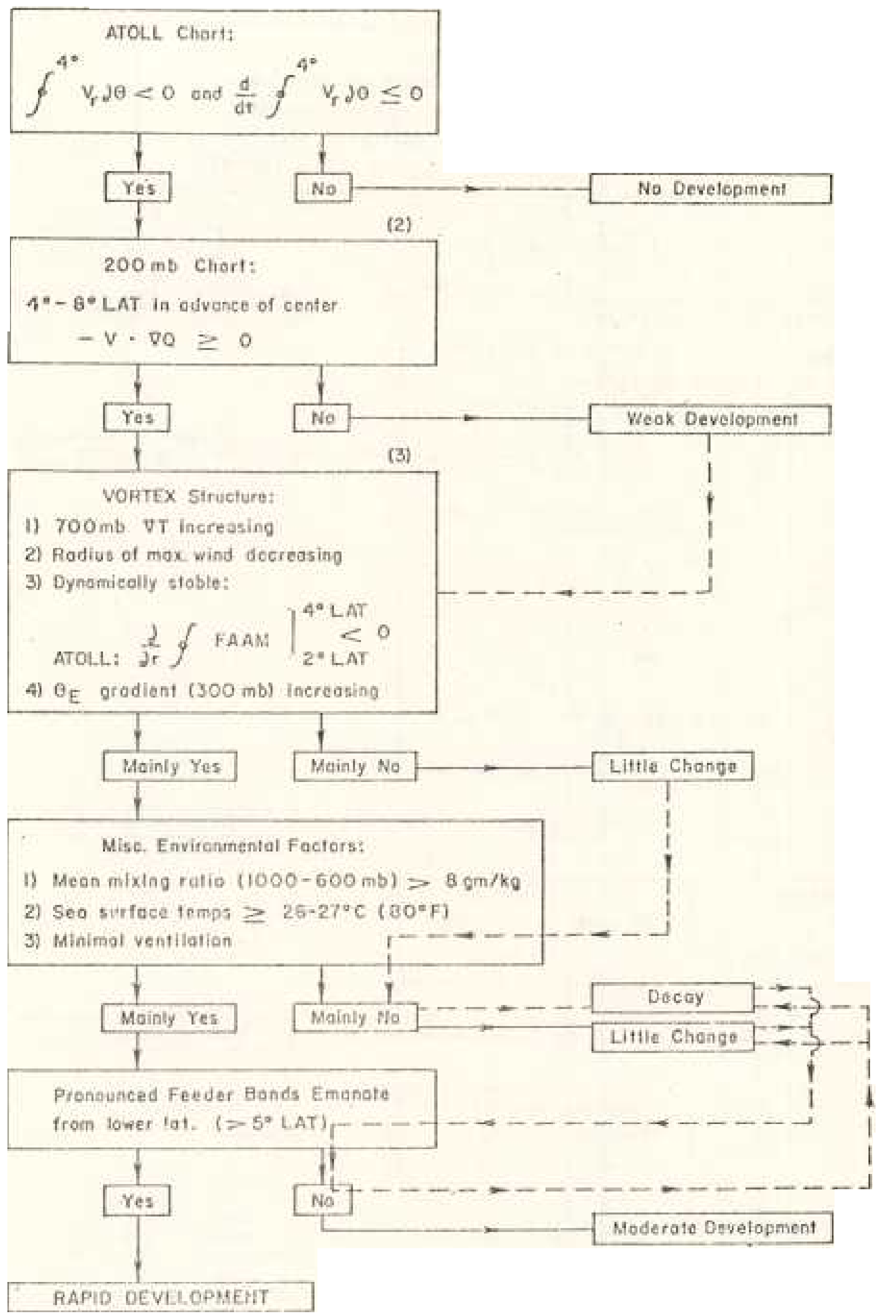
(3) Q = absolute vorticity.

Figure 1. Revised decision ladder for tropical waves and weak tropical depressions. Numbers 1–9 refer to criteria evaluated in table 3. See text for discussion of criteria.

VORTEX DEVELOPMENT POTENTIAL (1)

(Computations and factors apply to current through 24-hour conditions)

DECISION LADDER



(1) Strong depressions, storms, and hurricanes

(2) Q = absolute vorticity

(3) FAAM = Flux of absolute angular momentum

Figure 2. Revised decision ladder for strong tropical depressions, storms, and hurricanes. See text for discussion of criteria.

Weekly mean sea surface temperatures and anomalies are obtained from the NHC objectively analyzed charts which use composited ship data (Jarvinen, 1973). Satellites also supply daily sea-surface temperature and cloud mass and feeder-band information. Reconnaissance aircraft routinely furnish 700 mb horizontal temperature gradients and radius of maximum winds in a vortex.

This paper presents the results of a study for the five-year period 1968-1972 which evaluated the criteria in the decision ladder of Figure 1, together with further modifications of the criteria during the period 1973-1975. It does not address the even more difficult problem of the initiating mechanism(s) which formed the depressions. A recent study by Shapiro (1976) addresses this problem for some Atlantic tropical systems. The study is primarily concerned with the evolution of tropical waves into tropical depressions which continue to develop into tropical storms. The criterion for development versus non-development of a depression is a dynamical one based on wave number criteria of the tropical wave train moving across the Atlantic in the mean flow. It does not deal with other types of disturbances which develop into tropical storms.

The revised decision ladder of Figure 2 is presented here for completeness of the updated criteria. A detailed study of its criteria has not been made. Although the decision ladders require a 24-hour forecast of the various criteria, this study examined only the conditions existing 24 hours prior to the development or non-development of existing tropical depressions into tropical storms. Non-developing depressions were examined 24 hours prior to the time they reached their lowest sea level pressure, based on the assumption that conditions were then most favorable for development. Since depressions which develop into tropical storms usually do so within 36 hours after formation (Hebert, 1971), (Dvorak, 1975), it was felt that this approach would give the greatest input on critical decisions of tropical storm versus no tropical storm formation. However, the criteria are equally valid for assessing the development potential of a depression at any time.

DATA SAMPLE. A total of 134 depressions formed over the Atlantic, Gulf of Mexico, and Caribbean Sea during the five-year period 1968-1972. Table 1 shows the breakdown by years. Since some of the decision ladder criteria require upper air data, this limited the study to depressions which formed or moved into the area west of longitude 55 West and south of latitude 35 North. This reduced the sample size to 93 cases, and an additional 26 cases were lost because of insufficient data in the study area or the depression being over the water less than 12 hours. Finally, two strongly baroclinic storms (that is, definitely cold core) were not included. The final data sample consisted of 65 cases or 48% of the total number of possible cases. Of these, 38 or 58% developed into storms. Approximately 75% of all storms and 50% of non-developing depressions from the five-year total were used in the evaluation study.

Table Data base used to evaluate western North Atlantic tropical depression intensification criteria.

DEPRESSIONS	1968	1969	1970	1971	1972	TOTAL	YRLY. AVG.	%
Total cases	19	38[1]	29[1]	23	25	134	27	
West of 55W and south of 35N	13	28	21	19	12	93	19	69
Used in study	7	22		16	9	65	13	48

[1] Anna, Camille, and Inga each went from the depression stage to storm stage twice, while Francelia, Becky, and an un-named storm each degenerated into a tropical wave from a depression and subsequently became storms. All six are in the depression count twice.

As indicated by the footnote in this table, annual and five-year depression totals will differ from those presented by Frank (1973). The percent which became storms will also differ because of this and the fact that Frank only considered named storms.

Figure 3 shows the location of the depressions when the classification criteria were evaluated. Note that 75% of the depressions in the northwestern Caribbean Sea and north of Cuba between longitudes 73 West to 83 West developed into storms, as well as all of those located in the eastern Caribbean Sea. The latter area is considered climatologically to be very unfavorable for development. It should be pointed out here that most of the study period had subnormal tropical storm/hurricane activity, and these results may not be representative of a longer period. Most of the depressions which developed into tropical storms are north of the climatologically favorable areas of surface relative vorticity, vertical wind shear, sea surface temperature, and the vertical distribution of equivalent potential temperature as indicated by Gray (1968). Instead, development throughout most of the Atlantic, Caribbean, and Gulf of Mexico occurs as a result of favorable anomalies of intensification criteria from generally unfavorable climatological values.

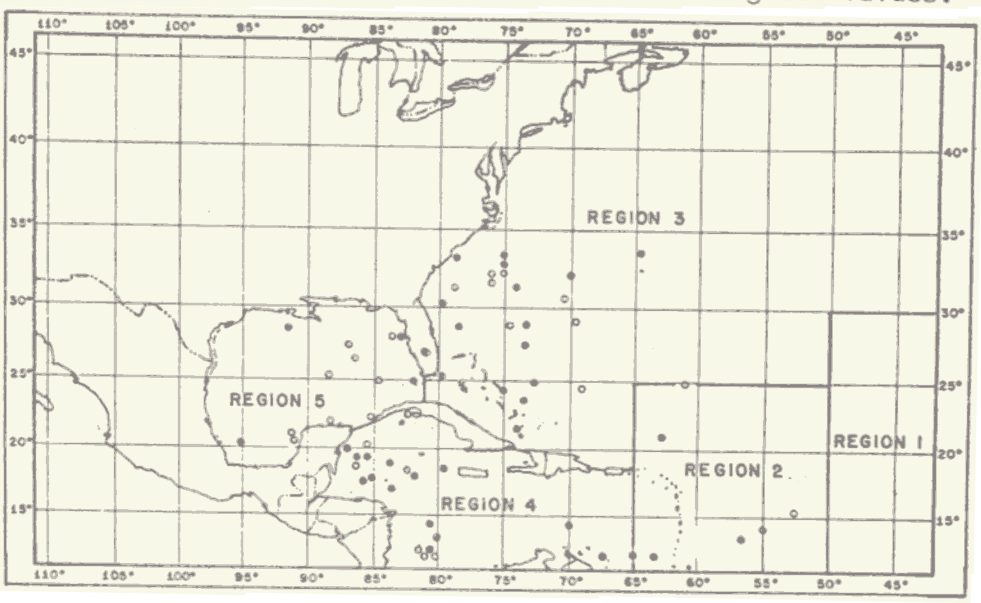


FIGURE 3. LOCATION OF DEPRESSIONS AT D-24 HOURS PRIOR TO REACHING STORM INTENSITY (SOLID CIRCLES) OR MINIMUM SEA LEVEL PRESSURE (OPEN CIRCLES) FOR PERIOD 1968-1972.

Table 2 gives a statistical breakdown of the synoptic origins (part a) of the depressions after Frank (1973), their regions of formation (part b) as shown in Figure 3, and months of formation (part c). As noted by Frank (1973) the importance of African waves in generating depressions is evident in part (a) of the table, as is the high percentage of depressions of baroclinic origin during this period. Part (c) of Table 2 shows not unexpectedly that the percentage of depressions which became storms increased as the hurricane season progressed. As mentioned previously, the depression totals for the five years of the study are not in complete agreement with those presented by Frank in his summary articles on Atlantic tropical disturbances.

Table 2a. Synoptic origins of depressions which became storms (S) or failed to acquire storm strength (D) for entire data sample and study sample. (H) indicates the number of storms which strengthened to hurricanes.

	TOTAL CASES							USED IN STUDY				
SYNOPTIC ORIGIN	S	S%	(H)	D	D%	TOTAL	% GRAND TOTAL	S	S%	D	D%	TOTAL
African wave	25	44	(12)	32	56	57	43	15	79	4	21	19
Tropical disturbance	6	67	(4)	3	33	9	7	6	75	2	25	8
Caribbean ITC disturb.	4	44	(3)	5	56	9	7	4	50	4	50	8
Atlantic ITC disturb.	1	33	(0)	2	67	3	2	0	0	0	0	0
Cold low	13	52	(7)	12	48	25	18	9	53	8	47	17
Frontal zone	9	41	(3)	13	59	22	16	4	40	6	60	10
Baroclinic zone	1	11	(0)	8	89	9	7	0	0	3	100	3
Grand totals	59	44	(29)	75	56	134	100	38	58	27	42	65

Table 2b. Same as 2a for regions of formation shown in figure 3 except for total cases only.

	TOTAL CASES					
REGION OF FORMATION	S	S%	D	D%	TOTAL	% GRAND TOTAL
1 Eastern Atlantic	9	29	22	71	31	23
2 Lesser Antilles	7	58	5	42	12	9
3 Western Atlantic	27	52	25	48	52	39
4 Western Caribbean	12	55	10	45	22	16
5 Gulf of Mexico	4	24	13	76	17	13
Grand totals	59	44	75	56	134	100

Table 2c. Same as 2b for months of formation.

	TOTAL CASES					
MONTH OF FORMATION	S	S%	D	D%	TOTAL	% GRAND TOTAL
May	2	29	5	71	7	5
June	4	33	8	67	12	9
July	6	35	11	65	17	13
August	15	45	18	55	33	25
September	21	46	25	54	46	34
October	7	50	7	50	14	10
November	4	80	1	20	5	4
Grand totals	59	44	75	56	[illegible]	[illegible]

Footnote 1 of table 1 applies to these tables.

THE DECISION LADDER CRITERIA. The nine criteria listed in the revised decision ladder for tropical waves and weak depressions (Figure 1) encompass the dynamic and thermodynamic factors considered important from both theoretical and empirical studies of tropical depression intensification. As a tropical cyclone reaches the stronger stages of development, the criteria take a somewhat different order of importance (Figure 2). The results of the evaluation of the criteria for the period 1968-1972 have led to further modifications during the period 1973-1975. These modifications will be presented later. While several of the criteria might appear to be different representations of the same factor, this is not necessarily so. The more favorable that conditions are for development, however, the more likely it is that the criteria are inter-related. This becomes important in any attempt to quantify the development criteria into a single development potential index such as Gray's (1968).

Before presenting the evaluation of the revised decision ladder criteria, the next three sets of figures serve to illustrate differences in the criteria for developing and non-developing depressions. These differences are reflected by the locations of developing and non-developing depressions relative to thickness ridges and troughs (or thermal anticyclones and cyclones) as depicted on the NHC vertical wind shear chart, and the 200 mb subtropical (or tropical) jet. In all three figures the non-developing depressions are in the upper panel and the developing depressions are in the lower panel.

For compositing purposes, the perpendicular distance of the depression in degrees of latitude from the ridge or trough axis was plotted along the azimuth of this perpendicular relative to true north. In the case of the jet, the distance was measured directly to the maximum of the jet and plotted relative to it according to a quadrant system. The actual orientation relative to true north of any type of axis for an individual depression can be obtained by subtracting ninety degrees from the azimuth along which the depression is plotted.

A synoptic scale thickness ridge is usually an area of above normal thickness and weak anticyclonic vertical wind shear. Above normal thickness anomalies should increase, and vertical wind shears should decrease the closer a depression is located to the ridge axis. In addition, the meso-scale thermal anticyclone of the depression may itself augment thickness anomalies and help diminish vertical shears.

An examination of Figure 4 reveals that 68% of depressions which developed into tropical storms within 24 hours were located within four degrees of latitude of a thickness ridge axis compared to only 37% of non-developing depressions. The proximity to the ridge axis of the depressions which developed strongly implies that they were already warm core in nature. In addition, developers tend to be clustered in the northwest sector of the composite while non-developers are located rather randomly.

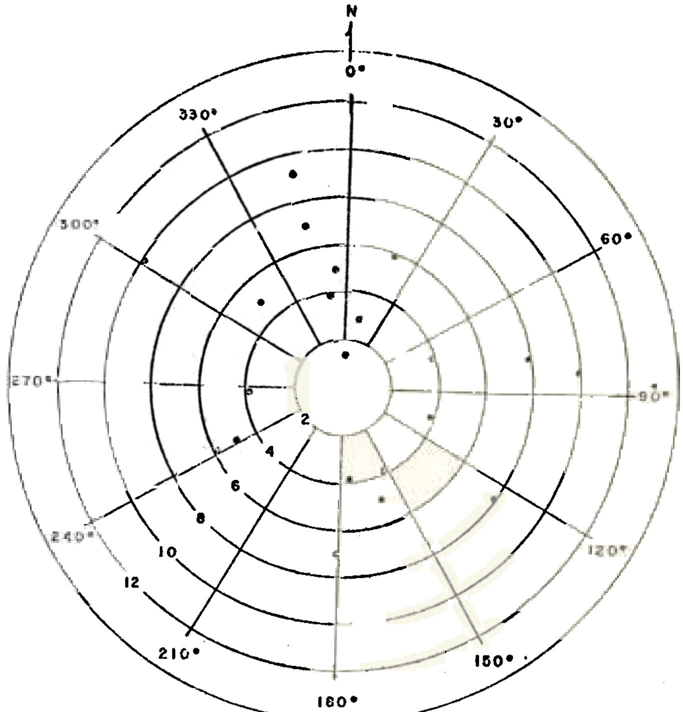


Figure 4a. Composite diagram of depression center locations relative to thickness ridges at D-24 hours prior to lowest sea level pressure (non-developing), plotted relative to true north. In each case the azimuth of the depression is determined by the direction of the line perpendicular from the depression to its corresponding ridge axis.

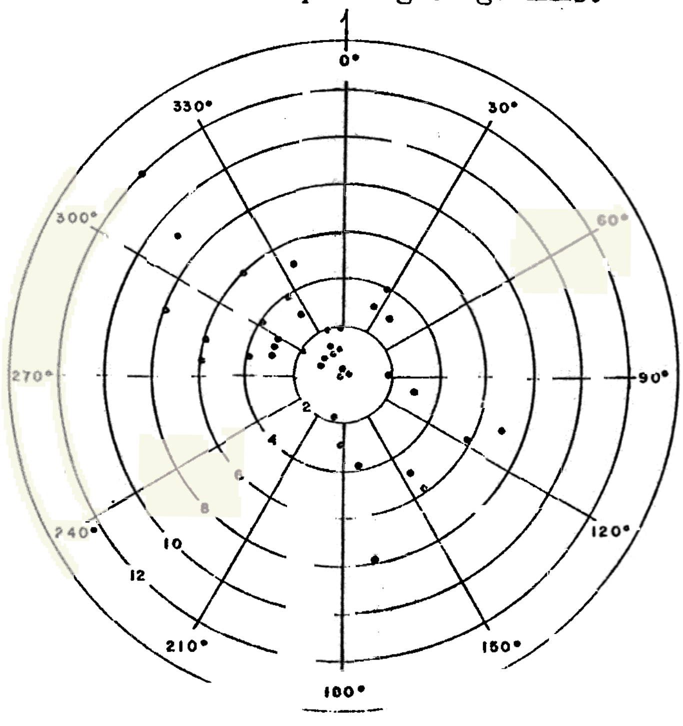


Figure 4b. Same as figure 4a for depressions at D-24 hours prior to reaching storm intensity.

Correspondingly, a synoptic scale thickness trough is usually an area of stronger vertical wind shear and/or below normal thicknesses. These conditions will be most pronounced when a depression is near the trough axis, but gradually taper off to little or no significance beyond a distance of ten degrees of latitude.

Figure 5 shows the location of developing and non-developing depressions relative to the nearest thickness trough on the NHC vertical wind shear chart. Forty-seven percent of developers lie within six to ten degrees of latitude east of the trough axis compared to only 22% of non-developers. The actual percentage for developers is not very high, but is significantly better than for non-developers. These lower percentages are probably a result of the fact that thickness ridges tend to be broader and more persistent than thickness troughs, and that depressions do not always interact with troughs in the westerlies. The distance range of six to ten degrees of latitude of a thickness trough in the westerlies from a depression has been selected to illustrate the importance of the interacting westerly trough. Whether or not the trough has a positive or negative influence on the development of a depression depends greatly on the strength of the trough and the relative speed of the trough to the depression.

Objective computations of vorticity advection at 200 mb were not available during the study period. In order to come up with a consistent means of evaluating the vorticity advection criterion, the depressions were located relative to the subtropical jet. In most cases the jetstream was oriented basically west-east with little curvature. In only two or three cases were the depressions located relative to a tropical or easterly jet. This is probably <u>not</u> representative of other areas of tropical cyclone development. The jet maximum was located and depressions were plotted relative to it according to a four quadrant system. The assumption was that the classical distribution of divergence, vorticity, and vorticity advection would prevail, since most of the jets were fairly straight or had only slight curvature.

Figure 6 shows that 74% of the depressions which reached tropical storm strength within 24 hours were located in the right rear (RR) quadrant more than six degrees of latitude away. Under the previous assumption this should be an area of divergence which enhances the outflow mechanism of a developing depression, while the depression itself would be far enough away from the jet axis to avoid excessive vertical wind shear. By contrast, only 30% of the non-developing depressions are found there. Thirty-three percent are within six degrees of latitude of the jet maximum, implying strong vertical shears, while another 33% are in the right front (RF) quadrant beyond six degrees of latitude. The assumed vorticity-divergence distribution would make this an area of high level convergence which would stifle the outflow of a convective system.

Figure 5b. Same as figure 5a for depressions at D-24 hours prior to reaching storm intensity.

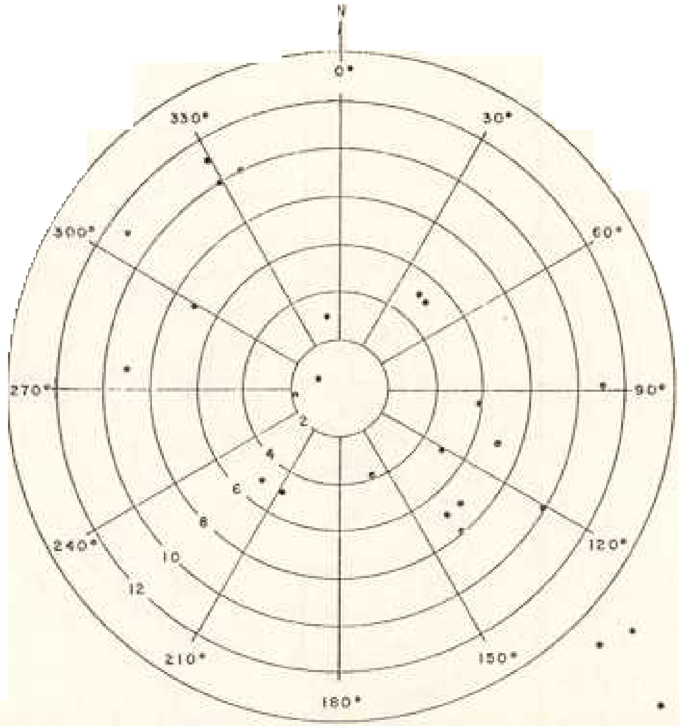


Figure 5a. Composite diagram of depression center locations relative to thickness troughs at D-24 hours prior to lowest sea level pressure (non-developing), plotted relative to true north. In each case the azimuth of the depression is determined by the direction of the line perpendicular from the depression to its corresponding trough axis.

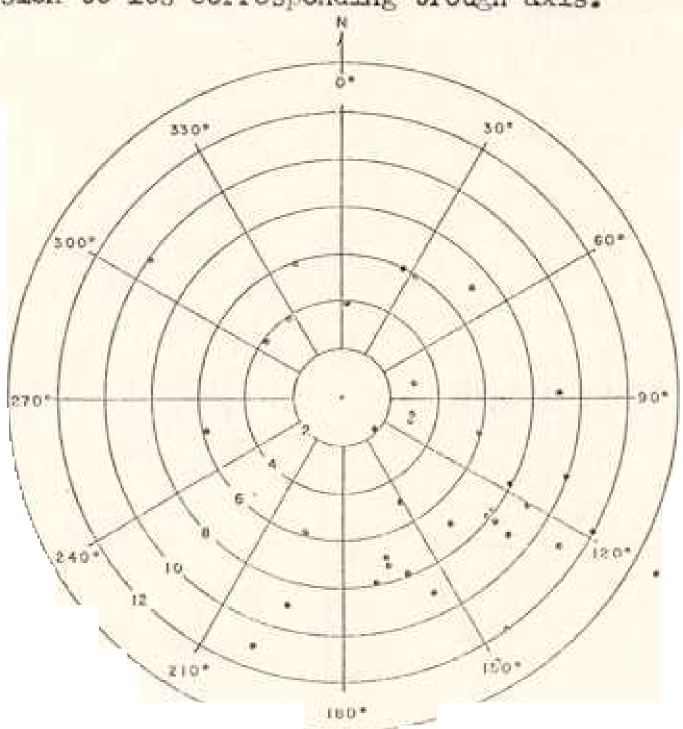


Figure 5b. Same as figure 5a for depressions at D-24 hours prior to reaching storm intensity.

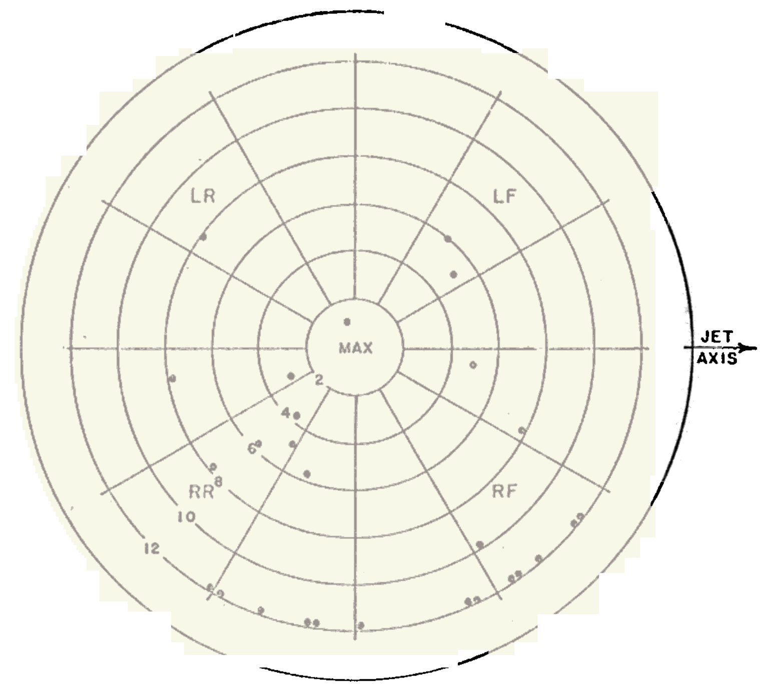


Figure 6a. Composite diagram of depression center locations relative to the 200 mb maximum wind (jet) at D-24 hours prior to lowest sea level pressure (non-developing). Locations are plotted in a four-quadrant system obtained by the intersection of the jet axis and its perpendicular through the jet maximum.

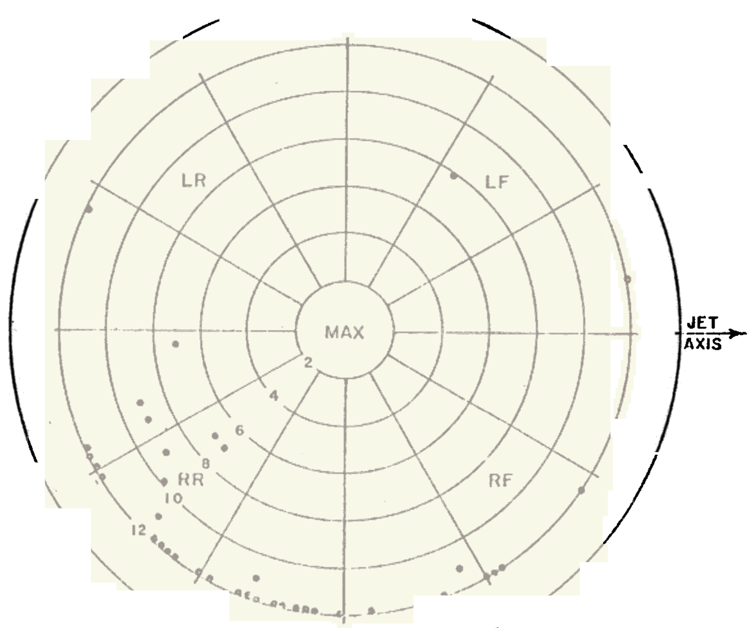


Figure 6b. Same as figure 6a for depressions at D-24 hours prior to reaching storm intensity.

EVALUATION OF THE DECISION LADDER CRITERIA. The purpose of this paper is to present an evaluation of the decision ladder criteria in their revised form, and subsequent modifications during the period 1973-1975 It is beyond the scope of this presentation to go into detailed discussions of the various criteria, most of which would be basic physica and dynamical meteorology. The primary intent of this study was to evaluate the individual criteria. The decision ladder itself cannot be strictly evaluated, since this study only looked at conditions 24 hours prior to development or non-development of a depression into a storm. However, the step-wise approach was evaluated under this constraint, and the results will be discussed briefly.

The revised decision ladder criteria of Figure I are basically those proposed by Simpson (1971) in his original decision ladder for tropical disturbances of less than storm strength. The three-year study by Hebert (1971) indicated the importance of the cloud mass location relative to a tropical wave axis or depression center, as well as the importance of the other environmental factors at this stage of development. Therefore, the first five criteria, which are basically thermodynamic in nature, have been placed first. The last four criteria are dynamic.

Application of the step-wise approach to the criteria as listed in Figure I resulted in a correct decision 49% of the time. Development was forecast correctly 34% of the time, while non-development was forecast correctly 71% of the time. The large difference for development versus non-development appears to be the more conservative nature of the thermodynamic criteria versus the dynamic criteria. The latter are influenced much more during the 24 hour forecast period. Unfavorable thermodynamic environmental conditions tend to persist, assuring continued non-development of a depression. For developing depressions, if favorable thermodynamic conditions exist, the change from unfavorable to favorable dynamic conditions in a twenty-four hour period can change many no development decisions to development decisions.

Table 3 summarizes the results of the evaluation of the individual criteria shown in Figure I. As indicated earlier, the location of the depression relative to the 200 mb jet maximum was substituted for the vorticity advection criteria. For those depressions which developed into storms the correct answer for an individual criteria to be met is YES, while for non-developers the correct answer is NO.

An examination of the percentages of correct answers in Table 3 gives an indication of the relative importance of the various criteria. The single most important criterion is the relative position of the convective cloud mass to the depression center. This is true for both developing and non-developing depressions. In addition, the presence or absence of an apparent feeder band from a southerly quadrant (southwest through southeast) is also highly significant. The success of the Dvorak technique for classifying tropical cyclones is strongly related to these criteria. They are probably highly correlated to the criteria of mean shear thickness, anticyclonic vertical wind shear, horizontal cyclonic wind shear, and 200 mb vorticity advection (or the alternate jetstream criteria substituted). The high level flow pattern strongly

Table 3. Evaluation of revised decision ladder criteria for development or non-development of a depression into a storm. Number of the individual criteria corresponds to the number in figure 1. Total number of cases are in parentheses.

CRITERIA	CRITERIA MET					
	STORMS-YES (38)		NON STORMS-NO (27)		TOTAL (65)	
	CASES	%	CASES	%	CASES	%
1 Cloud mass NE-E of wave axis or depression center.	36	95	17	63	53	82
2 Mean shear thickness above normal over disturbance.	32	84	12	44	44	68
3 Feeder bands emanating from southerly quadrant.	28	74	22	81	50	77
4 Mean mixing ratio (1000-600 mb) > 8 gm./kg. (not available 1968-69).	22	100	2	7	40	62
5 Sea surface temperature $\geq 26-27^{\circ}$ C.	38	100	2	7	40	62
6 Anticyclonic vertical shear $\leq$ 10 kt ($\leq$15 kt north of 30N) within 4° latitude.	29	76	12	44	41	63
7 Horizontal cyclonic shear between $2-6^{\circ}$ of latitude north of center.	23	61	10	37	33	51
8 Increasing negative vorticity advection at 200 mb between $2-6^{\circ}$ of latitude north of center. (Depression in RR quad. of jet > 6° latitude from cntr.)	27	71	15	56	42	65
9 Interacting westerly trough approaching and $\geq 10^{\circ}$ of latitude away.	21	55	15	56	36	55

influences the appearance of the cloud mass on satellite pictures. For example, a non-developing depression can have above normal mean shear thickness, light anticyclonic vertical shear, and low level horizontal cyclonic wind shear as a result of developing on the southeast periphery of a large, warm anticyclone, but there will be suppressed convection, and criteria one and three (the satellite criteria) will not be met.

Figure 7 illustrates this important difference. On August 30 only the low level horizontal cyclonic shear criterion was not met, and this became favorable during the succeeding 24 hours. Forty-eight hours later another depression has formed to the southwest of what is now tropical storm Carrie. Seven of the nine criteria are met, but <u>not</u> the two satellite criteria, and this depression failed to develop into a storm. Since the study has shown that the mean mixing ratio and sea surface temperature criteria are almost always met during most of the hurricane season, one can easily get at least five YES answers even though there is little or no chance of tropical storm development because of the lack of organized convection! These <u>always YES</u> answers for mean mixing ratio and sea surface temperature also reduce the number of possible NO answers for non-developers, leading to the rather poor percentages of correct answers for these criteria. Yet, development usually does not occur where and when these criteria are not met.

The importance of the vertical wind shear and thickness criteria have been discussed previously.

The poor percentages for the horizontal wind shear criterion for both developers and non-developers is partly a result of the 24 hour forecast problem. Depending on the speed, strength, and orientation of an interacting westerly trough, horizontal cyclonic wind shear may disappear completely while the other three dynamical factors may remain favorable for development. In addition, the two to six degree of latitude range was beyond the cyclonic wind maximum of the depression in many cases, and a zero to four degree distance would have improved the percentages considerably.

The role of the interacting westerly trough as discussed earlier, and shown in Figure 5, is most important for depressions recurving into the westerlies or being bypassed by a rapidly moving trough. In this study it involved the interaction of a depression with the high level (200 mb) mid-Atlantic trough in only a few cases.

The importance of the vorticity advection (or jetstream) criterion has been shown in Figure 6, and is reflected in the relatively high percentages of correct answers in Table 3.

Average values of thickness anomalies, mean mixing ratios, sea surface temperatures, and vertical wind shears showed no significant differences between developers and non-developers 24 hours prior to their reaching storm strength or lowest sea level pressure. Developers were slightly warmer and moister with sea level pressures averaging one millibar lower.

Figure 7a. ATS-3 satellite picture at 1359Z 30 August 1972 illustrating the importance of the satellite criteria for assessing development potential of a tropical depression. The depression center is marked by an X.

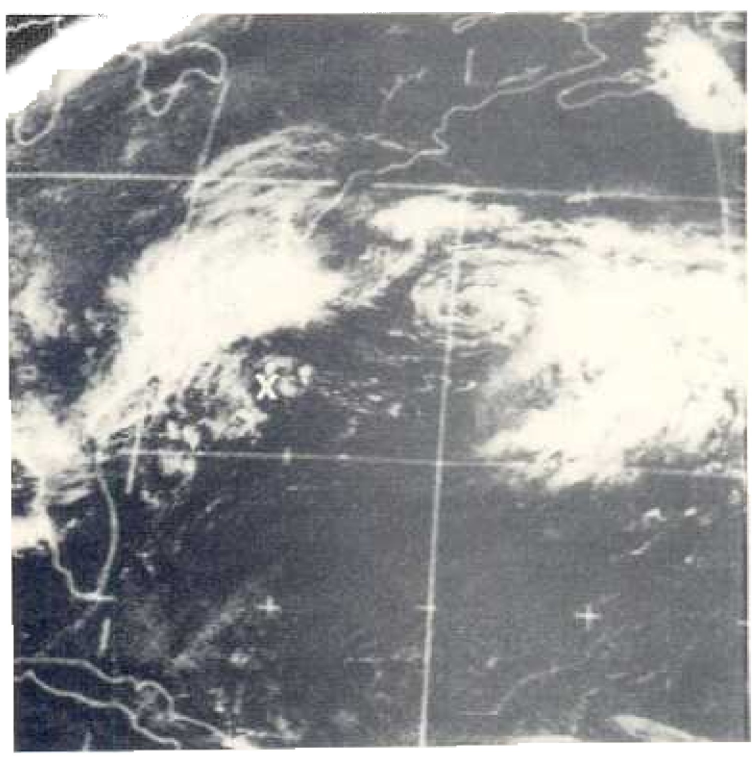


Figure 7b. ATS-3 satellite picture at 1252Z 1 September 1972. The non-developing depression center marked by an X has little organized convection near it.

OBJECTIVE COMPUTATIONS. A program for making objective computations of various dynamical parameters at the ATOLL and 200 mb level became operational at the National Hurricane Center in 1972. Table 4 shows the results of the objective computations made from subjective analyses of 1971 depressions in order to test the program. These are compared to objective computations made from objective analyses for a few cases in 1972 in order to illustrate that the program obtains the right order of magnitude for the various quantities at radii of 4° and 6° of latitude In general, data are not presently sufficient on the ATOLL chart to get meaningful results at radii less than 4°. A detailed discussion of these objective computations as well as results for the period 1972-1976 for tropical cyclones of all intensities will be in a forthcoming paper by Jarvinen and Hebert (1977) to be submitted as a separate technical memorandum.

SUMMARY AND CONCLUSIONS. Most of the original decision ladder criteria proposed by Simpson (1971) appear to be necessary for development of a tropical depression into a tropical storm. Early experience and advancing technology led to some modification of the criteria. As a result of the evaluation of the decision ladder criteria, together with the ability to obtain objective computations routinely, several additional modifications have been made to the revised decision ladders in order to have criteria which can be given a more definitive YES or NO answer, especially from current operational data.

Figures 8 and 9 present the checklists presently in use at NHC. For depression development, the mean mixing ratio and sea surface temperature criteria have been dropped. The interacting westerly trough criterion has been modified. The cyclonic horizontal wind shear has been changed to the distance of zero to four degrees of latitude. For storms and hurricanes, use has been made of the available objective computations and experience obtained since geostationary satellite data have been available. The attempt to use data routinely available has been given strong emphasis.

The stepwise approach used in the decision ladders resulted in correct answers only 49% of the time, based on current conditions. To a large extent this was because of the requirement to also make a 24 hour forecast of the criteria. The checklist approach has been adopted since the evaluation showed that any 6 or more out of 9 correct answers ($\geq$ 5 out of 8 in 1968-1969) led to a correct prediction of development or non-development 75% of the time. Especially significant was the increase for developing depressions from 34% to 82%. Only one less correct decision for non-developers resulted from this approach. A twenty-four hour forecast is still required for all criteria, but at present there is no objective forecast of any of the criteria routinely available for tropical and subtropical oceanic areas.

Table 4. Objective computations of selected dynamical quantities at radii of 4° of latitude and 6° of latitude for 1972 depressions which became storms (S), 3 cases, and those which failed to reach storm strength (D), 2 cases. Storm cases for 1971, 9 cases, are in parentheses.

	RADIUS					
	4° LATITUDE			6° LATITUDE		
DYNAMICAL QUANTITY	S		D	S		D
			ATOLL			
Flux of absolute angular momentum (10^{12} cm^3-s^{-2})	-10.7	(-9.0)	2.6	-20.7	(-11.2)	-12.6
Radial velocity (m-s^{-1})	-1.3	(-1.1)	2.6	-1.4	(-0.8)	-0.9
Areal divergence (10^{-5} s^{-1})	-0.6		0.0	-0.4		-0.4
Areal vorticity (10^{-5} s^{-1})	1.6		2.1	0.8		0.8
			200 MB			
Flux of absolute angular momentum (10^{12} cm^3-s^{-2})	2.3	(1.0)	7.7	12.2	(5.4)	28.2
Radial velocity (m-s^{-1})	1.2	(1.0)	1.0	1.6	(0.8)	1.3
Areal divergence (10^{-5} s^{-1})	1.2		1.0	0.6		0.9
Areal vorticity (10^{-5} s^{-1})	-4.8		-6.0	-1.5		-2.4

	CURRENT		24-HR TREND	
	YES	NO	YES	NO
1. Cloud mass NE-E of wave axis or depression center?				
2. Feeder bands emanating from southerly quadrant?				
3. Mean shear thickness above normal over disturbance?				
4. Anticyclonic vertical shear $\leq$ 10 kt ($\leq$ 15 kt north of 30°N) within 4° latitude?				
5. Cyclonic horizontal shear 0-4° latitude north of center?				
6. Disturbance/depression in right rear quadrant of subtropical jet and $>$6° latitude away?				
7. Interacting westerly trough approaching and $>$8° latitude away? (For systems north of 25°N)				
Total				

Figure 8. Checklist for tropical wave/depression development into a tropical storm.

	CURRENT		24-HR TREND	
	YES	NO	YES	NO
1. Net low level inflow across 4° radius calculation point?				
2. Net high level outflow across 4° radius calculation point?				
3. Feeder bands emanating from southerly quadrant?				
4. High level shear <u>not</u> uni-directional?				
5. Low level center under convective cloud mass?				
Total				

Figure 9. Checklist for storm/hurricane weakening/intensification.

Simpson (1971) pointed out that experience might lead to the proper weighting of the various criteria, and screening procedures established to develop an objective decision on development potential. The percentages of correct answers shown in Table 3 does give some measure of the relative importance of these criteria. While not presented here, the actual values of the various criteria in the decision ladder appear to influence the rate of development and ultimate intensity of many depressions. A REEP type (Miller, 1964) screening procedure will be made against the tabulated data values of each criterion in order to determine if a meaningful probability of development can be obtained from these criteria. Positive results from this approach could lead to a similar study for any intensity stage of a tropical cyclone.

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