

Observational Analysis of Tropical Cyclone Formation. Part II: Comparison of Non-Developing versus Developing Systems

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ABSTRACT

The thermodynamic and dynamic fields surrounding the composite tropical weather systems described in Part I (McBride, 1981a) are examined for differences between non-developing and developing systems. The main findings are as follows: (i) Both non-developing and developing systems are warm core in the upper levels. The temperature (and height) gradients are more pronounced in the developing system, but the magnitudes are so small that the differences would be difficult to measure for individual systems. (ii) The developing or pre-typhoon cloud cluster exists in a warmer atmosphere over a large horizontal scale, for example, out to 8° latitude radius in all directions. (iii) There is no obvious difference in vertical stability for moist convection between the systems. (iv) There is no obvious difference in moisture content or moisture gradient. (v) Pre-typhoon and pre-hurricane systems are located in large areas of high values of low-level relative vorticity. The low-level vorticity in the vicinity of a developing cloud cluster is approximately twice as large as that observed with non-developing cloud clusters. (vi) Mean divergence and vertical motion for the typical western Atlantic weather system are well below the magnitudes found in pre-tropical storm systems. (vii) Once a system has sufficient divergence to maintain 100 mb or more per day upward vertical motion over a 4° radius area, there appears to be no relationship between the amount of upward vertical velocity and the potential of the system for development. (viii) Cyclogenesis takes place under conditions of zero vertical wind shear near the system center. (ix) There is a requirement for large positive zonal shear to the north and negative zonal shear close to the south of a developing system. There is also a requirement for southerly shear to the west and northerly shear to the east. The scale of this shear pattern is over a 10° latitude radius circle with maximum amplitude at ~6° radius.

Under the assumption of a symmetric disturbance, these findings can be synthesized into one parameter for the potential of a system for development into a hurricane or typhoon: Daily Genesis Potential (DGP) = $\zeta_{900\text{ mb}} - \zeta_{200\text{ mb}}$, when applied over 0–6° radius.

Wind fields are examined surrounding 79 individual weather systems in the tropical Atlantic and it is shown that the composite findings are present on a case by case basis. The individual case analysis also reveals that the high values of DGP must be made up of fairly equal contributions from all directions around the disturbance. This is consistent with the requirement for the existence of zero lines in both zonal and meridional vertical shear.

1. Introduction

This is the second of a series of papers on the development of tropical cyclones. In Part I (McBride, 1981a) twelve composite data sets were constructed to represent mean tropical oceanic weather systems in the northwest Pacific and northwest Atlantic. The composite data sets included pre-typhoon, pre-hurricane and non-developing cloud clusters as well as tropical cyclones in various intensity stages. In Part I the basic thermodynamic and dynamic structure of the composite data sets was described. In this paper comparisons are made between the data

sets so that the features important for storm development can be distinguished. Three basic comparisons are made: non-developing versus pre-typhoon cloud clusters in the northwest Pacific; non-developing versus pre-hurricane cloud clusters in the northwest Atlantic; and non-developing versus pre-hurricane depressions in the northwest Atlantic. These three independent sources of comparison allow an opportunity to search for consistencies in the observational differences. An evaluation of how well the composite findings apply to individual cases is made by examining the wind fields around 79 individual weather systems in the northwest Atlantic.

2. Comparison of structure

a. Pacific cloud cluster: N1 vs D1, D2

The Pacific N1 non-developing cloud cluster and the Pacific D2 pre-typhoon cloud cluster were origi-

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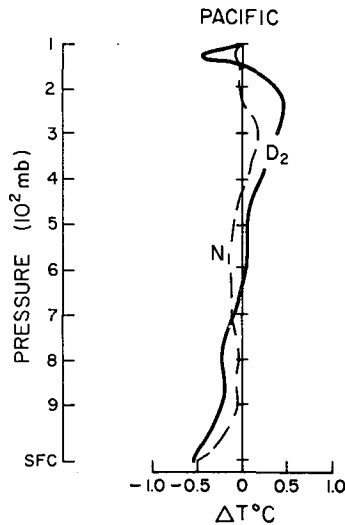


FIG. 1. Cluster minus environment vertical temperature profiles ΔT for the Pacific developing (D2) and non-developing (N1) cloud clusters. T cluster is the mean temperature within 3° latitude radius of the center of the system; T environment is the average temperature between 3 and 7° to the east and west of the system.

nally composited and analyzed by Zehr (1976).³ These two data sets include a similar number of observations and were used by Zehr to define the differences in structure between a system which would later develop into a typhoon and one which would not. Zehr found a number of differences between the two composite systems. A study of this type is subject, however, to the criticism that the findings may be symptomatic of development that has already begun to take place in the pre-typhoon systems. In other words the differences could be described as the differences between a non-developing cluster and a weak tropical cyclone, rather than between a non-developing and a developing cluster. To avoid this difficulty, the current study includes also an analysis of the pre-typhoon data set composited by S. Erickson (1977).⁴ This data set (Pacific D1 early pre-typhoon cloud cluster) is very much smaller than the others in terms of number of rawinsonde observations involved; but it consists of the very first one to two days existence of the pre-typhoon system as observed by visual and infrared DMSP satellite imagery. Because of the greater amount of noise present in the smaller D1 data set, the main comparison made here will be between D2 and N1. The D1 data set will be referred to in order to show that the differences found

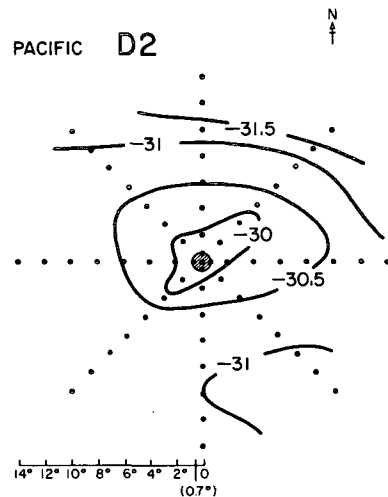
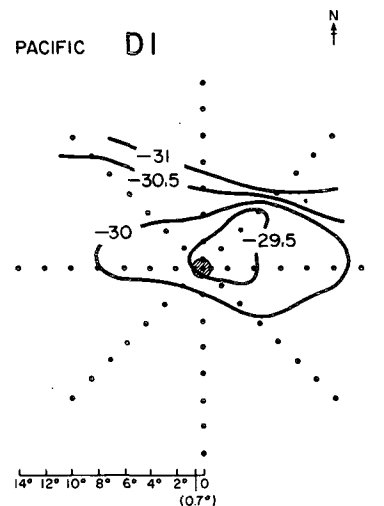
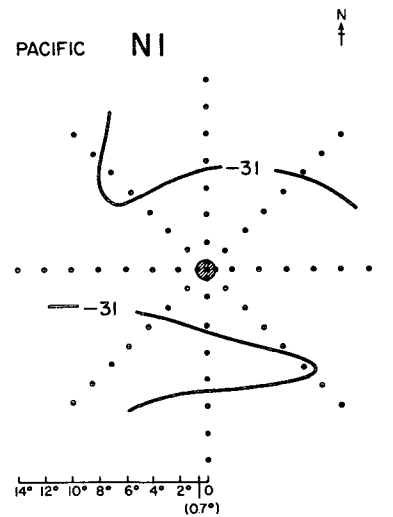


FIG. 2. Plan views of 300 mb temperature ($^\circ\text{C}$) for the Pacific N1 non-developing cloud cluster and for the developing (D1, D2) cloud clusters.

³ Zehr, R., 1976: Tropical disturbance intensification. Dept. Atmos. Sci. Pap. No. 259, Colorado State University, 91 pp. [NTIS PB 263 153].

⁴ Erickson, S. L., 1977: Comparison of developing vs. non-developing tropical disturbances. Dept. Atmos. Sci. Pap. No. 274, Colorado State University, 81 pp. [NTIS AD AO 48641].

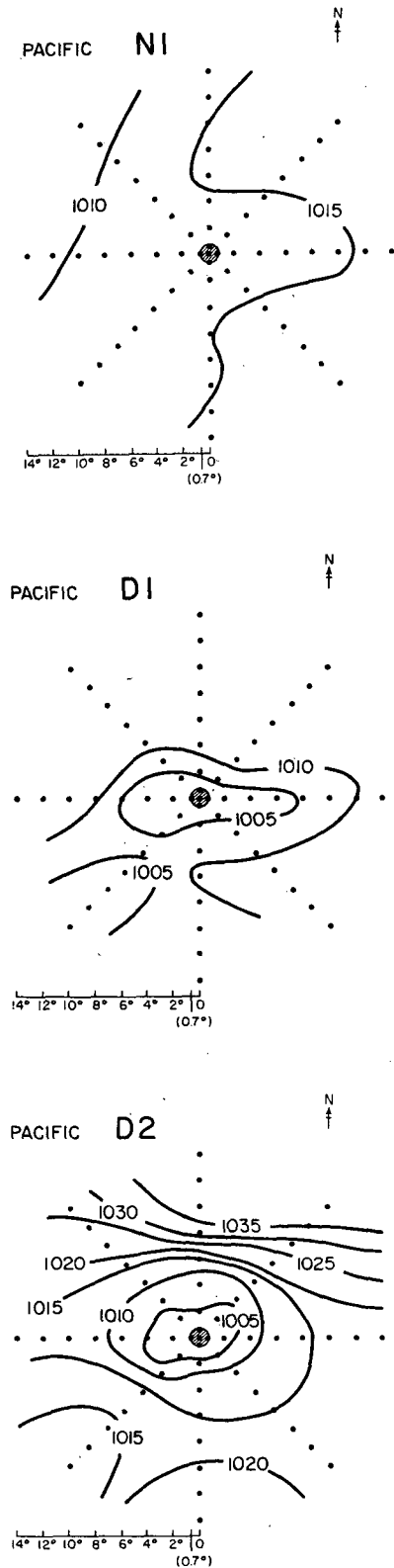


FIG. 3. Plan views of 900 mb heights (m) for Pacific N1 non-developing cloud cluster and for the developing (D1, D2) cloud clusters.

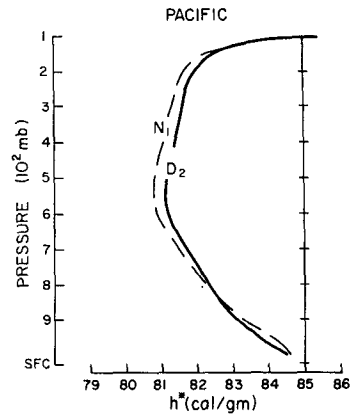


FIG. 4. Saturated moist static energy averaged over the 0-3° area for the Pacific N1 non-developing cloud cluster and D2 pretyphoon cloud cluster.

are pertinent to the very beginning of the cluster's existence.

Fig. 1 shows the vertical profiles of temperature anomaly (T_{0-3° minus $T_{\text{east-west}, 3-7^\circ}$). The developing system has a better defined upper level warm core than does the non-developing; but the gradients are small. Plan views of the temperature at 300 mb are shown in Fig. 2. A warm core can be seen for all three systems, but it is more distinct and of greater magnitude in the two developing systems. There are several features which should be noted in Fig. 2:

- 1) The warm core at 300 mb extends over a very large area. (The grid points along each radial arm are 2° latitude or 222 km apart).
- 2) The warm core is distinct and obvious on the composite analyses for the developing systems; but in an individual atmospheric system it would be hard to measure, being of the order of 1°C difference in temperature over several hundred kilometers.
- 3) For all systems the temperature perturbation is quite symmetric. The only asymmetry seen is associated with the cold temperatures at the higher latitudes to the north.
- 4) Besides having a greater temperature gradient the developing system also has a higher absolute value of temperature at 300 mb. The whole region out to 8° latitude in all directions around the developing cloud cluster is warmer than that around the non-developing cloud cluster.

Hydrostatically, the vertical integral of the differences in temperature between developing and non-developing systems is equivalent to a difference in low-level pressure. Fig. 3 shows plan views of the height of the 900 mb pressure level. There is an obvious difference between developing and non-developing systems, the developing have a distinct area of low height or low pressure centered

on the system. The 900 mb heights near the center of the developing cluster are ~ 1002 m as compared with 1012 around the non-developing cluster. Converted to a difference in surface pressure this relates to only 1 mb. Thus, even though the differences in vertically integrated temperature show up clearly on composite analyses, they are of too small a magnitude to be useful in distinguishing between developing and non-developing disturbances in the individual cases.

The vertical lapse rate stabilities are very similar in the developing and non-developing systems; in fact, the greater middle-level temperature in the developing case means that it actually has less potential buoyancy as measured by the vertical gradient of moist static energy h^* (Fig. 4).

Fig. 5 shows vertical profiles of mixing ratio of water vapor for the cluster ($0-3^\circ$) minus its surroundings ($3-5^\circ$). The magnitude of the moisture anomaly is similar in both systems, as is the absolute value of the moisture content. The precipitable water averaged over the $0-6^\circ$ area is 5.7 g cm^{-2} for the developing system (D2), and 5.6 g cm^{-2} for the non-developing system (N1).

Turning now to the wind or dynamic fields, the lower level (900 mb) and upper level (200 mb) flow patterns are shown in Figs. 6 and 7.

At 900 mb both developing and non-developing clusters have easterly trade wind flow to the north and westerly monsoon flow from the south. An area of convergence centered on the system can be seen in all cases. The main difference between the flow patterns is the magnitude of the wind, the composite developing systems having significantly stronger easterlies to their north.

One must be careful not to interpret Fig. 6 as implying that the developing systems have that much stronger low level winds. They do not. Table 4 of

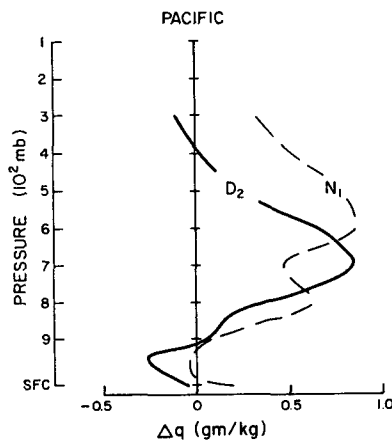


FIG. 5. Vertical profiles of mixing ratio of water vapor for the cluster ($0-3^\circ$) minus its surroundings ($3-5^\circ$) for the Pacific N1 and D2 systems.

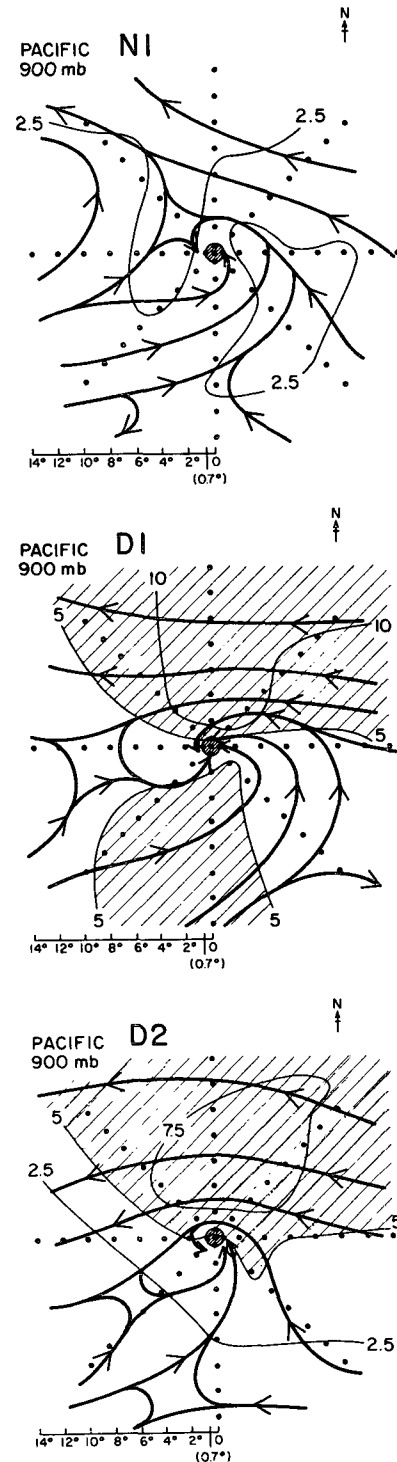


FIG. 6. 900 mb streamline and isotach analyses (m s^{-1}) for the Pacific non-developing (N1) and pre-typhoon (D1, D2) cloud clusters.

Part I shows that averaged over the $0-4^\circ$ area the mean wind speed at 950 mb is 7 m s^{-1} in the D2 system and 6.5 m s^{-1} in the N1 system. The large

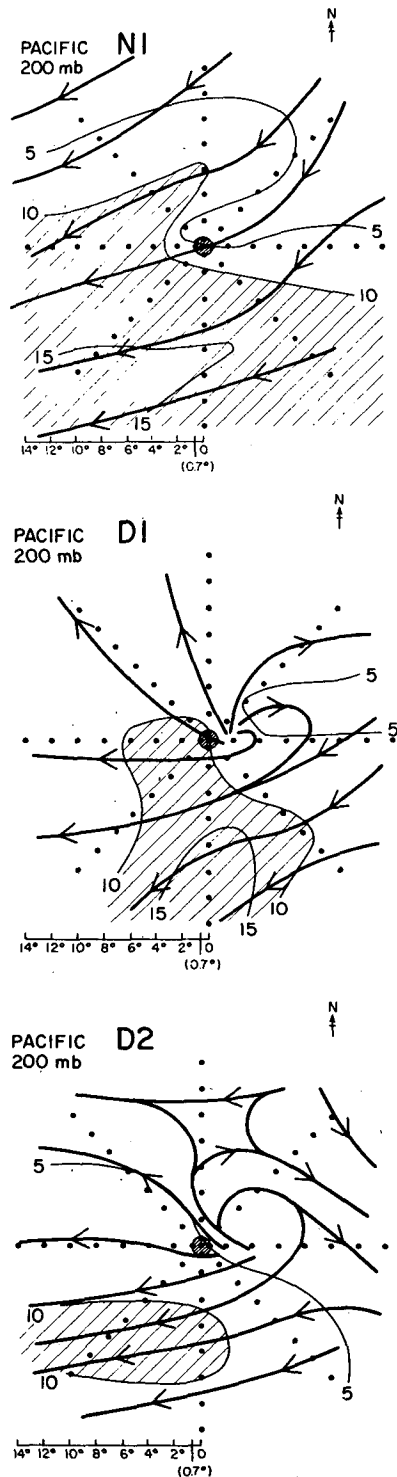


FIG. 7. 200 mb streamline and isotach analysis (m s^{-1}) for the Pacific non-developing (N1) and pre-typhoon (D1, D2) cloud clusters.

difference in wind speed that shows up on the plan view in Fig. 6 is really a reflection of the difference in organization of the systems. Thus, the many

rawinsonde observations going into each grid point in the non-developing case were highly variable in direction and yield a low magnitude mean vector wind. In the developing case, there was not much variability and the resultant vector mean had a high magnitude.

At 200 mb (Fig. 7) there is also a large difference between the developing and non-developing composite fields. The developing clusters have an anticyclone displaced $\sim 3^\circ$ latitude to the east of the system, whereas the non-developing cluster has no anticyclone.

Vertical profiles of the radial component of the wind at 4° radius and of the kinematically calculated vertical velocity averaged over the $0-4^\circ$ area are shown in Fig. 8. The developing systems have 30% more mass inflow and therefore greater upward vertical velocity than the non-developing systems.

Fig. 9 shows symmetric vertical cross sections of the tangential component of the wind. This field shows by far the most striking difference between the developing and non-developing systems. The developing clusters are characterized by very large values of positive tangential wind, more than twice as large as the tangential wind in the non-developing clusters. There are several other aspects of the fields shown in Fig. 9 which are worthy of discussion:

- 1) The radius of maximum tangential wind is $\sim 4^\circ$ latitude or 444 km. This is a fundamental difference between the cloud cluster and the fully developed tropical storm which has its radius of maximum wind at approximately 35 km from the center.

- 2) The large difference that exists in tangential wind between developing and non-developing systems extends out to 8° radius. Since the relative vorticity averaged over a $0-R^\circ$ area is equal to $2V_T/R$, the developing system exists in a very large horizontal extent (at least an 8° latitude radius circle) of large positive relative vorticity. The vorticity averaged over this area is three times as large as that over the same area surrounding the non-growing system.

- 3) The negative tangential wind observable at large radius in the upper troposphere for all systems is a reflection of the strong equatorial easterly winds to the south of all systems, which can be seen on the plan views in Fig. 7.

- 4) The non-developing cloud cluster has its maximum value of V_T at ~ 600 mb. By thermal wind considerations this implies that the system is cold core below that level. As shown earlier, horizontal temperature gradients are very weak and hard to measure; so this consideration of the vertical variation of tangential wind is actually the most reliable indicator of the sign of the temperature anomaly.

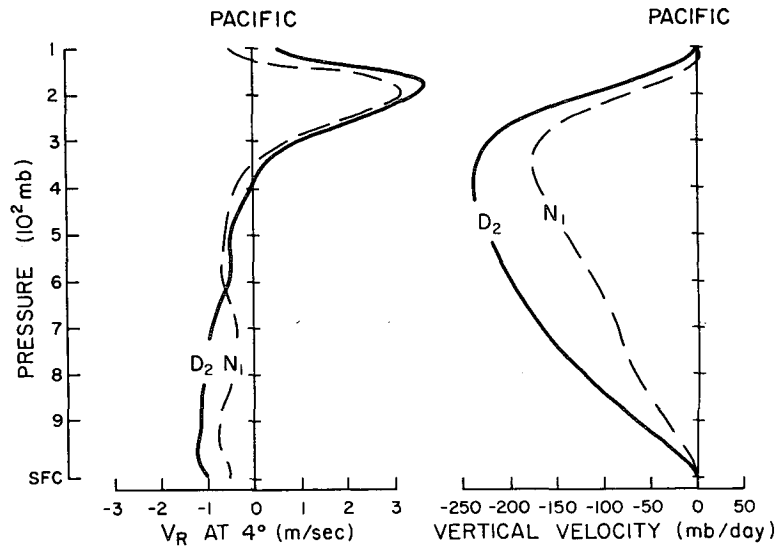


FIG. 8. Radial wind at 4° and vertical velocity averaged over the 0–4° area for Pacific developing and non-developing cloud clusters.

Of the developing systems, D2 has a clear low-level wind maximum, and therefore a warm core all the way down to 900 mb. This may be symptomatic of the fact that development has already begun, since the D1 system has an ambiguous temperature structure, with no clear temperature gradient being implied at all below the 500 mb level. Many authors in the past (e.g., Riehl, 1948; Yanai, 1961) have discussed the transition from a cold core to a warm core system as an important indicator of the potential of a system for development into a tropical storm. It has been shown here, and in earlier reports by Williams and Gray (1973) and Ruprecht and Gray (1976a,b) that all these systems are warm core in the

upper levels, and therefore direct circulations. In the lower atmosphere the current observations reveal that if a transition does take place from cold core to warm core, it happens very early, at about the D1 stage. This is two to three days prior to the beginning of the JTWC Guam official best track for the system, which in turn is several days before the system develops into a tropical storm. This could have some operational potential as a predictor of tropical cyclone development: if the tangential component of the wind averaged around the circumference of a 3° latitude radius circle centered on the system is greater at 900 mb than it is at 500 mb, the system is much more likely to develop.

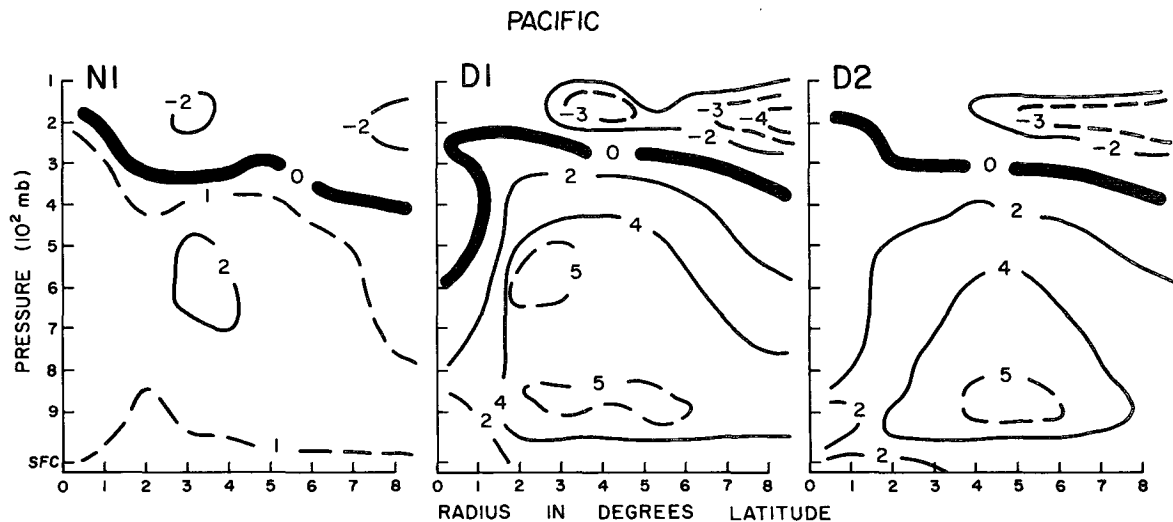


FIG. 9. Two-dimensional cross section of V_T for the Pacific non-developing (N1) and pre-typhoon (D1, D2) cloud clusters.

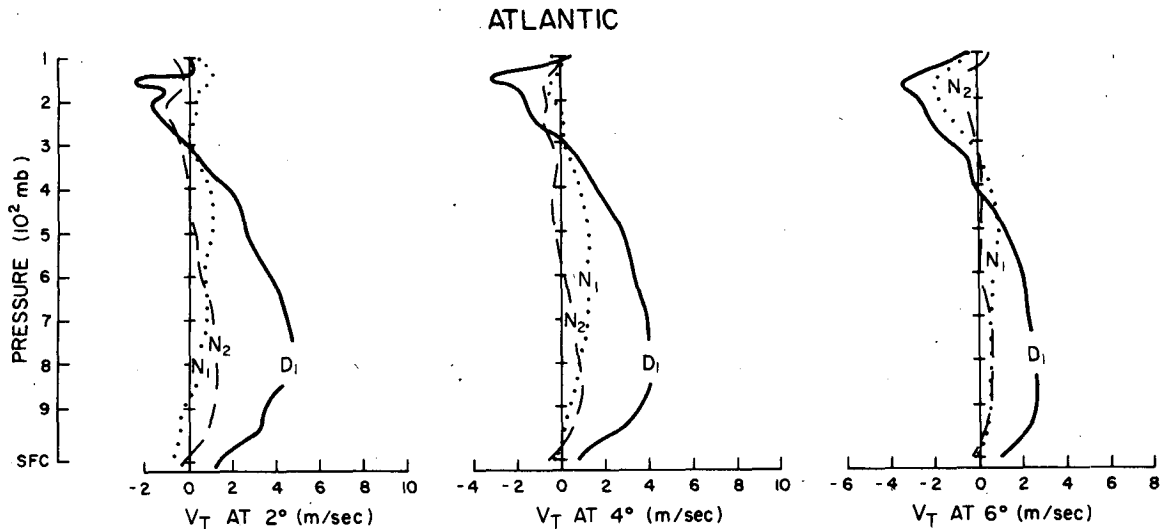


FIG. 10. Tangential wind (V_T) at 2, 4 and 6° radius for the Atlantic developing and non-developing cloud clusters.

b. Atlantic cloud clusters: N_1 , N_2 vs D_1

In the western Atlantic Ocean, two non-developing cloud cluster data sets, N_1 and N_2 , are available, along with one developing data set, D_1 . As in the Pacific, all systems are warm core in the upper levels. The developing system is slightly warmer but the magnitudes of both the temperature and the corresponding height gradients are so small that the differences would be extremely difficult to measure for an individual system. The total moisture content and the horizontal gradients of moisture are also very similar for developing and non-developing systems.

The biggest difference that showed up in the Pacific between developing and non-developing clusters was in the tangential component of the wind, V_T . Vertical profiles of V_T at 2, 4 and 6° radius are shown in Fig. 10. The developing cluster has much greater positive V_T at lower levels and much greater negative V_T at upper levels. These large differences extend out as far as 6° latitude radius and beyond. The N_1 data set has maximum V_T around 500 or 600 mb implying that it is cold core below that level; but the wave-trough cluster N_2 as well as the pre-hurricane cluster D_1 have a low-level maximum and therefore a warm core.

The 200 mb level flow patterns are shown in Fig. 11. The N_2 wave trough cluster has no anticyclone. The N_1 and the pre-hurricane D_1 system both have an anticyclone displaced $\sim 3^\circ$ to the east of the system center. The large-scale horizontal anticyclonic shear is very much greater for the developing system.

The vertical profiles of V_R at 4° and of 0–4° vertical velocity are shown in Fig. 12. The typical Atlantic weather systems, as represented here by N_1 , N_2 , have very weak vertical motion associated with them. This is in agreement with the large scale long-

term mean-vertical velocity in this region being downwards, as discussed in Part I. The pre-hurricane system, however, does have substantial upward vertical motion, of the same order of magnitude as found in the Pacific systems in Fig. 8.

c. Atlantic depressions: N_3 vs D_2

The tropical depression represents a later stage of development than the cloud cluster. In the depression stage, by definition, there already exists a well-defined closed vortex circulation at low levels. Approximately one-third of depressions later develop into tropical storms. The structure of developing depressions will now be compared with the structure of those depressions which do not develop. The depressions making up the non-developing composite data set N_3 are all from the northwest Atlantic region, longitude greater than 55°W , latitude less than 30°N during the months of June–October. The sea surface temperature in that location and season is always well above 26.5°C . In addition, no positions were included in the N_3 data set such that the system was within one degree latitude of land (including Cuba, Haiti, Jamaica and Puerto Rico) within the following 24 h. Thus the lack of development must be attributed to dynamic and thermodynamic structure rather than to topographic or land versus sea influences.

The non-developing N_3 and the pre-hurricane D_2 depressions are both well-defined tropical systems; so it would not be anticipated that all of the differences that were found between developing and non-developing clusters would carry over to them. For instance, inspection of the 200 mb level composite flow fields (not shown) reveals they both have a well defined upper level anticyclone. The warm core is

also of similar magnitude in the two systems, though vertically integrated it is better defined for the developing system as can be seen in the better defined symmetric low-level height gradient shown in Fig. 13. The greater moisture anomaly actually is in the non-developing system (Fig. 14), but the large scale 0–6° moisture is much the same. The vertical velocity curves are shown in Fig. 15. The non-developing system has much more upward vertical velocity than the developing system.

The major difference between the two data sets is in the tangential wind (Fig. 16). The low- and middle-level tangential winds for the developing depressions are twice as large as those for the non-developing, and the difference extends out to 6° radius and beyond. Inspection of the data also reveals a difference in upper level anticyclonic tangential wind, but the difference does not show up until 8° and beyond.

d. Discussion

One point which requires further emphasis is the large horizontal scale of the differences between the developing and the non-developing data sets. The plan views of 300 mb level temperature in Fig. 2 show that the warm sector of the atmosphere extends over an 8° latitude radius circle, while the cloud cluster itself is only of radius ~ 3°. The differences that have been demonstrated to exist in the low-level tangential wind also have a large horizontal extent. Fig. 17 shows plan views of V_T at 900 mb. In this figure the individual system motion vector has been subtracted from each rawinsonde wind field before the composite was made. It thus shows V_T in "motion" or "relative" coordinates. The positive tangential wind region extends over a 20° latitude diameter area.

The comparison of clusters in Sections 2a and 2b reveals that developing clusters have greater vertical motion than non-developing systems. In the Atlantic ocean, it seems a system must reach a stage of having on the order of 100 mb day⁻¹ upward motion before it can begin the transition toward a tropical storm. In the Pacific, the average cloud cluster already has that much vertical motion.

In a satellite study of typhoon development Arnold (1977)⁵ showed that there exists a variability in deep penetrative convection and cirrus (and therefore in vertical motion) in pre-typhoon cloud clusters of at least the same size as the mean cloudiness. The same variability exists in all later stages of development.

Given this variability, and the fact that for Atlantic depressions the composite non-developing system

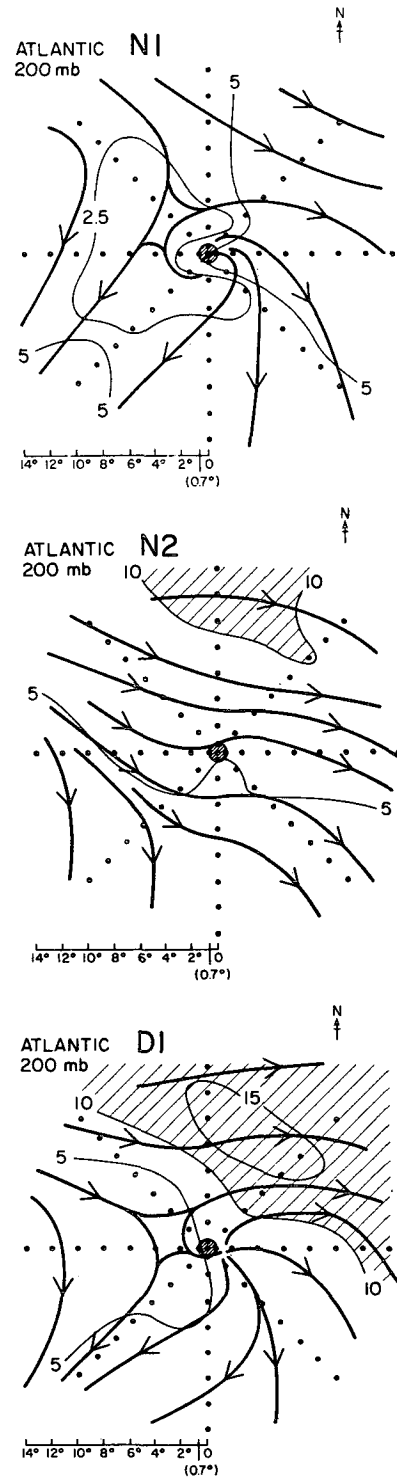


FIG. 11. 200 mb streamline and isotach analyses ($m s^{-1}$) for the Atlantic non-developing (N1, N2) and pre-hurricane (D1) cloud clusters.

has greater vertical motion than the developing system (Fig. 15), it must be concluded that no importance can be placed on the differences in vertical

⁵ Arnold, C. P., 1977: Tropical cyclone cloud and intensity relationships. Dept. Atmos. Sci. Pap. No. 277, Colorado State University, 154 pp.

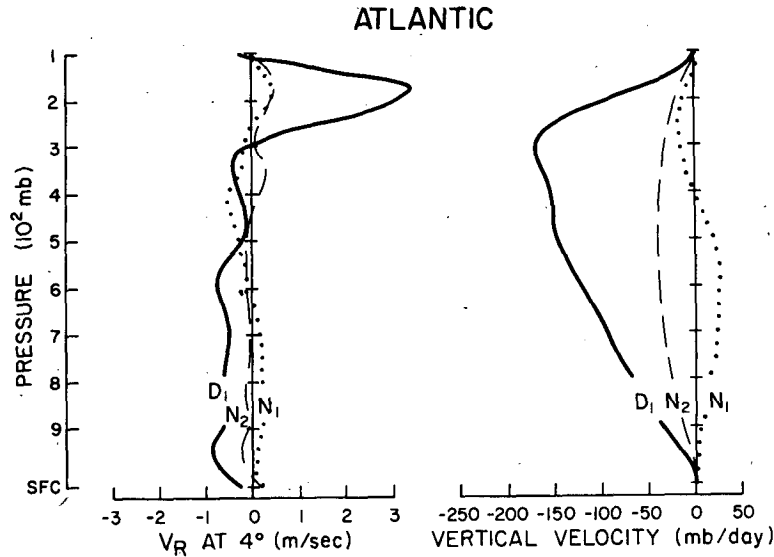


FIG. 12. Radial wind at 4° and vertical velocity averaged over the 0-4° area for Atlantic developing and non-developing cloud clusters.

motion found between Pacific developing and non-developing cloud clusters. The only restriction on development is that a cluster must reach a state of having $\sim 100 \text{ mb day}^{-1}$ upward motion averaged over the 0-4° area.

Another result which may require clarification concerns the existence or non-existence of the upper level anticyclone. The non-developing Pacific cluster and one of the Atlantic non-developing composite clusters have no anticyclones. All composite developing systems have an upper level anticyclone, and it is very clearly defined in the depression stage. If a cloud cluster is to develop into a tropical storm,

it must develop an anticyclone at some stage; so this is a definite indicator of development. It is not infallible though, as in the Atlantic both the non-developing cloud cluster N1 and the non-developing tropical depression N3 have upper level anticyclones. S. Erickson (1977)⁴ visually inspected DMSP satellite images of 49 non-developing Pacific summertime cloud clusters and 53 pre-typhoon clusters. By qualitatively following cirrus streaks on each image, he found that 10 out of the 49 (or 20%) of the nondeveloping had visible upper level anticyclonic outflow, as compared with 34 out of 53 (or 64%) of the developing systems.

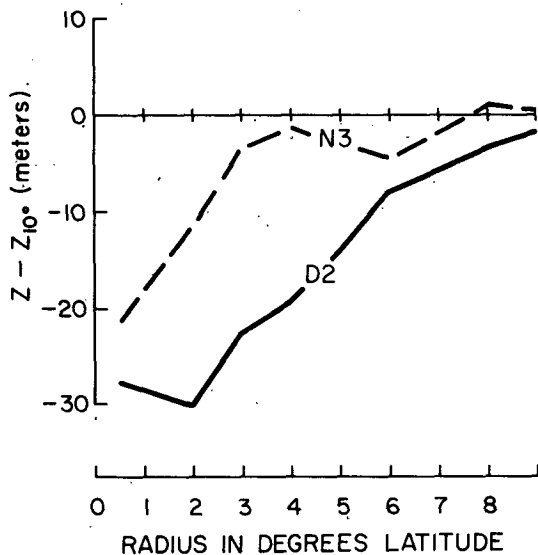


FIG. 13. D values ($Z - Z_{10^\circ}$) in meters at 900 mb for the Atlantic non-developing (N3) versus developing (D2) depressions.

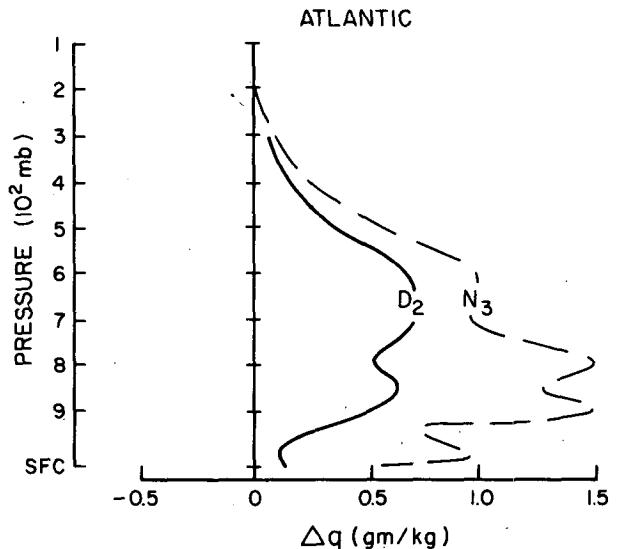


FIG. 14. q_{0-3° minus q_{3-5° for the Atlantic non-developing (N3) versus developing (D2) depression.

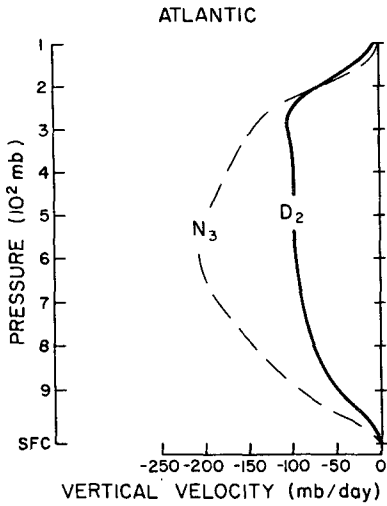


FIG. 15. Vertical velocity averaged over the 0-4° area for the Atlantic non-developing (N3) and pre-hurricane (D2) depressions.

3. Vertical wind shear

One dynamic parameter which is important for tropical storm development is the presence of low vertical wind shear (Gray, 1968). Physically, low shear is required so that enthalpy and moisture can accumulate in a vertical column. A system with low wind shear will lose little moisture and heat energy through horizontal ventilation or blow-through and thus will be more likely to organize itself into a vertically stacked tropospheric system such as a tropical storm.

Plan views of the mean shear of the zonal wind $U_{200\text{ mb}} - U_{900\text{ mb}}$ for the Pacific data sets are shown in Fig. 18. The developing systems (D1, D2, D3) have a region of zero shear close to their center. The non-developing cluster (N1) has no such region.

Besides possessing small shear, the developing data sets also show an additional characteristic of the tropospheric vertical shear field. Each system has a line of zonal vertical shear reversal close to its center. Taking into account the positioning problems inherent in the assembling of composite data sets, it is likely that the zero shear line lies directly above the developing system's center.

Further inspection of Fig. 18 shows that extremely strong horizontal gradients of vertical shear exist in the region extending $\sim 5^\circ$ latitude to the north and south of the developing systems. The vertical shears surrounding, but quite close to, the system are actually very strong. This effect stems partly from the superposition of an upper level anticyclone above a low-level cyclone, but the strong shear pattern extends well out into the environment.

If the only role played by vertical wind shear in storm genesis is that it has to be low to prevent ventilation, why is absolute zero shear rather than just low shear observed on the composite plan views? Why also are such large zonal shears observed close to the system center to the north and the south? Inspection of Fig. 18 leads to the conclusion that for tropical cyclogenesis in the western Pacific there is a requirement for the existence of an east-west extending line of zero tropospheric $\partial U/\partial p$ shear with a large gradient of this shear to the north and south.

Fig. 19 shows the plan views of meridional vertical shear $V_{200\text{ mb}} - V_{900\text{ mb}}$ for the Pacific systems. Once again, there is a striking difference between the non-developing cluster (N1) and the pre-typhoon clusters (D1, D2). The non-developing system exists in a large area of low meridional vertical shear. The developing systems have zero shear over them with strong anticyclonic vertical shear to the east and

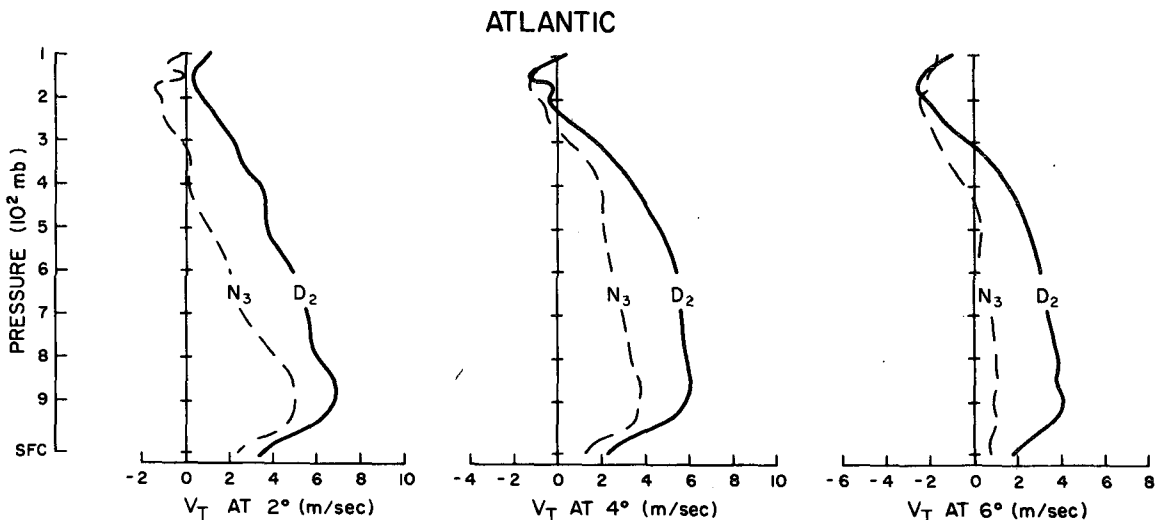


FIG. 16. V_T at 2, 4 and 6° radius for the Atlantic depressions.

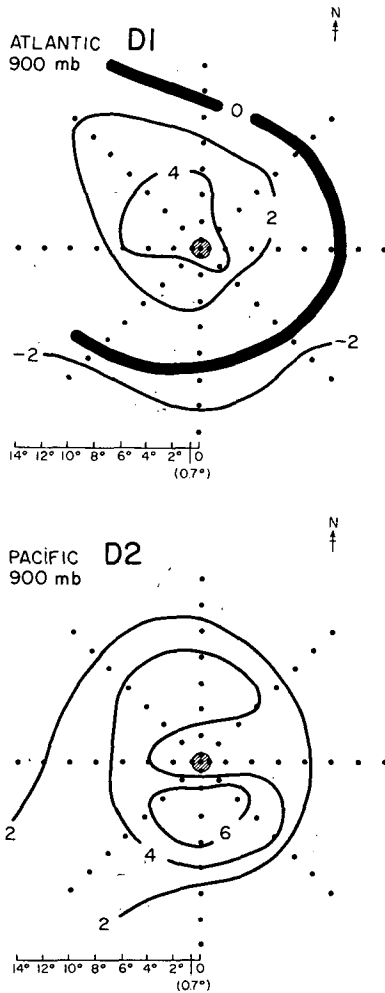


FIG. 17. Plan views of V_T in "motion" coordinates at 900 mb for the developing cloud cluster in each ocean ($m\ s^{-1}$).

west. Comparing Figs. 18 and 19, it is seen that the effect is much greater in the zonal than in the meridional shear pattern.

The plan views of zonal shear for the Atlantic systems are shown in Fig. 20. Comparing non-developing clusters N1, N2 with pre-hurricane systems D1, D2 and D3, the distinctive feature is that the pre-hurricane systems have very strong anti-cyclonic vertical shear north of them and zero or close to zero shear over them. The non-developing depression N3 also has the zero shear with strong positive shears to the north, indicating that these conditions are also highly favorable for the system to undergo the transition from cloud cluster to depression status. It should be noted, however, that for the N3 system the shear pattern does not extend over as large an area, particularly toward the north, as it does for the developing systems.

The Atlantic patterns of vertical shear of the

meridional wind are shown in Fig. 21. The meridional shears in the Atlantic are stronger than in the Pacific. All developing Atlantic systems have a north-south extending line of zero vertical meridional shear going over the system center, positive shear to the west and very strong negative shear to the east. A difference also shows between developing D2 and non-developing N3 depressions, the positive-zero-negative pattern being better defined in the former case.

An inspection of the composites of Gray (1968) shows that the same situation exists in other tropical storm regions of the world. Fig. 22 reproduced from Gray's paper is a plan view of the zonal shear for tropical disturbances in the South Pacific Ocean which later develop into tropical storms. Fig. 23 is for prestorm disturbances in the North Indian Ocean. Both figures show the same features: an east-west line of zero zonal vertical shear accompanied by strong westerly shear to the poleward side and strong easterly shear equatorward.

This result helps clear up some of the confusion that has existed in the past concerning vertical wind shear and tropical cyclogenesis. There has been some resistance, for example, to acceptance of low tropospheric vertical shear as a cyclogenesis requirement. This hesitation has stemmed partly from synoptic observations of strong shears close to the developing systems. Forecast schemes based on low shear will give a high score to a tropical area of low shear. Such schemes work well on a climatological basis, but for individual situations the above data suggest that there is actually a requirement not only for very small vertical shear near the system center but also for two adjoining regions of strong 200-900 mb vertical shear of opposite sign on either side of the system.

In the comparison of the structure of non-developing versus developing systems in the previous sections, the major differences found to exist were in the tangential wind or large-scale vorticity fields at lower and upper levels. The vertical shear criterion found here is in agreement with the following statement.

$$\begin{aligned}
 &\text{a large north-south} \\
 &\text{gradient of } -\partial U/\partial p \\
 &\text{in combination with} = \frac{\partial}{\partial y} \left(-\frac{\partial U}{\partial p} \right) + \frac{\partial}{\partial x} \left(\frac{\partial V}{\partial p} \right) \\
 &\text{a large east-west} \\
 &\text{gradient of } \partial V/\partial p \\
 &= \frac{\partial}{\partial p} \left(-\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right) \\
 &= \text{a large vertical gradient} \\
 &\text{of relative vorticity.}
 \end{aligned}$$

The genesis potential for a developing disturbance

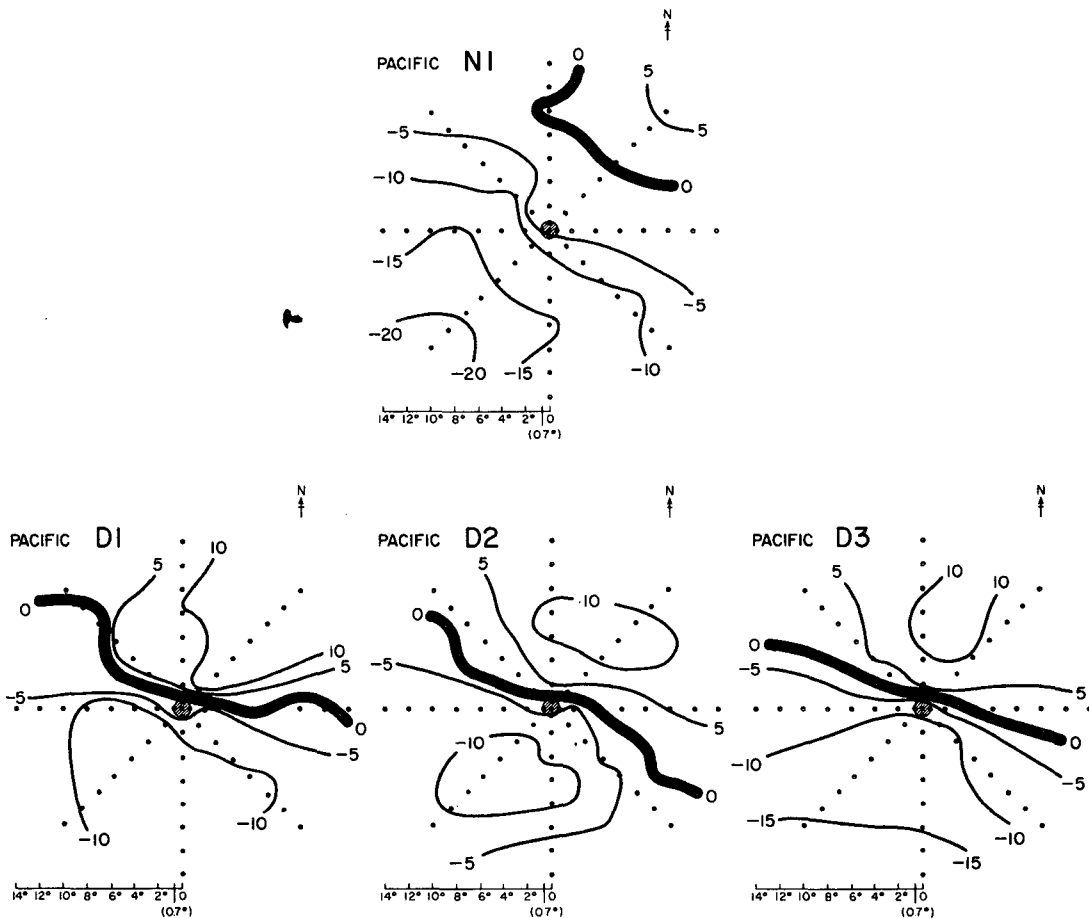


FIG. 18. Plan views of zonal shear, $U_{200\text{ mb}} - U_{900\text{ mb}}$ (m s^{-1}) for the Pacific data sets.

may thus be quantified as

Daily Genesis Potential (DGP)

$$= \zeta_{900\text{ mb}} - \zeta_{200\text{ mb}} \quad (1)$$

Values of DGP for the 12 composite data sets are shown in Table 1. Comparing the Pacific cluster (N1) with the Pacific pre-typhoon clusters (D1, D2), it is seen that the latter developing systems have larger values of DGP at all radii. Comparing Atlantic clusters (N1, N2 versus D1) and depressions (N3 vs D2) the same comments apply.

Inspection of the data shows that at 2 and 4° the difference is due mainly to the developing systems having greater low-level vorticity. At 6° radius there is also a major contribution from the 200 mb level anticyclonic horizontal shear.

To the extent that it includes a contribution from both levels, plus it emphasizes the larger scale of the differences compared to the much smaller scale of the actual satellite observed cloud region, DGP evaluated at 6° radius is probably the best single

parameter synthesizing the results of the analysis of the composite fields. Table 2 shows genesis potential averaged for non-developing and developing data sets. At 6° radius this parameter is three times greater for the developing systems than for the non-developing.

4. Individual-day cyclogenesis

The above analysis of the composite fields is directed at determining the differences in structure between the *average* non-developing and the *average* pre-typhoon or pre-hurricane system. It gives no information, however, on the variance about these means. It was discussed in Part I that compositing must be considered as complementary to the case study approach. Compositing can be considered as the first step. By averaging together many different cases it smooths out interior class differences and enhances average system differences. This section deals with the second step, the analysis of individual cases, to see to what extent the composite characteristics fit the individual situations.

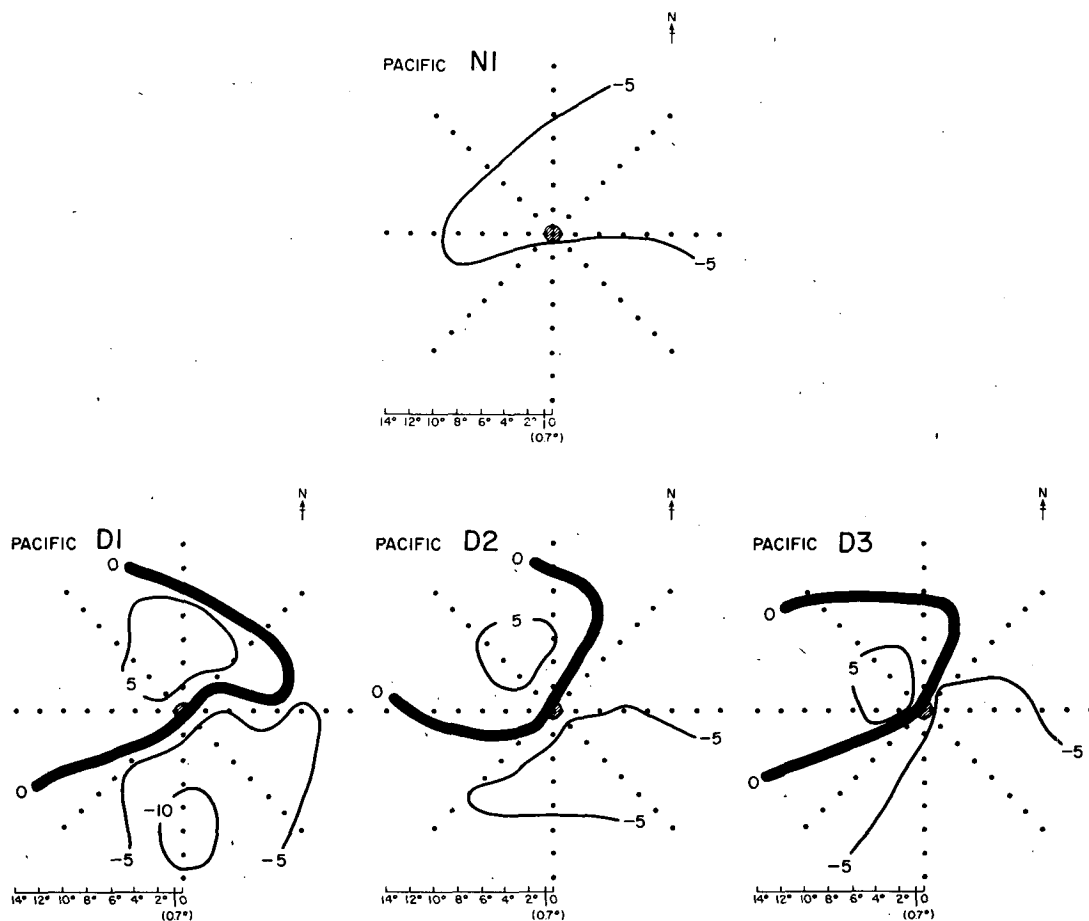


FIG. 19. Plan views of meridional shear, $V_{200\text{ mb}} - V_{900\text{ mb}}$ (m s^{-1}) for the Pacific data sets.

The major differences obtained by the composite analysis are in the upper and lower tropospheric wind fields, and as discussed in the previous section can be expressed in terms of the vertical shear between 900 and 200 mb. Vertical shear data were provided to the authors by the National Hurricane Center (NHC) in Miami. During the hurricane season the NHC routinely performs computer analyses over the North Atlantic Ocean of the wind fields at the 200 mb level and at the ATOLL level (Analysis of the Tropical Oceanic Lower Layer, ~ 900 mb). Maps of vertical shear of the zonal and meridional components of the wind at 1.5° grid resolution were provided twice daily for the hurricane seasons of 1975, 1976 and 1977. The data were taken from the operational data tapes of the NHC, so there were some retrieval problems and some periods of missing data.

Of the 22 named tropical cyclones in the Atlantic during 1975 to 1977, 16 were selected for study. Of the remaining six, two were excluded due to lack of data. Four were excluded because they developed

from midlatitude-type, upper level, cold-core systems. As discussed by Gray (1968), such baroclinic developments are atypical and accordingly were not considered relevant to the evaluation of the composite results.

The vertical shear fields surrounding the remaining 16 cyclones were compared with the vertical shear fields surrounding 63 tropical weather systems which did not later develop into tropical storms. The tracks of the non-developing systems were obtained from similar sources to those for the non-developing composite data sets, and included cloud clusters, easterly waves and depressions. Details of the actual tracks for both cyclones and non-developing systems as well as numerical values of the vertical shear surrounding each system are tabulated in the project report by McBride (1979).⁶

⁶ McBride, J. L., 1979: Observational analysis of tropical cyclone formation. Dept. Atmos. Sci. Pap. No. 308, Colorado State University, 230 pp.

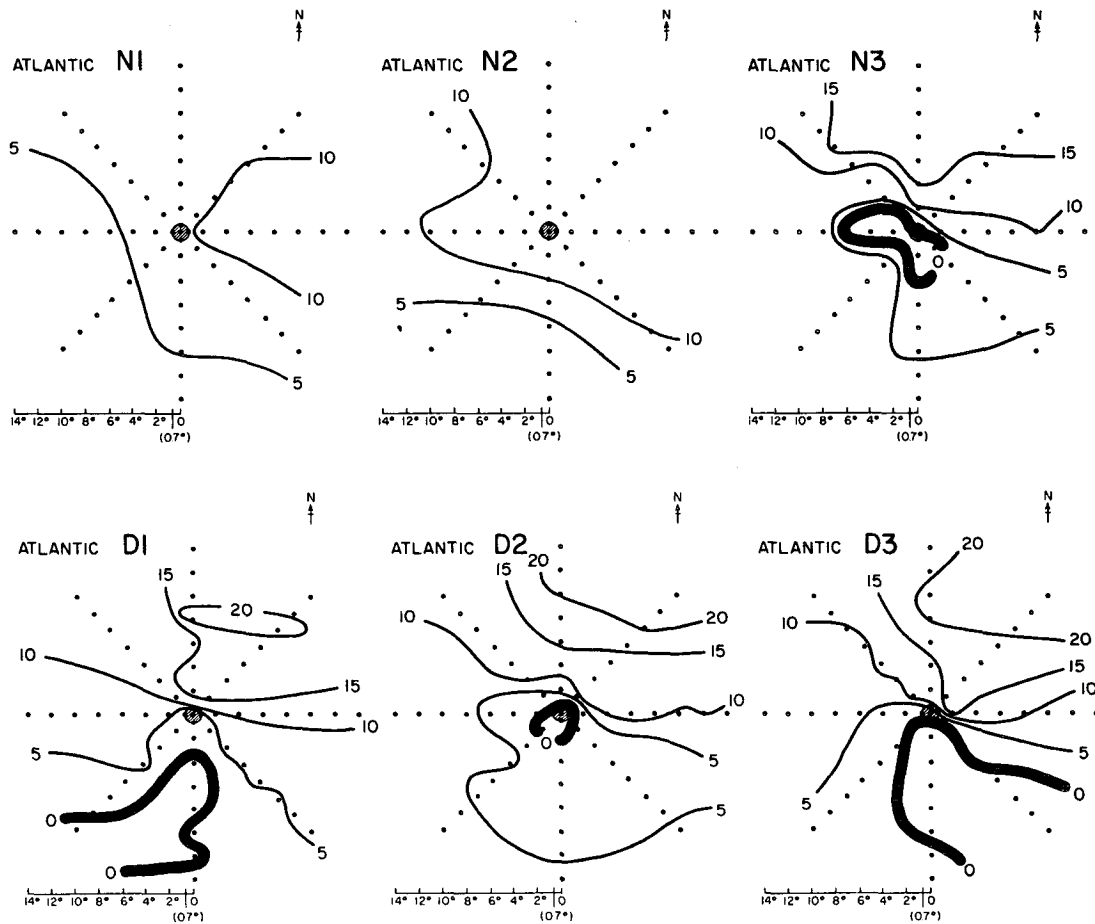


FIG. 20. As in Fig. 18 except for the Atlantic data sets.

For the 16 tropical cyclones, the maps of the vertical shear of the zonal and meridional wind were examined for every 12 h, beginning 60 h before the point at which the system first attained a maximum sustained wind of 35 kt (18 m s⁻¹). The former time is labeled -60, the latter 00. Example shear maps are shown in Fig. 24. Figs. 24a, b are for 60 h prior to the development of Tropical Storm Amy (1975). Point × is the position of the prestorm disturbance. Point T marks the location at which it becomes a named tropical storm. Figs. 24c, d are for 60 h prior to the development of Hurricane Blanche (1975). Both examples show clearly the same features revealed by the composite analysis (see Figs. 18–21): an east–west extending line of zero vertical shear of the zonal wind component with positive shear to the north and negative shear to the south of the prestorm disturbance, and a north–south extending line of zero meridional vertical shear with positive shear to the west and negative to the east.

These observations were quantified by examining the following five parameters for each system:

- ΔU : the value of the vertical shear of the zonal wind at a point 6° latitude north of the position of the system minus the value of the shear at point 6° south of the system; ΔU is proportional to $\partial/\partial y \times (-\partial U/\partial p)_{900-200 \text{ mb}}$.
- ΔV : the vertical shear of the meridional wind 6° west of the system minus the shear 6° east of the system; ΔV is proportional to $\partial/\partial x(\partial V/\partial p)_{900-200 \text{ mb}}$.
- $\Delta U + \Delta V$: this is proportional to $\zeta_{900 \text{ mb}} - \zeta_{200 \text{ mb}}$, averaged over the 0–6° area, that is to the daily genesis potential (DGP) as defined in Eq. (1).
- Existence of a zonal zero line: the value of this parameter is Yes if the vertical U shear is positive 6° to the north and negative 6° to the south; otherwise the value is No.
- Existence of a meridional zero line: the value is Yes if the vertical V shear is positive 6° to the west and negative 6° to the east.

The values of each parameter averaged for the sixteen systems are shown in Table 3. The table shows a steady increase in the magnitude of the Daily Genesis

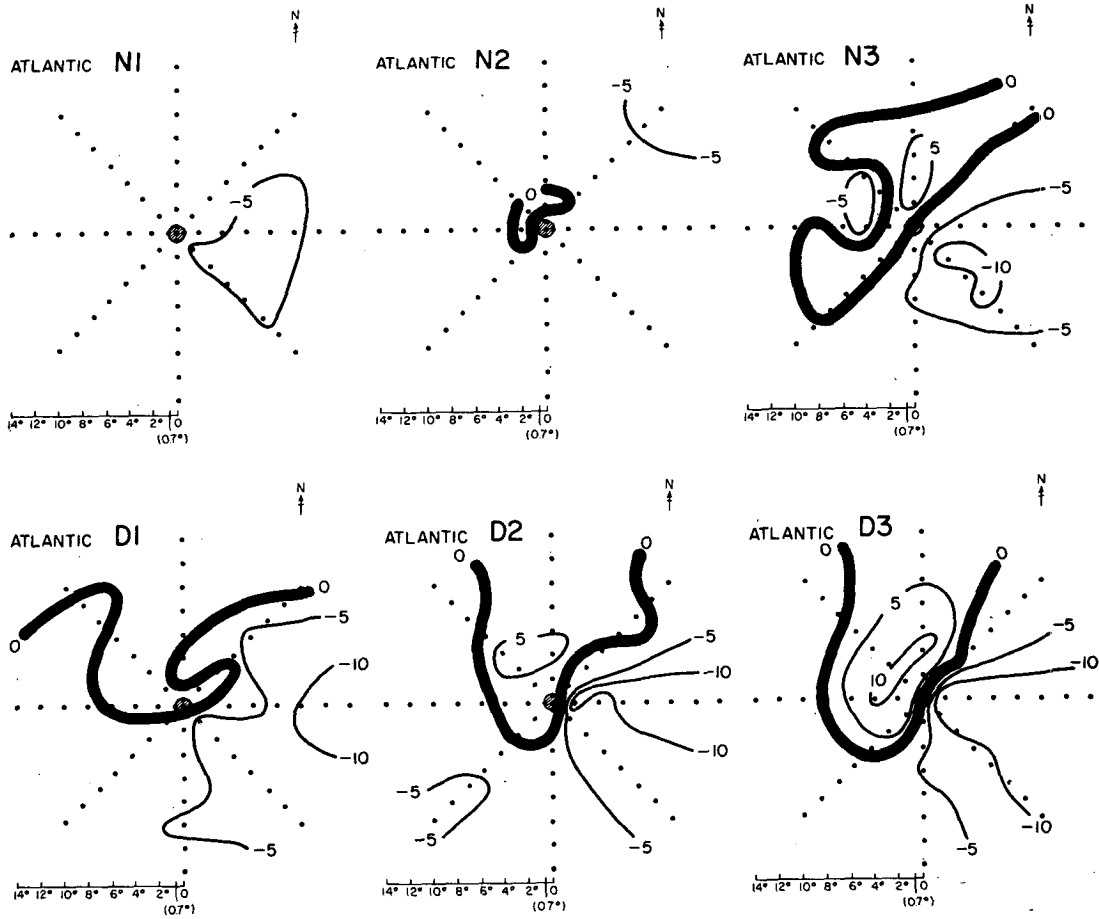


FIG. 21. As in Fig. 19 except for the Atlantic data sets.

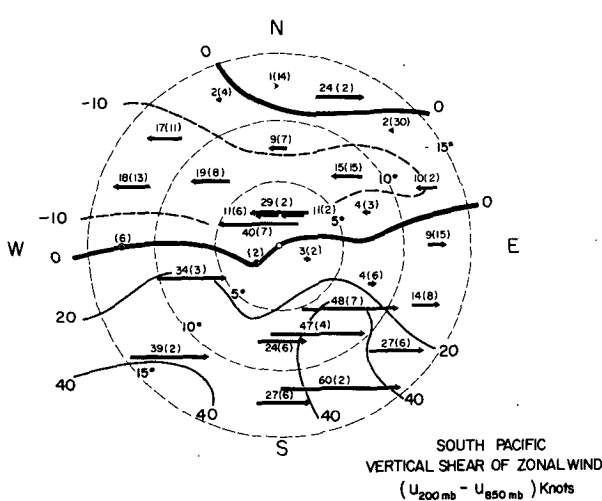


FIG. 22. Composite zonal vertical wind shear for average rawin information in each area relative to the center of 84 tropical disturbances in the South Pacific which later developed into tropical storms. Length of arrows is proportional to wind shear in knots (at left). Values in parentheses are number of wind reports in each area average. Distance from the center is given by the lightly dashed circular lines at 5° latitude increments. (Reproduced from Gray, 1968.)

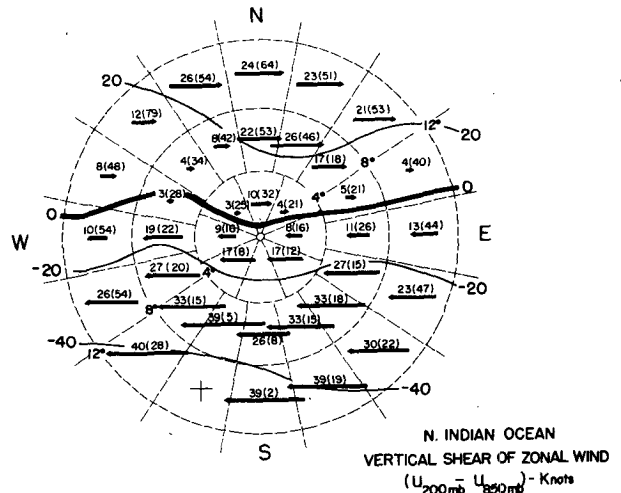


FIG. 23. Composite zonal vertical wind shear for average rawin information in each area relative to the center of 54 tropical disturbances in the North Indian Ocean which later developed into tropical storms. Length of arrows is proportional to wind shear in knots (at left). Values in parentheses are number of wind reports in each area average. Distance from the center is given by the lightly dashed circular lines at 4° latitude increments. (Reproduced from Gray, 1968.)

Potential ($\Delta U + \Delta V$) as the systems approach the tropical storm stage. The value of DGP for the Atlantic pre-hurricane cloud cluster composite data set in Table 1 is $1.6 \times 10^{-5} \text{ s}^{-1}$. Table 3 shows that for the individual cases, this magnitude is typically reached 36 h before the system is named a tropical storm. The existence of zero lines in zonal and meridional vertical shear does not show up as clearly as does the high value of DGP. The table shows that 36 h prior to genesis the zero line in the zonal shear is present in 9 out of 14 or 64% of the cases; but the zero line in the meridional shear is present in only 6 of 13 or 46%. This is partly a result of the objective criteria used to establish the existence of the zero line; thus, for example, a zonal zero line exists at time -60 for storm Amy shown in Fig. 24a, but it is recorded as a No score since the shear 6° to the south of the system is positive.

Looking at the individual systems, 13 of them have consistently favorable values of the five parameters. Establishing objective criteria such that (i) $\Delta U > 8 \times 10^{-6} \text{ s}^{-1}$, (ii) $\Delta V > 8 \times 10^{-6} \text{ s}^{-1}$, (iii) a zonal zero line exists, and (iv) a meridional zero line exists, each of the 13 systems have a period of at least 36 h prior to cyclone development such that three of the four criteria are satisfied.

For the 63 non-developing systems shear patterns were analyzed at the synoptic observation time of 1200 GMT. Data were available for 178 situations, an average of 2.8 per system. Two randomly chosen examples of the zonal and meridional vertical shear patterns surrounding the positions (marked \times) of non-developing disturbances are shown in Fig. 25. Table 4 shows the mean values of the shear parameters for these systems. Also shown are the standard

TABLE 2. Daily Genesis Potential (DGP) based on average of developing and non-developing data sets (10^{-5} s^{-1}).

	0-2°	0-4°	0-6°
Average non-developing (Pacific N1; Atlantic N1, N2, N3)	2.3	1.1	0.7
Average developing Weak systems (D1, D2)	5.2	3.1	2.0
Average developing All systems (D1, D2, D3)	6.5	6.0	2.7

deviations of ΔU and ΔV . As we already know from the composite results, on average the non-developing systems have very low values of ΔU ($0.3 \times 10^{-5} \text{ s}^{-1}$) and ΔV ($-0.1 \times 10^{-5} \text{ s}^{-1}$). Also on average they do not have a zero line present, a zonal zero line existing for only 25% of the systems and a meridional zero line for only 19%. This compares with 46 and 58% for pre-hurricane systems 48 h prior to development. The standard deviations, however, of ΔU and ΔV are quite high, and there are 45 instances where zonal zero lines exist and 33 where meridional zero lines exist for non-developing systems. This indicates that large values of ΔU or ΔV are fairly frequent events in the northwest Atlantic. *The important factor for tropical cyclogenesis is whether they exist concurrently and whether they persist for more than one day.*

The 178 non-developing positions were examined for the concurrent appearance of (i) $\Delta U > 8 \times 10^{-6} \text{ s}^{-1}$, (ii) $\Delta V > 8 \times 10^{-6} \text{ s}^{-1}$, (iii) the existence of a zonal zero line, and (iv) the existence of a meridional zero line. There were only 14 positions out of 178 (or 8%) such that three of the four criteria were

TABLE 1. Daily Genesis Potential (DGP) based on mean relative vorticity differences between 900 and 200 mb for each composite data set: $\text{DGP} = \bar{\zeta}_{900 \text{ mb}} - \bar{\zeta}_{200 \text{ mb}}$. Values are in units of 10^{-5} s^{-1} .

	0-2°	0-4°	0-6°
Pacific non-developing			
N1 Cloud cluster	2.0	1.6	0.7
Pacific developing			
D1 Early pre-typhoon cloud cluster	6.0	4.0	2.3
D2 Pre-typhoon cloud cluster	4.8	3.2	2.4
D3 Intensifying cyclone	8.5	4.8	3.0
D4 Typhoon	12.4	6.4	4.4
Atlantic non-developing			
N1 Cloud cluster	-0.5	0.4	0.7
N2 Wave trough cluster	2.1	0.6	0.4
N3 Non-developing depression	5.5	2.0	1.0
Atlantic developing			
D1 Pre-hurricane cloud cluster	4.7	2.4	1.6
D2 Pre-hurricane depression	5.2	2.8	1.8
D3 Intensifying cyclone	9.8	4.2	2.8
D4 Hurricane	10.8	5.2	3.7

TABLE 3. Mean characteristics of the patterns of vertical shear for the 16 pre-tropical storm disturbances. ΔU is proportional to $\partial/\partial y(-\partial U/\partial p)_{900-200 \text{ mb}}$; ΔV is proportional to $\partial/\partial x(\partial V/\partial p)_{900-200 \text{ mb}}$; $\Delta U + \Delta V$ is proportional to $\bar{\zeta}_{900 \text{ mb}} - \bar{\zeta}_{200 \text{ mb}}$, averaged over the $0-6^\circ$ radius area centered on the system. Values are in vorticity units of 10^{-5} s^{-1} . The entries in the last two columns give the number of cases showing the existence or non-existence of the zonal and meridional vertical shear zero lines. The number of cases does not uniformly add to 16 due to missing data and/or to the system being close enough to the edge of the grid to preclude the computation of horizontal gradients.

Position	ΔU	ΔV	Daily genesis potential $\Delta U + \Delta V$	Zonal zero line	Meridional zero line
-60	0.4	0.3	0.7	3 Yes 10 No	5 Yes 8 No
-48	0.7	0.4	0.9	6 Yes 7 No	7 Yes 5 No
-36	1.1	0.7	1.8	9 Yes 5 No	6 Yes 7 No
-24	1.4	1.0	2.5	8 Yes 5 No	9 Yes 4 No
-12	1.9	1.3	3.2	12 Yes 4 No	11 Yes 4 No
00	2.1	1.3	3.3	12 Yes 4 No	9 Yes 6 No
Mean	1.3	0.8	2.1	50 Yes 35 No (59%, 41%)	47 Yes 34 No (58%, 42%)

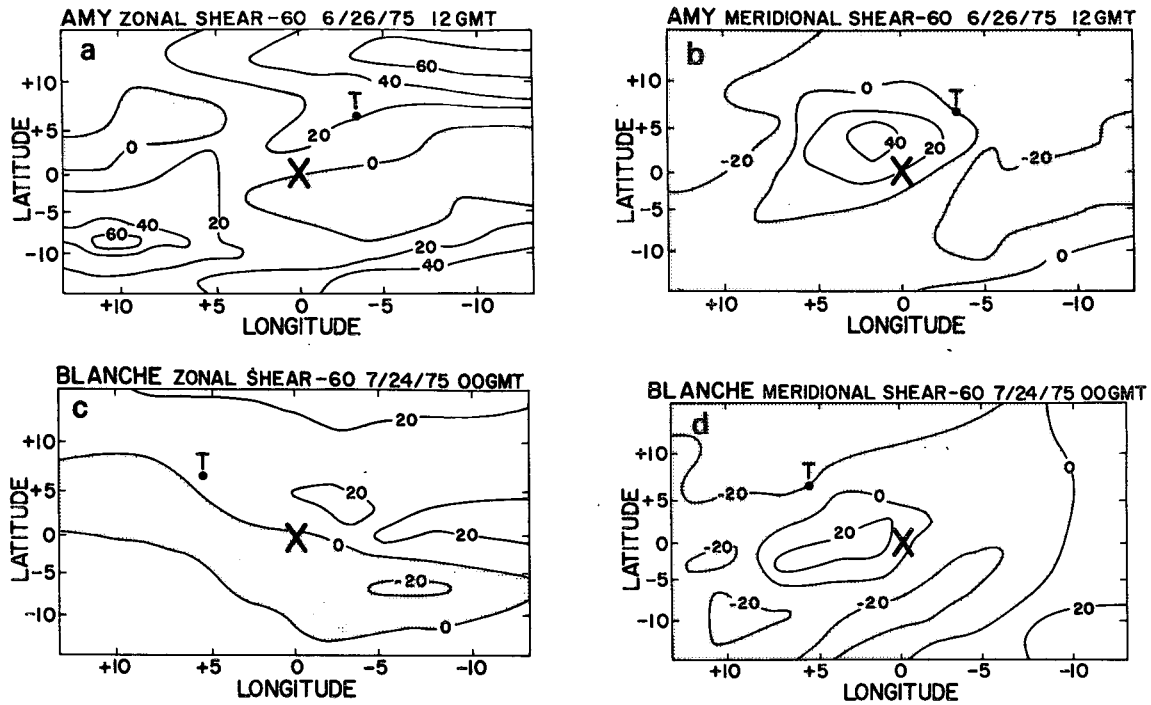


FIG. 24. Maps of vertical shear (knots) of the zonal wind ($U_{200\text{ mb}} - U_{\text{ATOLL}}$) and the meridional wind ($V_{200\text{ mb}} - V_{\text{ATOLL}}$) surrounding pre-tropical storm disturbances. \times marks the current position of the disturbance. T marks the position it will be in when it attains tropical storm status. The abscissa is degrees longitude; the ordinate is degrees latitude relative to the position of the disturbance. (a, b) Maps for 60 h prior to the development of Tropical Storm Amy; (c, d) Maps for 60 h prior to the development of Hurricane Blanche.

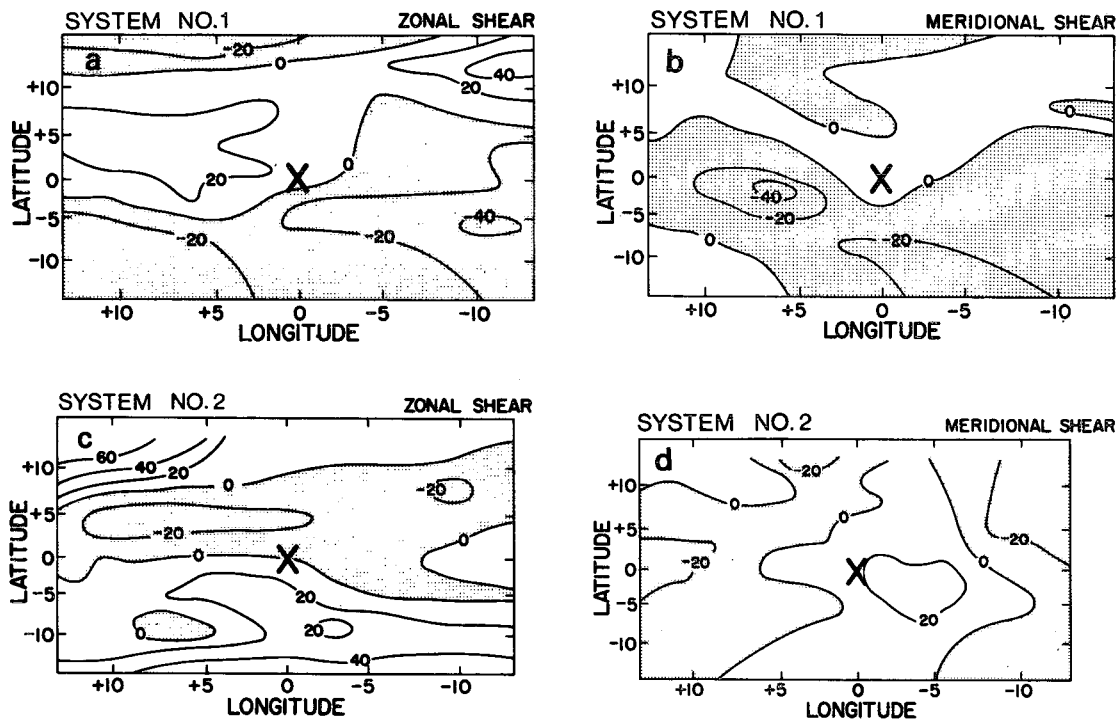


FIG. 25. Maps of vertical shear of the zonal (a, c) and meridional (b, d) wind surrounding two (labelled 1 and 2) non-developing tropical disturbances.

TABLE 4. Mean properties of the vertical shear for the 63 non-developing disturbances (units are 10^{-5} s^{-1}). ΔU is proportional to $\partial/\partial y(-\partial U/\partial p)_{900-200 \text{ mb}}$; ΔV is proportional to $\partial/\partial x(\partial V/\partial p)_{900-200 \text{ mb}}$; $\Delta U + \Delta V$ is proportional to $\zeta_{900 \text{ mb}} - \zeta_{200 \text{ mb}}$, averaged over the $0-6^\circ$ radius area centered on the system.

Number of systems	Number of positions	ΔU	ΔV	Daily genesis potential $\Delta U + \Delta V$	Zonal zero line		Meridional zero line	
					45 Yes (25%)	133 No (75%)	33 Yes (19%)	145 No (81%)
63	178	0.3	-0.1	0.2				
Standard deviation =		1.2	0.9	1.8				

satisfied. This contrasts with 13 out of 16 (82%) of the developing systems satisfying three of the criteria for at least 36 h sometime in the 60 h prior to development. Of the 63 non-developing systems only 2 (3%) had more than one time period satisfying three of the four criteria.

These results indicate that the findings of the composite analyses are representative of the individual cases. For the developing systems on average the criteria were satisfied beginning at 48 h before cyclone development. This predictive skill would be useful in an operational forecasting situation, but it should be noted that 48 h is much less than the three or more days by which the composite data set D1 precedes development. Possibly predictive skill could be obtained at an earlier stage by the use of high horizontal resolution, geostationary satellite-derived winds. The upper and lower tropospheric levels of 200 and 900 mb are the same levels at which these satellite winds are most easily measured.

5. Summary and discussion

The main findings from the comparison of non-developing versus developing composite data sets are as follows:

- 1) Both non-developing and developing systems are warm cored in the upper levels. The warm area at 300 mb is much more pronounced in the developing system; following this the low-level height anomaly also is much more pronounced. The actual magnitudes, however, of the temperature and height gradients are so small that they would be extremely difficult to measure for an individual system.
- 2) The developing or pre-typhoon cloud cluster exists in a generally warmer atmosphere over a large horizontal scale, for example, out to 8° latitude radius in all directions.
- 3) There is no obvious difference in vertical stability for moist convection between the systems.
- 4) The moisture anomaly and moisture content are similar for the developing and non-developing systems.
- 5) Pre-typhoon and pre-hurricane systems are located in large areas of high values of low level rela-

tive vorticity. The low-level vorticity in the vicinity of a developing cloud cluster is approximately twice as large as that observed with non-developing cloud clusters.

6) Mean divergence and vertical motion for the typical western Atlantic weather system are well below the magnitudes found in pre-tropical storm systems.

7) Once a system has sufficient divergence to maintain 100 mb or more per day upward vertical motion over a 4° radius area, there appears to be little relationship between the amount of upward vertical velocity and the potential of the system for development.

8) Cyclogenesis takes place under conditions of zero vertical wind shear near the system center.

9) There is a requirement for large positive zonal shear to the north and negative zonal shear close to the south of a developing system. There also is a requirement for southerly shear to the west and northerly shear to the east. The scale of this shear pattern is over a 10° latitude radius circle with maximum amplitude at $\sim 6^\circ$ radius.

The major differences found between non-developing and developing systems are numbers 5, 7, 8 and 9 of the above list. These all relate to dynamic parameters, i.e., the wind field surrounding the disturbance. This is in agreement with the analysis in Part I of Gray's climatological genesis parameter. Of Gray's six climatological variables required for a region to spawn tropical cyclones, the three thermodynamic parameters were shown to be generally present throughout the whole season, whereas the three dynamic parameters had a large day-to-day variation.

Under the assumption of a symmetric disturbance, the above nine findings can be synthesized into one parameter for the potential of a system for development into a hurricane or typhoon

$$\text{Daily Genesis Potential (DGP)} = \zeta_{900 \text{ mb}} - \zeta_{200 \text{ mb}},$$

when applied over $0-6^\circ$ radius. As shown in Table 2, DGP is three times greater for developing tropical weather systems than for non-developing systems.

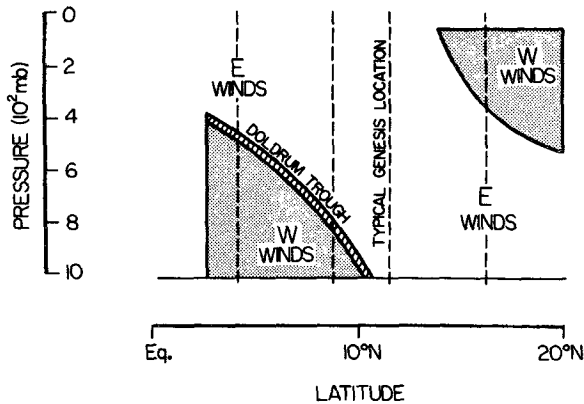


FIG. 26. Schematic north-south cross section of zonal winds relative to the position of a doldrum or monsoon equatorial trough.

The analysis of the fields of vertical wind shear for the 79 individual weather systems in the northwest Atlantic revealed that the composite characteristics are well representative of the individual situations. It also revealed a requirement for symmetry in the wind field surrounding the prestorm disturbance. This is seen in the large standard deviations of DGP for non-developing systems shown in Table 4. The important condition for cyclone development is not just a high total value of $\Delta U + \Delta V$, but rather that ΔU and ΔV separately both have high values, so that there is zero shear near the center with uniformly high anticyclonic vertical shear surrounding the system in all directions.

Certain of the results of this paper relate to previous observational studies of tropical cyclogenesis. The favorable vertical shear pattern is a function of both the upper level and the lower level flow. Previous researchers including Riehl (1948, 1950), Yanai (1961), and Sadler (1976, 1978) and Dvorak (1975) have placed emphasis on a requirement for a superposition of favorable upper level and lower level large-scale flow features prior to disturbance intensification.

More specifically, Dvorak (1975) states that development will not take place underneath a unidirectional upper tropospheric flow pattern. Such a flow pattern is inconsistent with a large north-south gradient of $\partial U/\partial p$. Riehl (1975)⁷ documented several case studies of development of tropical storms in the Gulf of Mexico and Caribbean. In each of Riehl's cases, development was preceded by mid-tropospheric cold air advection 500 to 1500 km north of the system. By thermal wind considerations this implies an increase of positive zonal shear between the cold air and the system center.

Sadler (1975,⁸ 1978) presents evidence that northwestern Pacific cyclogenesis within the trade winds is associated with a westward extension of the Tropical Upper Tropospheric Trough (TUTT) existing to the northwest of the developing system. Sadler (1976) has also documented cases of low-latitude (ITCZ) cyclogenesis taking place to the south of the TUTT. In the former situation the TUTT being to the west of the disturbance enhances the anticyclonic vertical shear close to the disturbance. In both situations the upper level westerlies to the south of the TUTT overlie trade winds, thus bringing about the required positive zonal shear to the north of the incipient disturbance.

Gray (1968) has shown that climatologically cyclogenesis takes place just to the poleward side of a monsoon or doldrum equatorial trough. A schematic north-south cross section of the usual zonal winds for such a trough is shown in Fig. 26. Note the positive zonal shear to the north and negative shear to the south.

Certain earlier researchers (e.g., N. Frank, 1963; Shapiro, 1977) have questioned the importance of the upper levels, claiming that cyclone development is mainly dependent on the state of the lower troposphere. The possibility does remain open that the observed differences at the 200 mb level are forced by the atmosphere's response to the differences that exist at 900 mb.

Despite this, the observational analysis of this paper finds differences between developing and non-developing systems at both lower and upper tropospheric levels; so both levels must be retained in any parameter synthesizing the observational results. The large contribution from the upper levels can be seen clearly in Table 5 which gives the separate contribution of upper and lower levels to DGP.

The concept of a favorable superposition of upper and lower level flow features raises the question of whether tropical cyclone development is determined by the properties of the incipient disturbance or, alternatively, whether it is forced by the large-scale surrounding flow. The analysis in this paper would indicate the latter, mainly on the basis of the large scale over which the observational differences extend. For example, the shear patterns shown in Fig. 18 and the corresponding temperatures in Fig. 2 extend over a 10° latitude radius area, whereas the satellite-observed cloud cluster has a typical radial extent of ~3°. It is unlikely that the large areal extent of positive relative vorticity shown in Fig. 17 for the early cloud cluster stage of development could be produced by contraction of vortex tubes as mass converges into the cloud cluster. The scale of the

⁷ Riehl, H., 1975: Further studies on the origin of hurricanes. Dept. Atmos. Sci. Pap. No. 235, Colorado State University, 23 pp. [NTIS COM 75 11226].

⁸ Sadler, J. C., 1975: Tropical cyclone initiation by the tropical upper tropospheric trough. UHMET 75-02. [Available from Dept. of Meteorology, University of Hawaii.]

TABLE 5. Separate contributions of lower level (900 mb) and upper level (200 mb) vorticities to the Daily Genesis Potential measured at 6° radius, averaged for the non-developing and developing composite data sets (units are 10^{-5} s^{-1}).

	$\zeta_{900 \text{ mb}}$	$\zeta_{200 \text{ mb}}$	$\zeta_{900} - \zeta_{200}$
Average non-developing (Pacific N1; Atlantic N1, N2, N3)	0.3	-0.4	0.7
Average developing Weak systems (D1, D2)	1.2	-0.8	2.0
Average developing All systems (D1, D2, D3)	1.6	-1.1	2.7

region of positive V_T makes it more likely that its origin is external to the system.

This corresponds to a picture of tropical storm development being a result of large-scale influences. It appears that the unique feature to specifying time and location of tropical cyclogenesis is not so much the characteristic of the individual mesoscale system itself. These systems are common and occur in all seasons and at most locations. Once the climatological conditions are met, it appears that favorable large scale changes in the tropical general circulation are the primary factors determining whether the often present individual organized mesoscale systems will intensify or not. It appears that genesis occurs when an organized tropical cloud cluster exists in a favorable large-scale environment. In particular, both low-level positive relative vorticity and upper level negative relative vorticity over a very large surrounding area must be present. These large-scale vorticity requirements can also be interpreted in terms of vertical shear: large vertical shears of a particular configuration must be present close to the developing disturbance.

The composite analysis in this paper has delineated a number of differences in structure, and in particular in the surrounding wind field, between developing and non-developing tropical disturbances. These observations can hopefully form a foundation on which to build theories and models of tropical

cyclogenesis. The analysis of the individual cases in Section 4 of the paper also indicates a potential applicability of the findings for operational forecasting.

The following paper (Part III, McBride, 1981b) extends the analysis by performing budget studies on the composite data sets. It also contains a brief discussion of the implications of the results of the three parts of the study concerning the physical processes of tropical cyclone development.

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