HURRICANE SPAWNED TORNADOES

by

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ABSTRACT

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Hurricane spawned tornadoes are most frequent at the time when hurricanes initially cross land and undergo rapid filling. This paper presents data composite information on all available rawinsonde and pibal reports surrounding this type of tornado genesis in the United States and Japan. Information has also been gathered on tropical storms entering land which did not produce torandoes.

The most important difference between storms which produce tornadoes and those which do not is a very large increase of the vertical shear of the horizontal wind between the surface and 4-5 thousand feet. This averages about 40 knots for the tornado cases, but is much less in the cases which do not produce tornadoes. Differences in vertical stability are observed to be small.

An overland hurricane dissipation model is proposed whereby the boundary layer frictional inflow towards the hurricane center occurs without the usual ocean sensible heat gain and is not, as over the ocean, isothermal. Over land the inward spiraling air parcels cool. This reverses the usual hurricane boundary layer baroclinicity and allows for large observed low level positive vertical wind shear during the short period of rapid filling. This large magnitude vertical wind shear is required for tornado formation. It should be used as a forecast tool in hurricane tornado prediction.

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I. INTRODUCTION

The literature on hurricane tornadoes consists of about ten articles which deal with individual case studies or the climatology of a number of cases. Table I is a summary of these earlier studies. Although very informative, these previous studies (with the exception of Wills, 1969) appear not to have come to grips with the crucial environmental process operating to explain this type of vortex genesis.

In this study, an updated climatology of hurricane tornadoes is presented from information gathered for U. S. cases from 1948-72 and typhoon induced tornadoes over Japan from 1950-71. This paper presents a qualitative tornado genesis model which attempts to demonstrate the crucial importance of large low level vertical wind shear in the genesis mechanism. A forecasting guide is also given.

Although hurricane spawned tornadoes are typically less intense then the classical Great Plains type, they cannot be overlooked for they contribute up to 10% of the overall fatalities and up to a half percent of the overall damage caused by the hurricanes that spawn them (see Appendix I).

Smith (1965) proposed a climatological hurricane spawned tornado model which emphasized the hurricane's directional heading (northeast--favorable for tornadoes) and a so-called "significant tornado sector" of the hurricane (right front quadrant). Smith's model, however, would not have predicted the tornadoes of hurricane Beulah

(1967). Beulah deviated significantly from the climatological norm of hurricanes spawning tornadoes and established herself as "queen" of all tornado bearing hurricanes, generating over one hundred. Beulah's marked deviation from the climatological norm suggested that a more dynamical approach should be adopted in studying these vorticies.

Hill, Malkin, and Schulz (1966) did a climatological study of hurricane tornadoes and listed a number of practical forecast aids. They proposed convective instability from dry air intrusions as a fundamental genesis mechanism.

Wills (1969), compositing tornado proximity soundings for the entire United States discovered some remarkable low level vertical wind shears associated with hurricane induced tornadoes. This study was initiated as an attempt to further document and extend the previous work of Wills (1969) and Gray (1969, 1971) on the importance of low level vertical wind shear in tornado formation.

Table 1

1. Malkin, W., and J. G. Galway, (1953): Tornadoes associated with hurricanes. Mon. Wea. Rev., 81, 299-303.

A case study of a tornado spawned by Hurricane Able (1952). This paper was one of the first to show some of the characteristic environmental feature differences between hurricane tornadoes and the Great Plains ones.

2. Kellerstrass, E. J., (1962): Hurricane spawned tornadoes: A case study of Carla, September 11-13, 1961. Thesis (M.S.), St. Louis University.

A case study of tornadoes associated with Carla. This work attempts to demonstrate the futility of applying mid-latitude tornado forecast techniques to hurricane tornadoes.

3. Pearson, A. D., and A. F. Sadowski, (1965): Hurricane induced tornadoes and their distribution. Mon. Wea. Rev., 93, 461-464.

A ten-year study of hurricane spawned tornadoes which shows the preferred distribution of hurricane tornadoes in the storm's right front quadrant.

4. Smith, J. S., (1965): The hurricane-tornado. Mon. Wea. Rev., 93, 453-459.

A data synthesis is developed for hurricane spawned tornadoes which shows the preference for genesis in the right front quadrant and for hurricane recurvature to the northeast.

5. Hill, E. L., W. Malkin, and W. A. Schulz, (1966): Tornadoes Associated with Cyclones of Tropical Origin--Practical Features. J. of Appl. Meteor., 5, 745-763.

A review of the climatology of hurricane tornadoes is given. The article emphasizes the importance of convective instability. Some practical forecasting guides for hurricane tornadoes are summarized.

6. Grice, G. K., J. R. Scoggins, and R. A. Clark, (1967): An Investigation of the Tornadoes Associated with Hurricane Beulah. 26 pp.

Table 1 (cont'd)

A case study is made of the record tornado outbreak of Hurricane Beulah with a hypothesis of dry air intrusions as the primary genesis mechanism.

7. Goldstein, M. G., (1968): Differential Advection Associated with Tornadoes of Tropical Cyclone Origin. M.S. Thesis, 32 pp.

A thermal buoyancy hypothesis (based on 23 hurricanes) is developed that tries to explain hurricane tornado genesis in terms of differential temperature advection.

8. Wills, T., (1969): Characteristics of the Tornado Environment as Deduced from Proximity Soundings. Sixth Conf. on Severe Local Storms. 8-10 April, Chicago, Ill.

An observational study of tornado proximity soundings for the entire U. S. A portion of the study is directed to hurricane spawned tornadoes. It shows that a large lower 150 mb vertical wind shear is associated with hurricane tornadoes.

9. Orton, R., (1970): Tornadoes Associated with Hurricane Beulah on September 19-23, 1967. Mon. Wea. Rev., 98, 541-547.

The record tornado outbreak of Hurricane Beulah is analyzed from a climatological point of view. The best relationships on location of the hurricane tornado in the parent cyclone were obtained with respect to true azimuth and were superior to those obtained using an orientation based on storm heading.

10. Fujita, T. T., K. Watanabe, K. Tsuchiya, and M. Shimada, (1972): Typhoon-associated tornadoes in Japan and new evidence of suction vorticies in a tornado near Tokyo. J. of Meteor. Soc. of Japan.

Typhoon-associated tornadoes during a 22-year period were listed in terms of location, time of day, etc.

II. CLIMATOLOGY

Table 2 lists all the hurricanes and tropical storms during the period from 1948 to 1972 that have come on shore in the United States. Of these 83 U. S. hurricanes and tropical storms, 25% spawned tornadoes (a total of 373). Hurricane Beulah (1967) had 141 tornadoes (all time record), accounting for 38% of all hurricane tornadoes. Excluding Beulah, the average hurricane which spawned tornadoes had ten. These tornadoes have occurred from May through October but most frequently in September. Note that very few hurricane tornadoes were reported until the middle 50's.

Table 3 (Fujita, 1972) is a similar tabulation for Japanese typhoons which spawned tornadoes in the period from 1950 to 1971. The average number of tornadoes per typhoon is only 2.3, and the largest number of tornadoes per single typhoon is 8. These values are much smaller than the U. S. ones.

Figures 1 and 2 show the tracks of U. S. hurricanes which had and did not have tornadoes, respectively. Note that hurricanes which spawned tornadoes showed a preference to recurve to the northeast while those storms which did not have tornadoes did not show this preferred directional heading. Figure 3 shows the tracks of the Japanese typhoons which had tornadoes. Nearly all recurved to the northeast.

Tornadoes Relative to Hurricane Direction. Most hurricane-typhoon tornadoes occur close to the time the storms cross land. Figure 4 is a histogram of hurricane and typhoon direction frequency at

Table 2

U. S. Hurricanes With/Without Tornadoes.

Hurricane Name	Month	Year	Number Tornadoes	% of Tornadoes
Agnes	Aug	1972	17	5.4
Beth	Aug	1971	0	0
Doria	Aug	1971	1	.3
Edith	Sep	1971	8+	2.1
Fern	Sep	1971	4	1.1
Heidi	Sep	1971	0	0
Celia	Aug	1970	9+	2.4
Felice	Sep	1970	0	0
Becky	Jul	1970	1	.3
Alma	May	1970	0	0
Greta	Oct	1970	0	0
Camille	Aug	1969	1	.3
Jenny	Oct	1969	0	0
Gerda	Sep	1969	0	0
Abby	Jun	1968	4	1.1
Brenda	Jun	1968	0	0
Candy	Jun	1968	19	5.5
Dolly	Aug	1968	0	0
Gladys	Oct	1968	3	.8
Beulah	Sep	1967	141	38.4
Doria	Sep	1967	0	0
Alma	Jun	1966	9	2.4
Inez	Oct	1966	1	.3
Betsy	Sep	1965	6	1.6
Unnamed	Jun	1965	0	0
Abby	Aug	1964	0	0
Unnamed	Jun	1964	0	0
Cleo	Sep	1964	12	3.2
Dora	Sep	1964	2	.5
Hilda	Oct	1964	11	3.2
Isbell	Oct	1964	12	3.2
Cindy	Sep	1963	0	0
Ginny	Oct	1963	0	0
Alma	Sep	1962	0	0
Carla	Sep	1961	26	7.4
Donna	Sep	1960	5	1.3
Ethel	Sep	1960	9	2.4
Unnamed	Jun	1960	0	0
Brenda	Jun	1960	0	0
Florence	Sep	1960	0	0

Table 2 (cont'd)

Hurricane Name	Month	Year	Number Tornadoes	% of Tornadoes
Unnamed	Jul	1959	0	0
Debra	Jul	1959	5	1.3
Arlene	Jun	1959	0	0
Irene	Oct	1959	0	0
Unnamed	Jun	1959	0	0
Gracie	Oct	1959	5	1.3
Judith	Oct	1959	1	.3
Cindy	Jul	1959	11	3.2
Helene	Oct	1958	0	0
Alma	Jun	1958	0	0
Ella	Sep	1958	0	0
Audrey	Jun	1957	23	6.6
Ester	Sep	1957	0	0
Bertha	Aug	1957	0	0
Unnamed	Jun	1957	0	0
Debbie	Sep	1957	0	0
Flossy	Sep	1956	5	1.3
Unnamed	Jun	1956	0	0
Connie	Aug	1955	6	1.6
Diane	Aug	1955	1	.3
Brenda	Aug	1955	0	0
Unnamed	Aug	1955	0	0
Ione	Sep	1955	0	0
Alice	Jun	1954	0	0
Barbara	Jul	1954	0	0
Hazel	Oct	1954	0	0
Carol	Aug	1954	0	0
Hazel	Oct	1953	1	.3
Alice	Jun	1953	0	0
Florence	Sep	1953	0	0
Barbara	Aug	1953	0	0
Able	Sep	1952	3	.8
How	Oct	1951	0	0
Baker	Aug	1950	2	.5
Love	Oct	1950	0	0
King	Oct	1950	0	0
Unnamed	Aug	1949	4	1.1
Unnamed	Sep	1949	0	0
Unnamed	Oct	1949	0	0
Unnamed	Sep	1948	2	.5
Unnamed	Sep	1948	1	.3
Unnamed	Oct	1948	2	.5

Table 3

Japanese Typhoons With Tornadoes.

Typhoon Name	Month	Year	Number Tornadoes	% of Tornadoes
Jane	Sep	1950	1	2
Ruth	Oct	1951	2	3
Mamie	Aug	1953	1	2
Grace	Aug	1954	2	3
Lorna	Sep	1954	5	6
Louise	Sep	1955	2	3
Babs	Aug	1956	1	2
Emma	Sep	1956	3	4
Agnes	Aug	1957	1	2
Helen	Sep	1958	1	2
Vera	Sep	1959	2	3
Bess	Aug	1960	1	2
Nancy	Sep	1961	2	3
Violet	Oct	1961	1	2
Thelma	Aug	1962	5	6
Della	Aug	1963	2	3
Helen	Aug	1964	1	2
Marie	Aug	1964	1	2
Lucy	Aug	1965	3	4
Unnamed	Jul	1967	1	2
Dinah	Oct	1967	3	4
Trix	Aug	1968	1	2
Della	Sep	1968	5	6
Cora	Aug	1969	7	9
Olga	Jul	1970	1	2
Anita	Aug	1970	1	2
Ivy	Jul	1971	1	2
Trix	Aug	1971	8	12
Virginia	Sep	1971	2	3

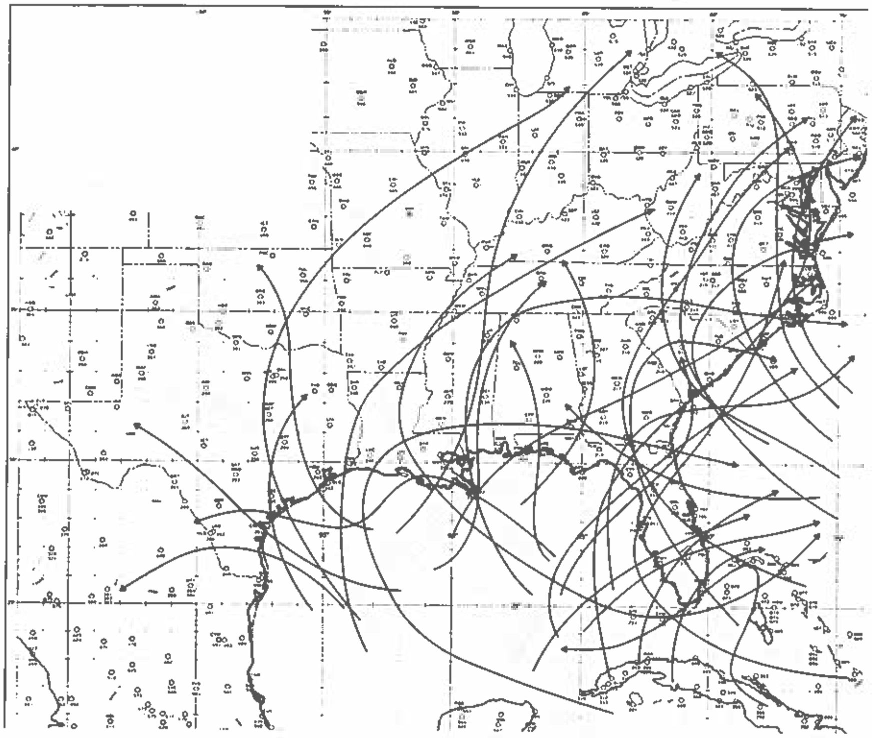

Fig. 1. Tracks of hurricanes with tornadoes (1948-1972).

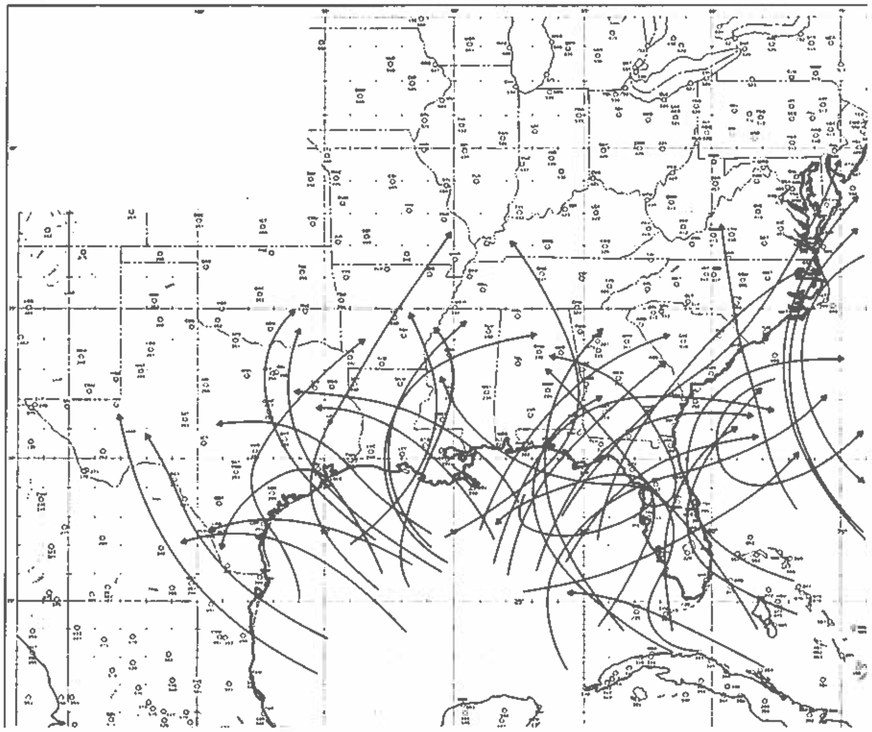

Fig. 2. Tracks of hurricanes without tornadoes (1948-1972).

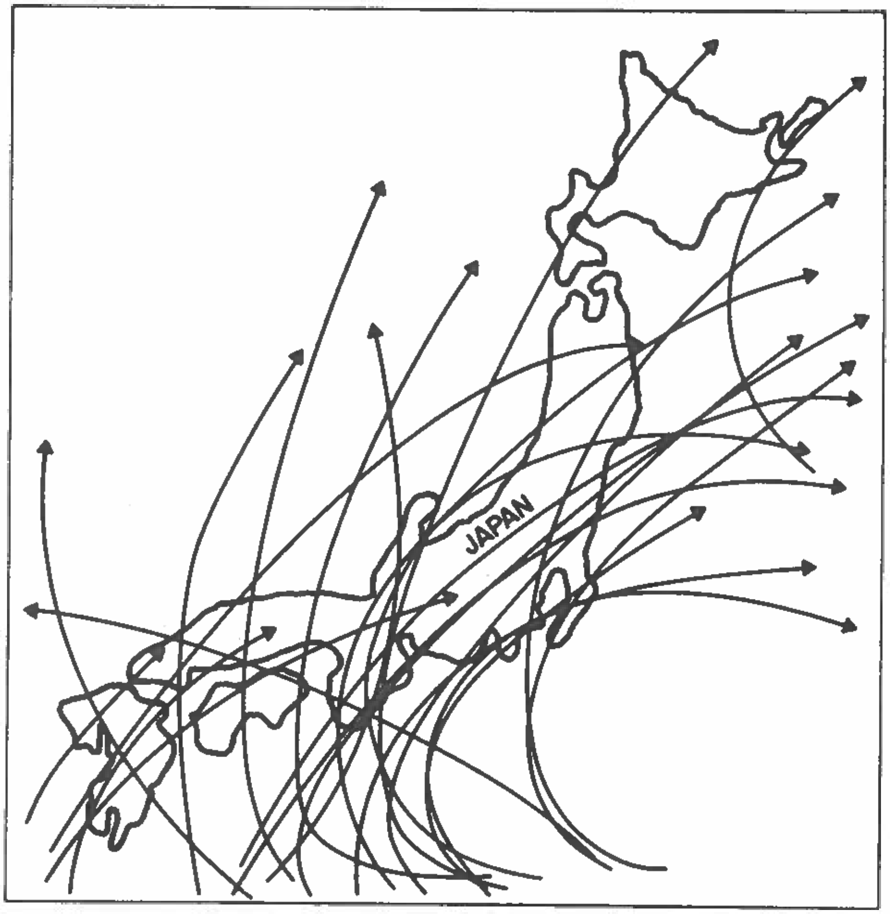

Fig. 3. Tracks of typhoons with tornadoes (1950-1971).

landfall. Direction at landfall of hurricanes which did not spawn tornadoes is also shown. These results agree with the findings of Hill et al. (1966), and Smith (1965). They showed that hurricanes recurving to the northeast have a higher probability of having tornadoes than those hurricanes which continued to move westward. The already noted exception to this average was Beulah (1967) which traveled in a 300° direction and later moved toward 240°. Typhoons in the period from 1950 to 1971 that moved inland over Japan and spawned tornadoes were moving with an average direction of 20° at landfall. This is in very good agreement with the U. S. cases. There were, however,

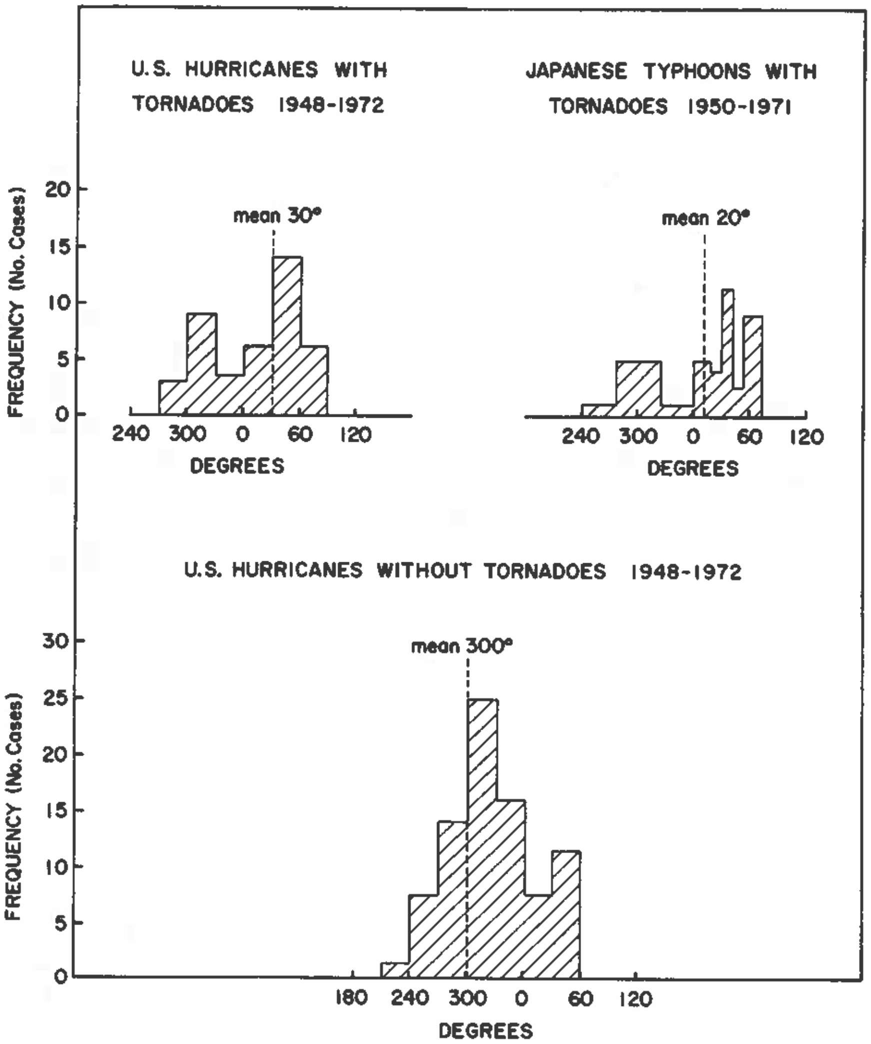

Fig. 4. Frequency diagrams of storm direction (in degrees) at landfall for U. S. hurricanes with and without tornadoes (1948-1972) and Japanese typhoons with tornadoes (1950-1971).

many other storms crossing land and moving in a north to northeasterly direction which did not produce tornadoes. In a statistical sense, there is little difference in storm direction for hurricanes with and without tornadoes.

Preferred Sector of the Hurricane. Figure 5 composites all the U. S. tornadoes in a plan view display with respect to true north and distance from the center of the hurricane in nautical miles (n. mi.) Orton (1967) has shown that a frame of reference with respect to true

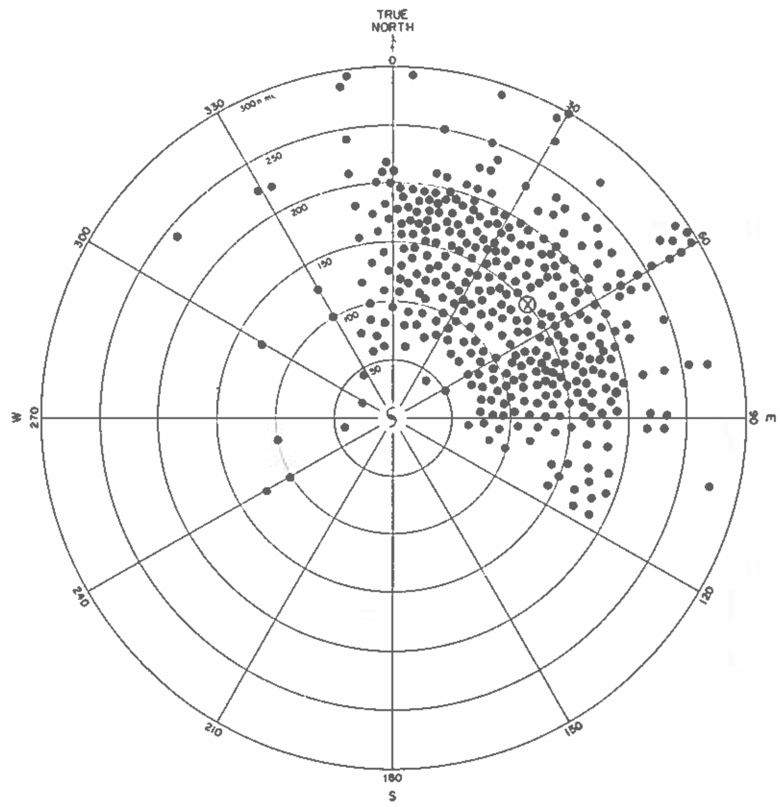

Fig. 5. Plan view display of 373 U. S. hurricane tornadoes (1948-1972) with respect to the hurricane center (S) and true north. The symbol ⊗ refers to the centroid of all cases which is located at 50° azimuth, 150 n. mi. from the hurricane center.

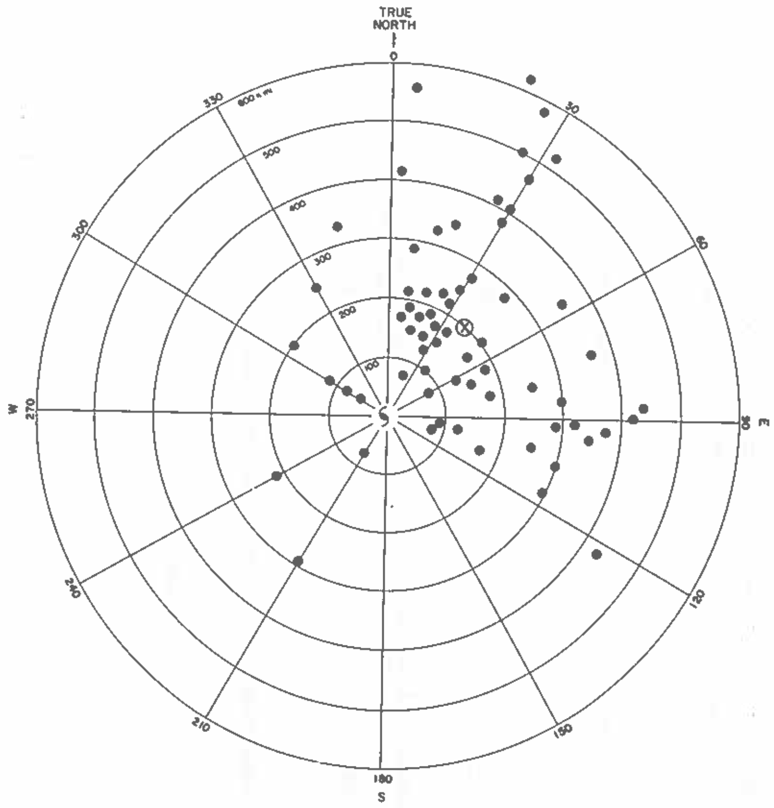

Fig. 6. Plan view display of 68 Japanese typhoon tornadoes (1950-1971) (Fujita et al., 1972) with respect to the hurricane center and true north. ⊗ refers to the centroid of all cases at 40° azimuth, 200 n. mi. from the center of the typhoon.

north was superior to one with respect to the directional heading of the hurricane. It can clearly be seen that there is indeed a preferred sector for hurricane tornadoes from 0° to 120° azimuth and 60-250 n. mi. out from the storm center (centroid point of 50°, 150 n. mi.). Figure 6 which was constructed from the data of Fujita _et al._, (1972) shows how the Japanese cases closely agree with the above results (with a centroid point of 40°, 200 n. mi.). Figure 7 is a composite of the U. S. tornadoes with respect to the direction of the storm's movement. The centroid now becomes 80°, 150 n. mi.). Note that part of Beulah's tornadoes were located in her right rear quadrant.

It should also be noted that overall, a greater percentage of hurricane induced tornadoes occurred from hurricanes that moved inland from the Gulf of Mexico than from hurricanes entering the United States from the Atlantic. This undoubtedly is due to the geometry of recurving hurricanes which places the right front quadrant on shore for Gulf hurricanes and typically out to sea for the Atlantic storms which more nearly parallel the coastline.

Sea Level Pressure. Figure 8 shows a histogram of tornado frequency compared to sea level pressure at the location where the tornado occurred. These results agree with Hill _et al._ (1966) who showed that most tornadoes occurred at sea level pressures from 1000 mb to 1014 mb (with an average of 1009 mb). In further analysis of pressure, Hill _et al._ found that tornadoes occurring in the hurricane stage of the tropical cyclone were located on or very near the 1004

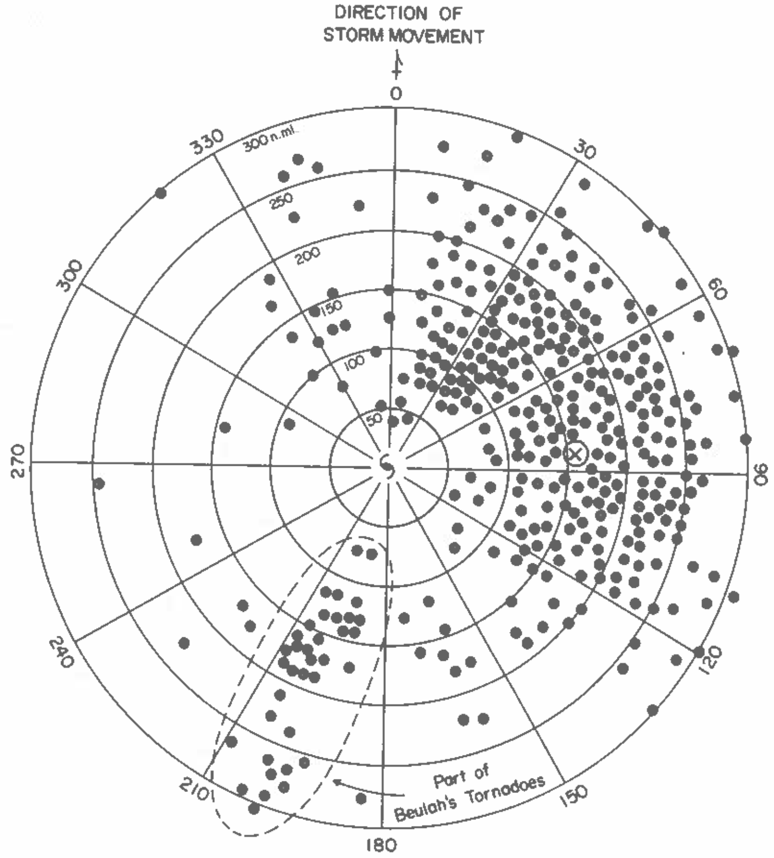

Fig. 7. Plan view of 373 U. S. hurricane tornadoes (1948-1972) with respect to the hurricane center and its direction of motion. ⊗ is the centroid point of all tornadoes which is located at 80° azimuth, 150 n. mi. from the hurricane center.

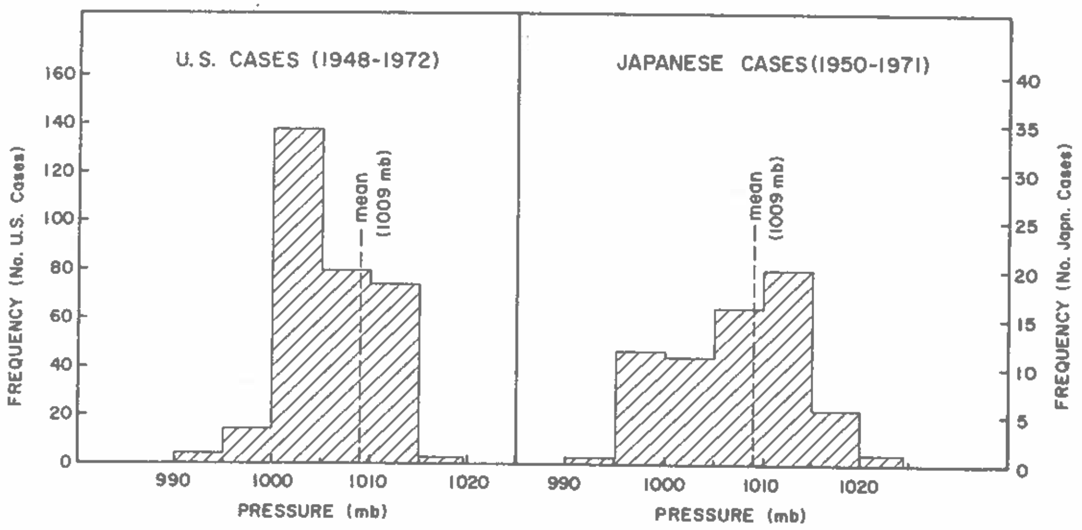

Fig. 8. Sea-level pressure at the tornado location for hurricane and typhoon generated cases in 5 mb intervals.

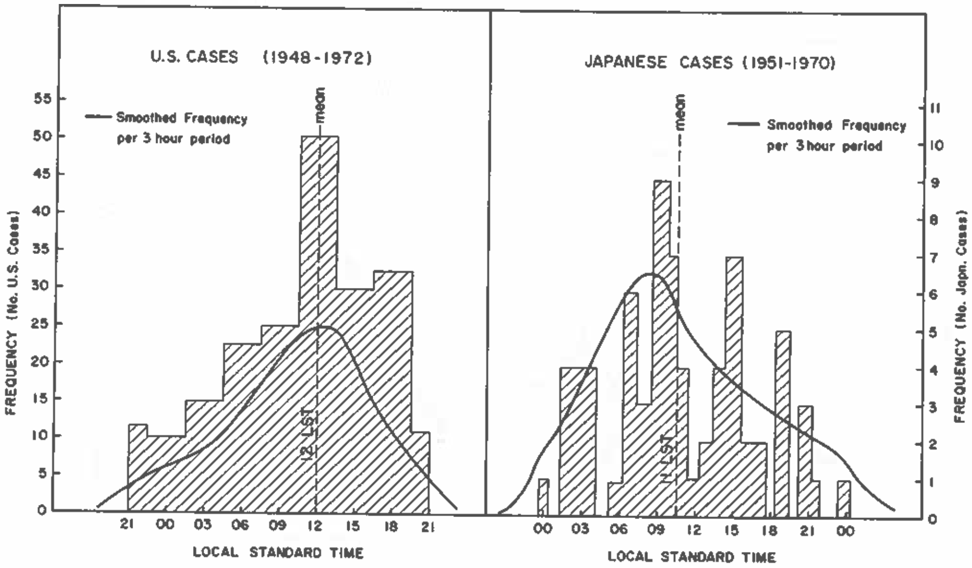

Fig. 9. Hurricane and typhoon tornado distribution with respect to time of day.

isobar; those in the dissipating stage near the 1012 isobar. The average sea level pressure at the tornado location points for the Japanese typhoon cases was 1009 mb.

Time of Day, Hurricane Speed and Distance from Shore. Figures 9, 10 and 11 are histograms of tornado frequency with respect to the time of day, hurricane speed, and distance of the hurricane center on land and off shore. Fujita et al. (1972) has noted a six-hour oscillation period for typhoon tornadoes and has also discovered a similar six-hour variation when applying Fourier analysis to the hurricane tornadoes studied by Hill et al. (1966). This observational periodicity is very difficult to correctly define however. It is not believed to be a fundamental factor to understanding these vortices. Speed of the hurricane is likewise not a significant feature. Figure 10 shows that

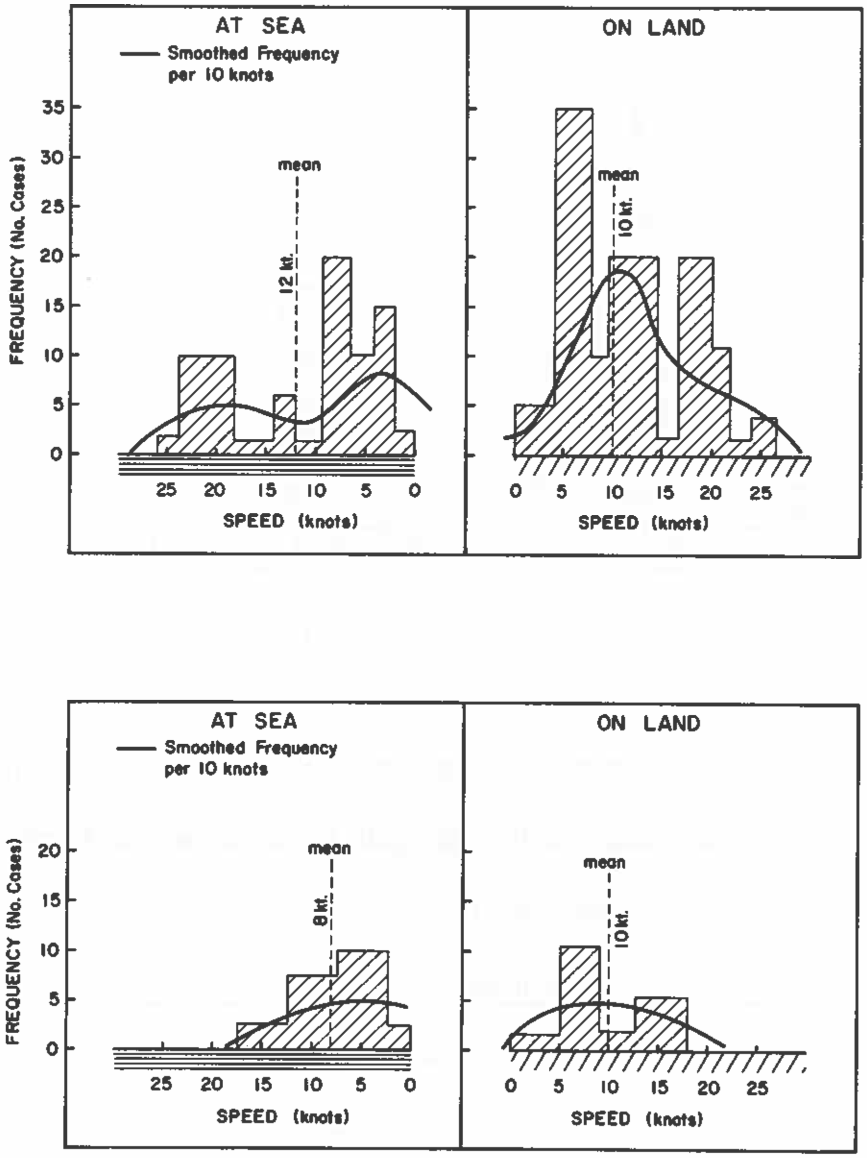

Fig. 10. Frequency of hurricane speed on/off shore for U. S. hurricanes (1948-1972) with and without tornadoes. The number at the dashed vertical line gives the mean values.

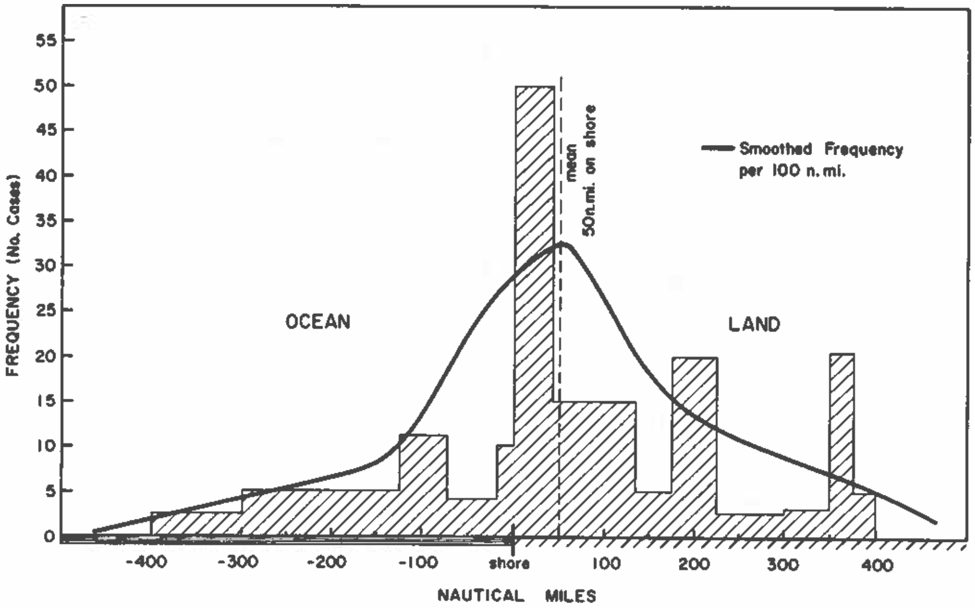

Fig. 11. Hurricane tornado frequency with respect to the hurricane center's distance on and off shore (U. S. hurricanes 1948-1972). The mean position is 50 n. mi. on shore.

hurricanes that did not spawn tornadoes move only slightly slower than tornado bearing hurricanes. Figure 11 shows that the greatest frequency of tornadoes occurs when the storm center has moved about 50 n. mi. on shore.

Cyclone Intensity. About two-thirds of all tornadoes were spawned during the dissipating stages of previously intense storms. Approximately one-third occurred while the cyclone was still at hurricane intensity. Hill et al. (1966) has indicated that the more intense storms and/or the storms that were intensifying at sea produced nearly all the hurricane tornadoes during the period 1955-1964. Weaker tropical cyclones or those weakening already at sea typically do not produce vorticies. This study has verified Hill et al. findings. There appears

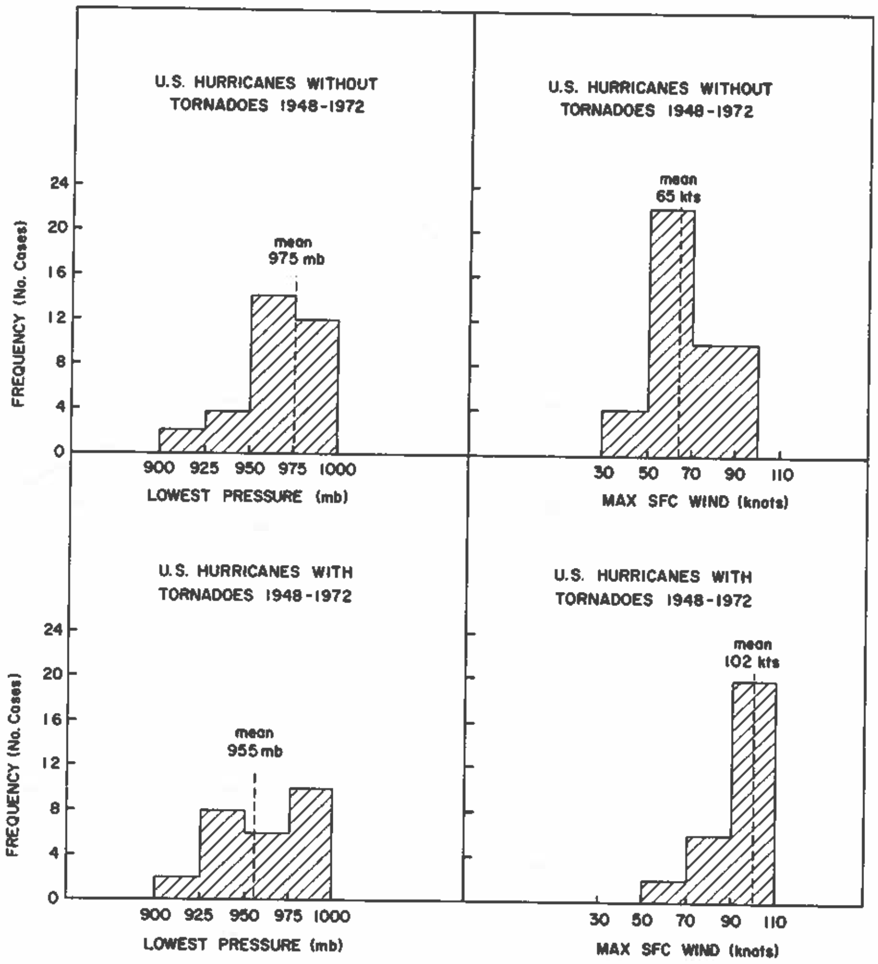

Fig. 12. A comparison of maximum surface winds and lowest sea level pressures for hurricanes with and without tornadoes at landfall. Mean values are indicated on each histogram.

to be a direct relationship between tropical cyclone intensity and tornado incidents. Figure 12 verifies that hurricanes with lower pressures and/or stronger maximum surface winds at landfall are more likely to produce tornadoes than other storms.

Tornado Location Inland. Figures 13 and 14 show that the majority of hurricane induced tornadoes were located on land within 100 n. mi.

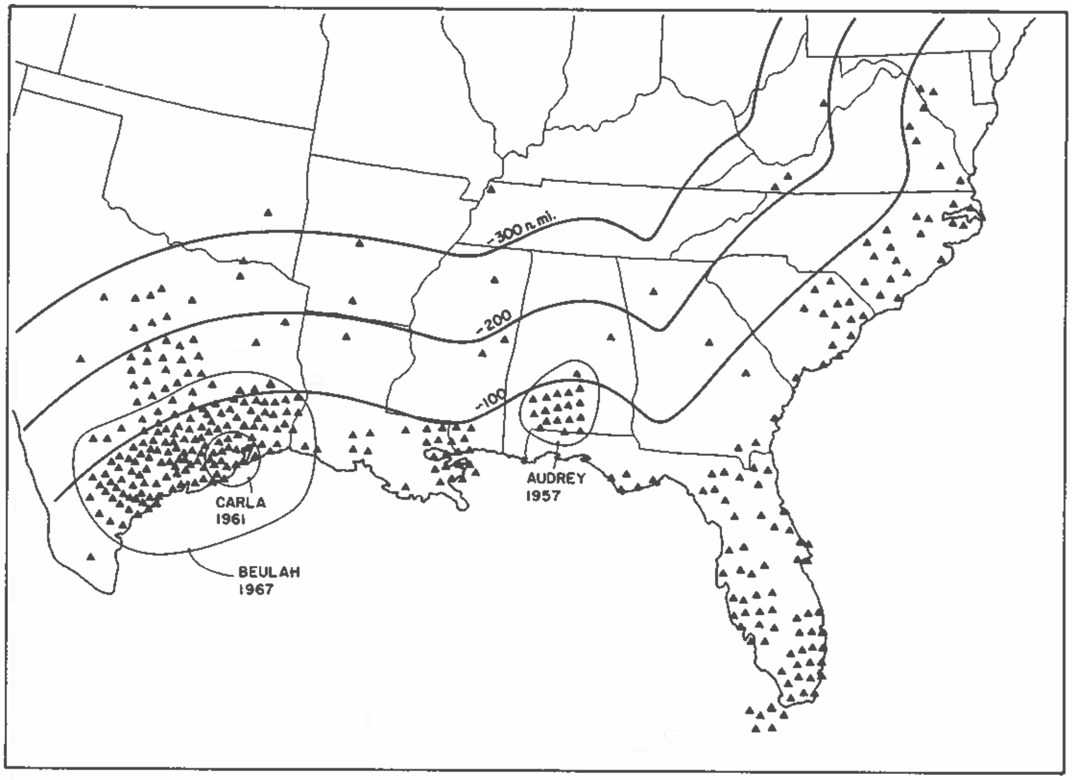

Fig. 13. Geographical distribution of hurricane tornadoes 1948-1972.

of shore. This demonstrates, as will be shown later, that tornadoes occur when the hurricane undergoes rapid dissipation as it first comes on shore.

<u>Summary.</u> Hurricane tornadoes occur in the right front quadrant of the cyclone. They are directly related to the storm intensity as it strikes land. The majority of tornadoes occur inland within 100 n. mi. of shore. There appears to be very little correlation of tornado occurrence with storm velocity, direction or time of day. Most tornadoes are spawned at an environmental pressure of 1009 mb and at the time when the hurricane's center is 50 n. mi. inland.

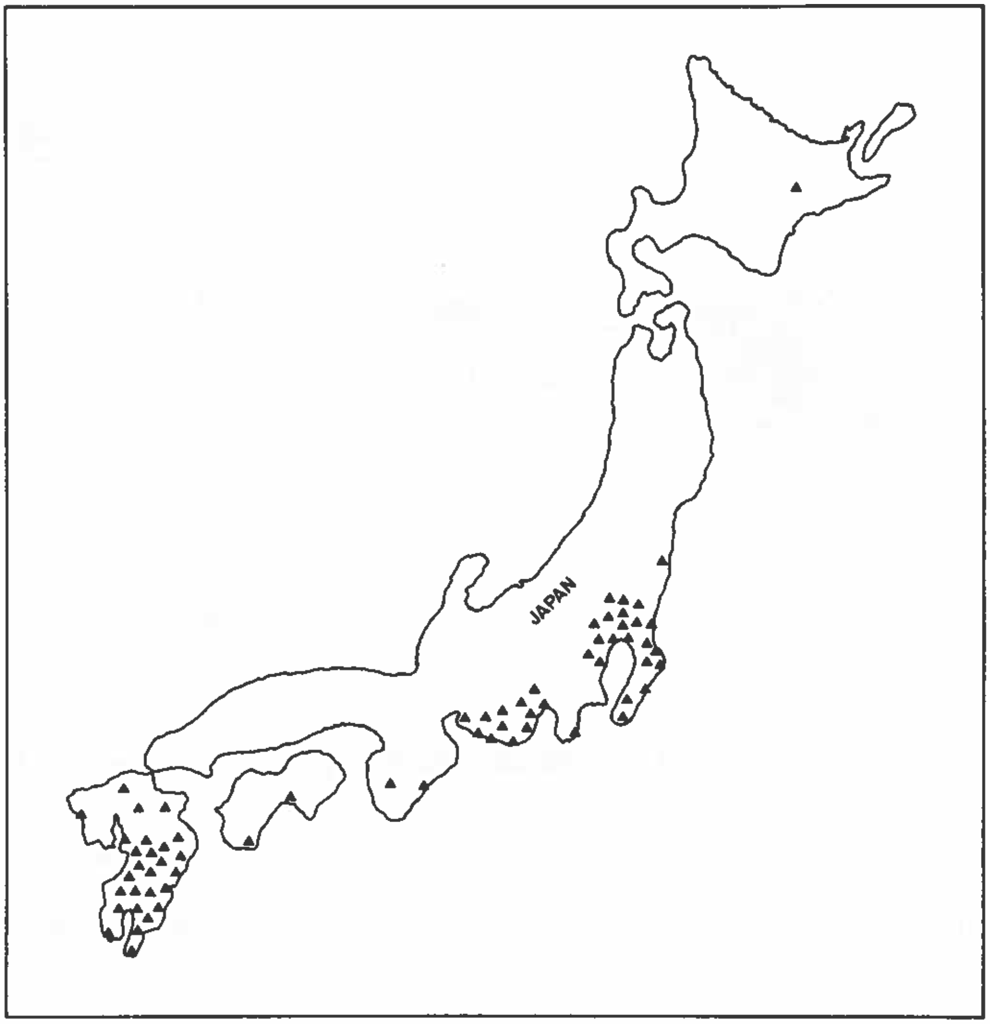

Fig. 14. Geographical distribution of typhoon tornadoes 1950-1971 (Fujita, 1972).

III. ENVIRONMENTAL WIND AND STABILITY CONDITIONS

Hurricanes have been divided into two classes: (1) those producing tornadoes and (2) those not producing tornadoes. Rawinsonde and pibal reports were constructed for both classes of storms. Seventy-five proximity soundings were gathered for the tornado cases. These are all the soundings which were available. A proximity sounding was defined as one within 100 n. mi. and three hours of the tornado occurrence. Seventy-five soundings were also compiled for non-tornado storms. These latter soundings were selectively paired with the tornado ones, matching, as close as possible the same storm track, storm trajectory, distance from the storm center, and azimuth angle.

Very few hurricane spawned tornadoes were reported in the 1940's and 50's. This was partly due to a sparser observational network and lack of knowledge that such vortices existed. Some of the tornado damage may have been confused with that of the hurricane damage. Hurricane tornadoes often occur over uninhabited swamplands or in areas where people have been evacuated for the hurricane. More attention was focused on these types of tornadoes after Audrey (1957) spawned 23 of them. The WSR-57 weather radar does not have the same success in picking up the weaker hurricane tornadoes as it does in detecting the more intense Great Plains ones. The radar scope generally sees only the strong convective elements of the hurricane. If the tornadoes happen to be very close to the radar site however, then the WSR-57 can monitor them (Rudd, 1964).

Vertical Wind Shear. A remarkable fact about tropical storm spawned tornadoes is that while winds 4000-5000 feet above the surface average 55 knots and greater, the surface winds are relatively light, averaging only about 15-20 knots (Wills, 1969). This is shown in Figs. 15 and 16 which are plan views of all the U. S. and Japanese proximity wind soundings (tornado centered) for the surface and 850 mb, respectively.

These tornadoes are small meso-scale features lasting on the average only 20 minutes. The data compiled has been averaged and taken ± 3 hours of the tornado occurrence, thus it is likely that the wind shear values might even be higher at the actual time and place of tornado occurrence. Fifty-six percent of the tornado proximity soundings analyzed were taken prior to the tornado occurrence time. Figure 17 is an example of some of the proximity soundings of vertical wind shear for a few hurricanes and typhoons that spawned tornadoes. Both Kellerstrass (1962) and Hill et al. (1966) have noted the failure which results in applying classical mid-latitude tornado forecasting techniques to hurricane induced tornadoes. Hill et al. has attributed this to the warm core structure and negative vertical wind shear of the hurricane (in the hurricane the strongest winds are near the surface).

Figure 18 shows the vertical wind shear profiles for both the tornado and the null or non-tornado cases. The marked "low level" vertical wind shear for the tornadoes is very apparent. Note that the

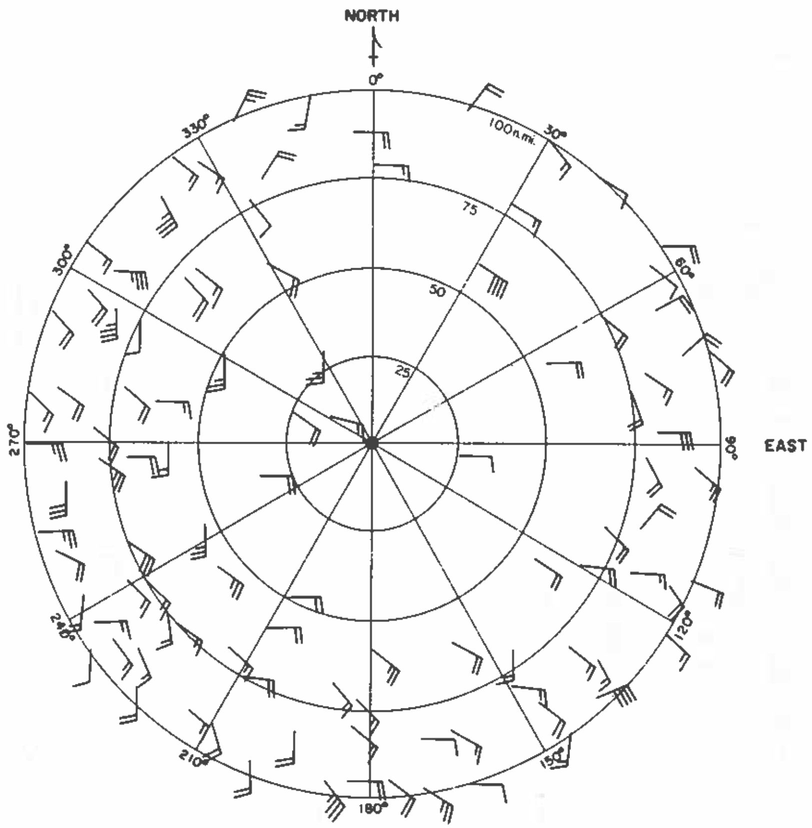

Fig. 15. Composite of all U. S. and Japanese proximity surface wind soundings centered on the tornado.

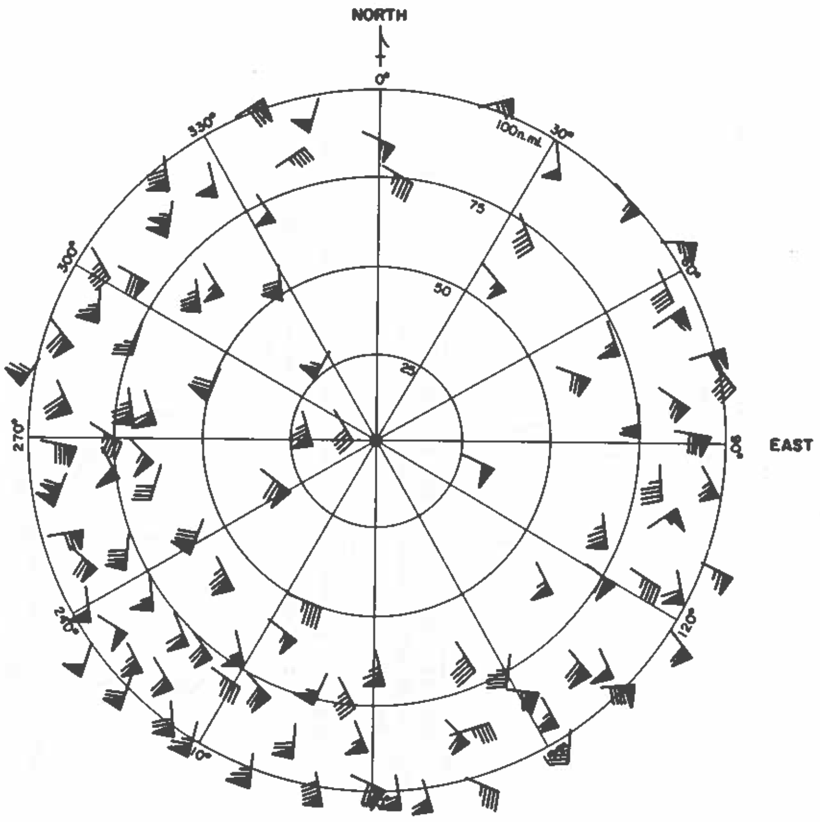

Fig. 16. Composite of all U. S. and Japanese proximity 850 mb wind soundings centered on the tornado.

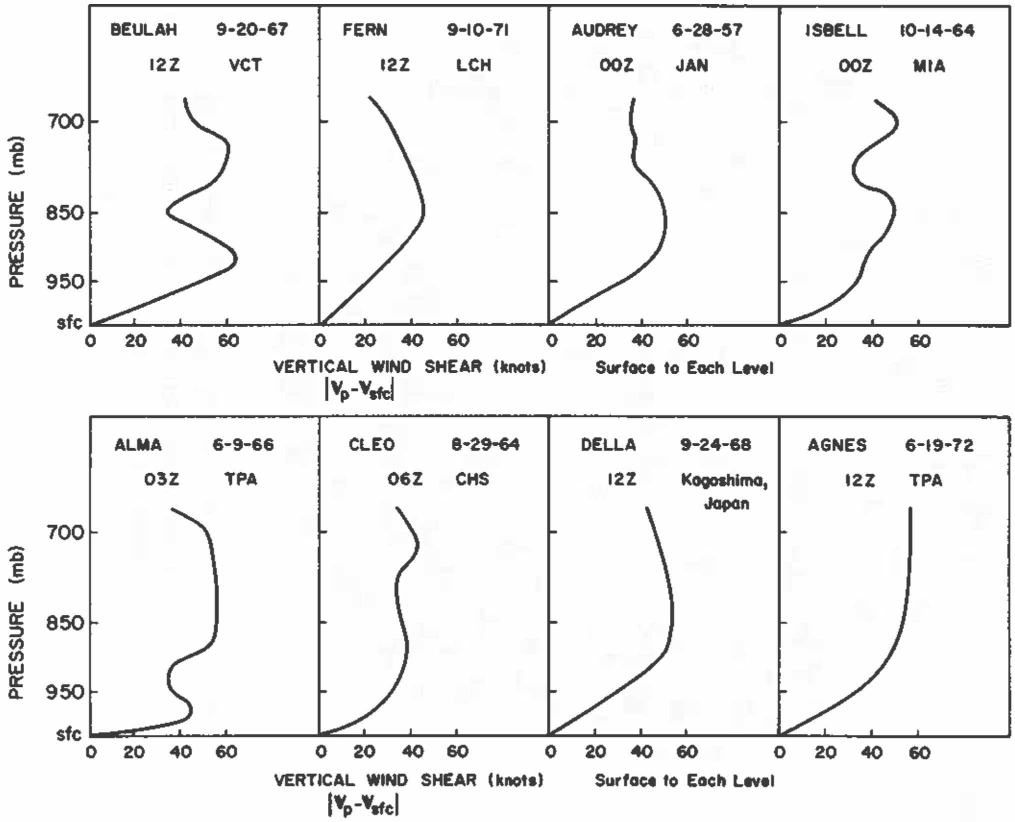

Fig. 17. Examples of proximity soundings of the vertical shear of the horizontal wind at various pressure levels (V_p) with respect to the surface wind (V_{sfc}) for several hurricane tornadoes.

null cases show only one-half the magnitude of vertical wind shear as the tornado cases. Also note the close similarity of the Japanese and U. S. tornado cases. The large low level wind shears for the tornado cases are a direct reflection of the hurricane's rapid dissipation in the surface layers as it moves inland. The dynamics of this process will be discussed in full detail in section IV.

The maximum vertical wind shear in the Japanese cases is about 2000 feet higher than the shear for the U. S. vorticies. This may be due to the greater topography of Japan. Fendell et al. (1971) considers

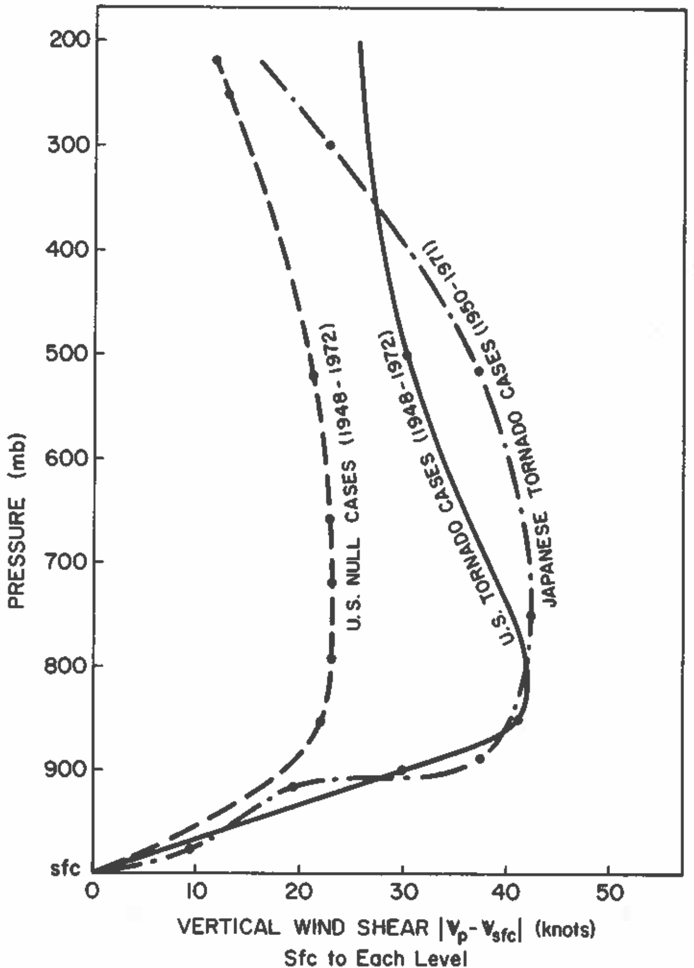

Fig. 18. Proximity vertical wind shear profiles for hurricane and typhoon tornadoes and right front quadrant wind shears for U. S. hurricanes <u>without</u> tornadoes. $|\mathbb{V}_p - \mathbb{V}_{sfc}|$ gives the magnitude of the vertical wind shear between any pressure level wind ($\mathbb{V}_p$) and the surface wind ($\mathbb{V}_{sfc}$).

the lifting of the dying hurricane over raised topography to be an important genesis mechanism. This certainly could not be the case for the Florida and the Gulf States tornadoes, however.

Figures 19 - 28 result from compositing data in all the hurricane quadrants for both tornado and non-tornado hurricanes separately (U. S. cases 1948-1972). Note in Figs. 19 and 27 that the tornado hurricanes show a definite cold core structure at the surface while at 850 mb a semi-warm core is observed. This supports the idea that tornado bearing hurricanes dissipate and lose their warm core structure in the boundary layer first.

In order to obtain a vertical wind shear profile as shown in Fig. 18 (40 kt shear between the surface and 5000 feet), the cylindrical thermal wind equation requires the establishment of a cyclone center temperature between the surface and 850 mb which is $\approx 8^{\circ}$C colder than the ambient air temperature 100 n. mi. out from the center. Figure 19 shows that the observed temperature data closely support this contention. Observed cyclone center surface temperatures average 6°C colder than do the temperatures 100 n. mi. out from the center.

Filling Rates. Figure 29 shows the very important result that hurricanes having tornadoes fill about three times as fast (average 30 mb/12 hrs), as they undergo dissipation over land, as do the non-tornado hurricanes (average 10 mb/12 hrs). Japanese typhoon cases that had tornadoes also were observed to fill on the average of 30 mb per 12 hrs. This result agrees with the plan views in Figs. 19-28. Hurricanes which fill the fastest develop the most intense cold core structure and produce the largest vertical wind shear (see Fig. 18). On the other hand, a slowly filling hurricane will not develop a strong low level cold core structure and intense vertical wind shear pattern.

Directional Shear. Although considerable low level vertical wind shear was obtained in hurricanes spawning tornadoes, very little directional shear (surface to 850 mb and surface to 500 mb) was found. Veering in the right front quadrant in the tornado hurricane averages

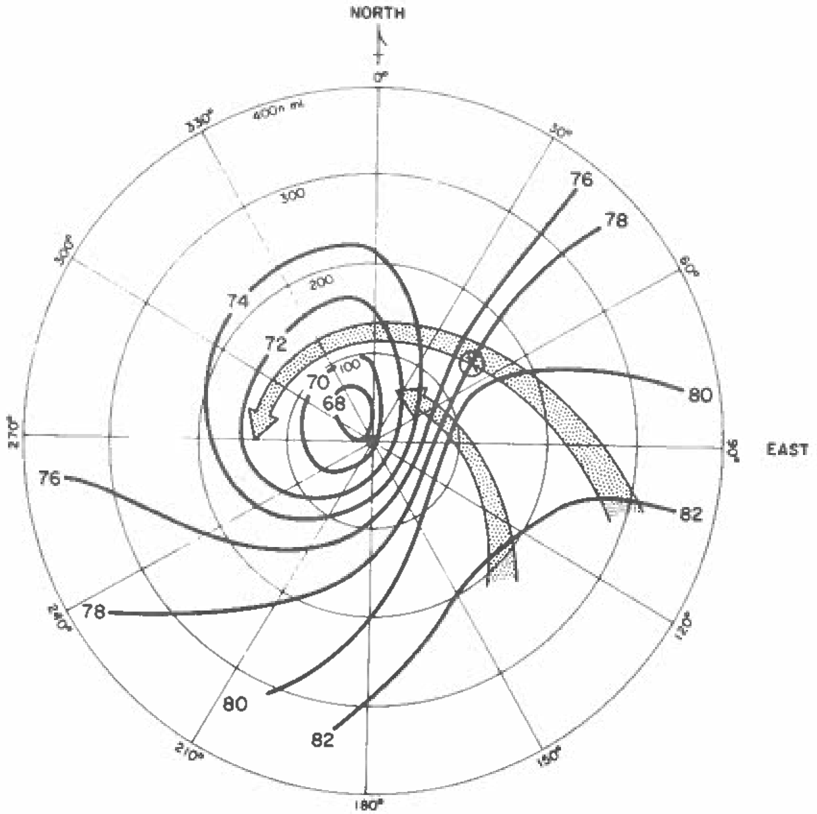

Fig. 19. Plan view of U. S. hurricanes with tornadoes. Surface temperature in °F. Hurricane centered. Note air spiraling toward a cold core. Compare with Fig. 20. ⊗ is centroid point for all tornadoes.

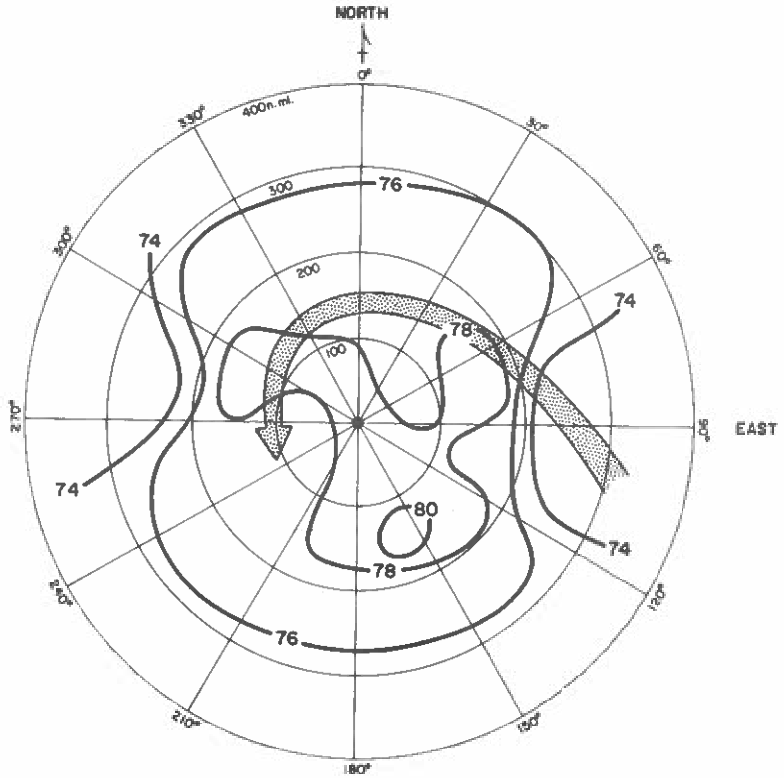

Fig. 20. Plan view of U. S. hurricanes without tornadoes. Surface temperature in °F Note the warm center area in comparison with Fig. 19.

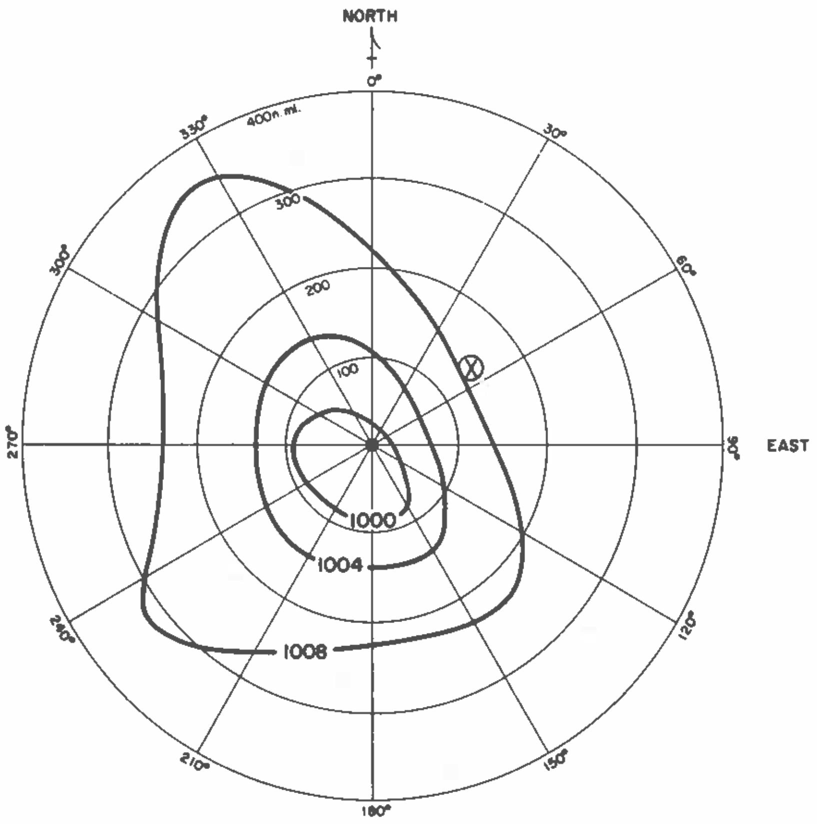

Fig. 21. U. S. hurricanes with tornadoes. Surface pressure in (mb). Hurricane centered. ⊗ is the centroid for all tornadoes.

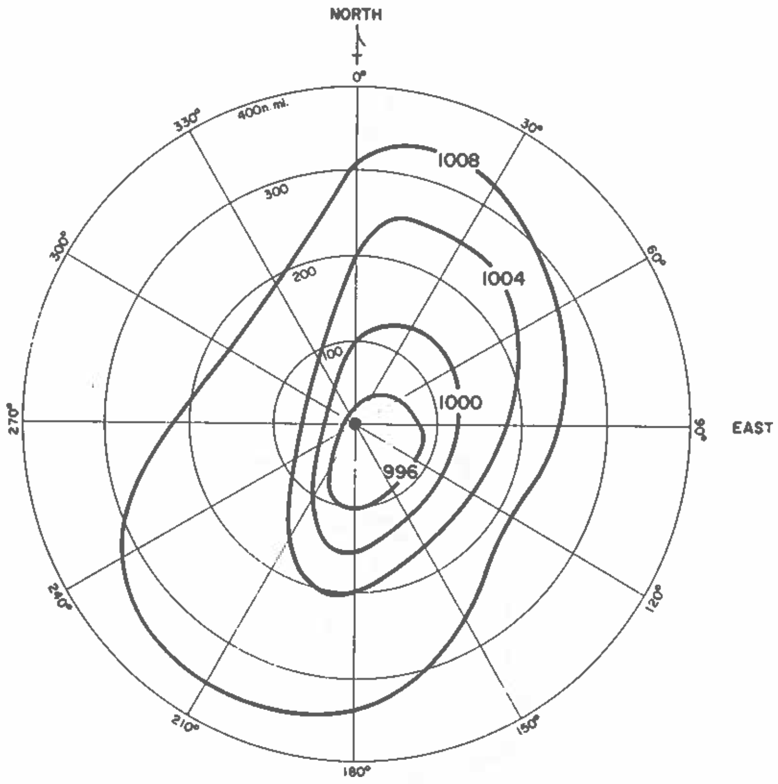

Fig. 22. U. S. hurricanes without tornadoes. Surface pressure in (mb). Hurricane centered.

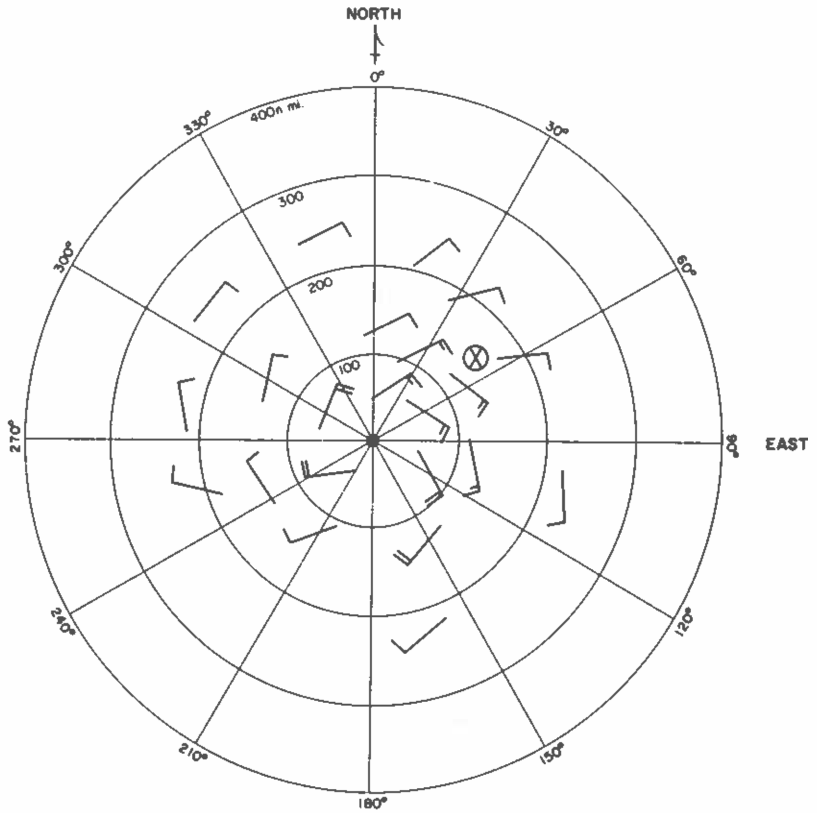

Fig. 23. Hurricanes with tornadoes. Averaged surface winds (knots). Hurricane centered. Note how weak the winds are around the centroid point for all tornadoes (⊗).

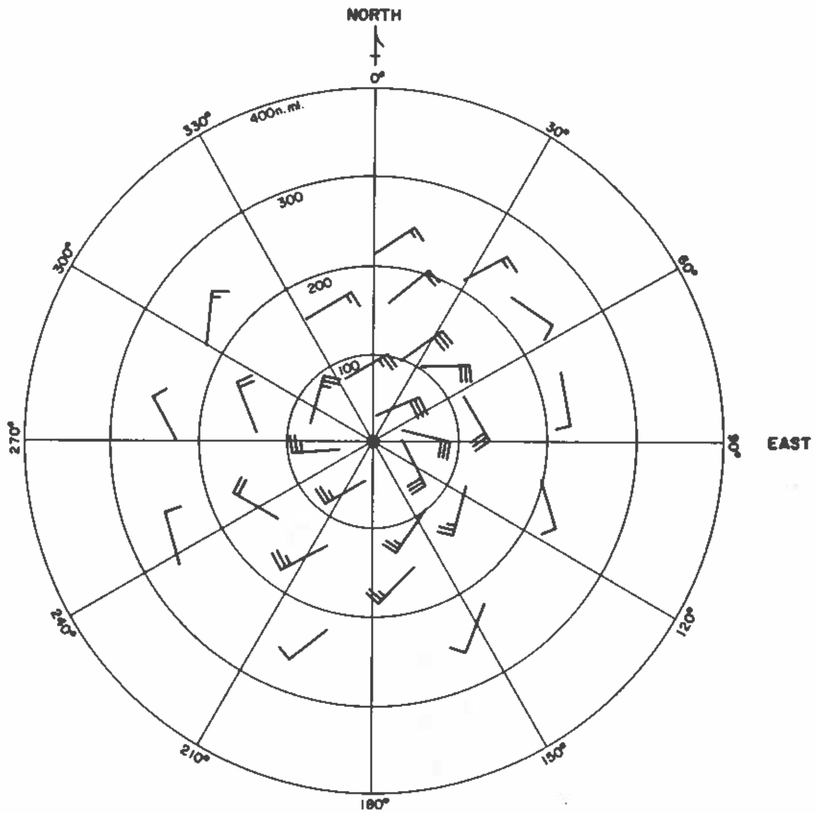

Fig. 24. U. S. hurricanes without tornadoes. Averaged surface wind (knots). Hurricane centered. Note in the right front quadrant 150 n. mi. out from the center that the winds are twice as high as the winds in Fig. 23.

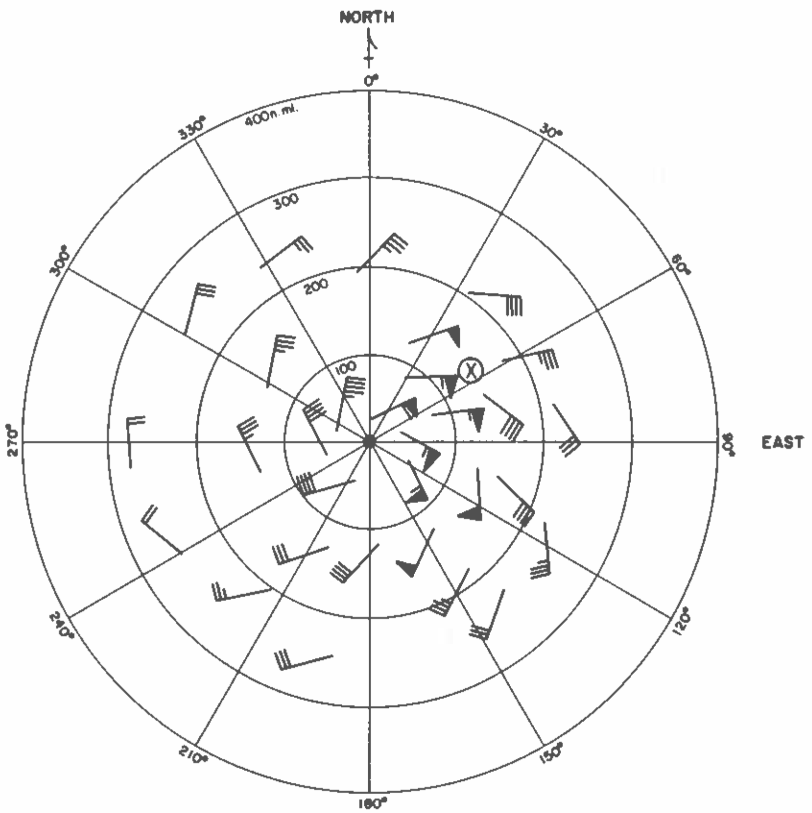

Fig. 25. U. S. hurricanes with tornadoes. Averaged 850 mb winds (knots). Hurricane centered. ⊗ is the centroid of all tornadoes.

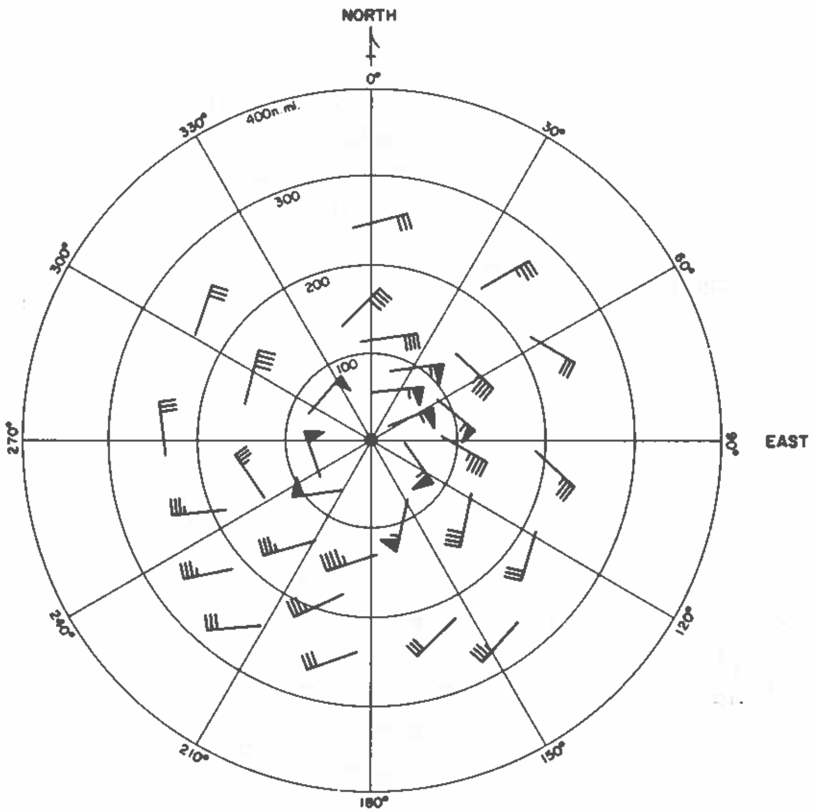

Fig. 26. Plan view of U. S. hurricanes without tornadoes. Averaged 850 mb winds (knots). Hurricane centered. Note the similarity to Fig. 25.

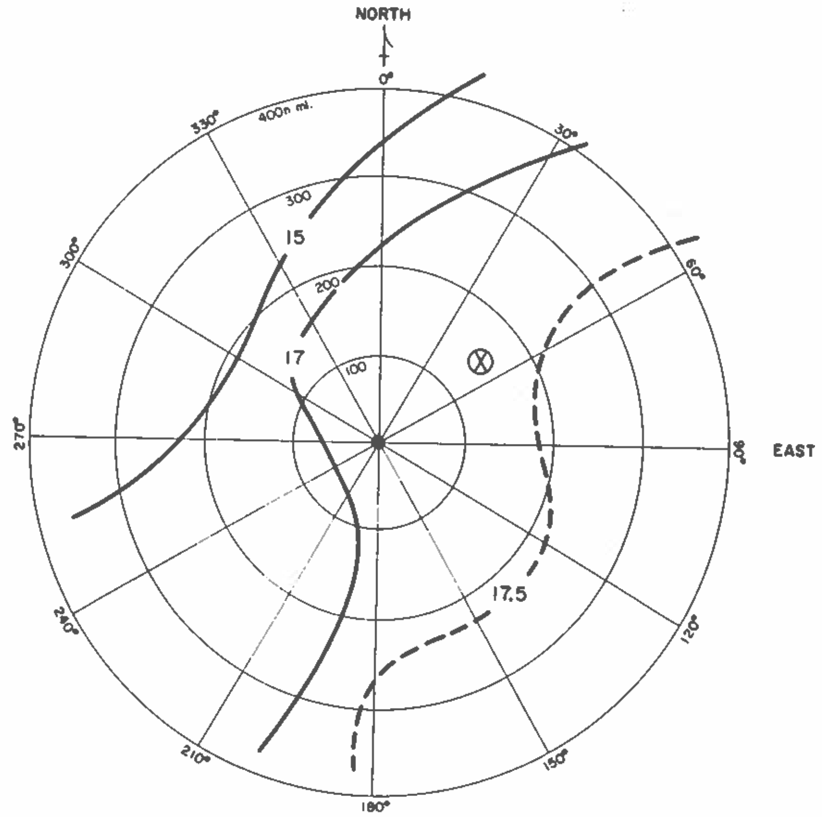

Fig. 27. Plan view of U. S. hurricanes with tornadoes. 850 mb temperature in ^{o}C. Hurricane centered. ⊗ is the centroid of all tornadoes.

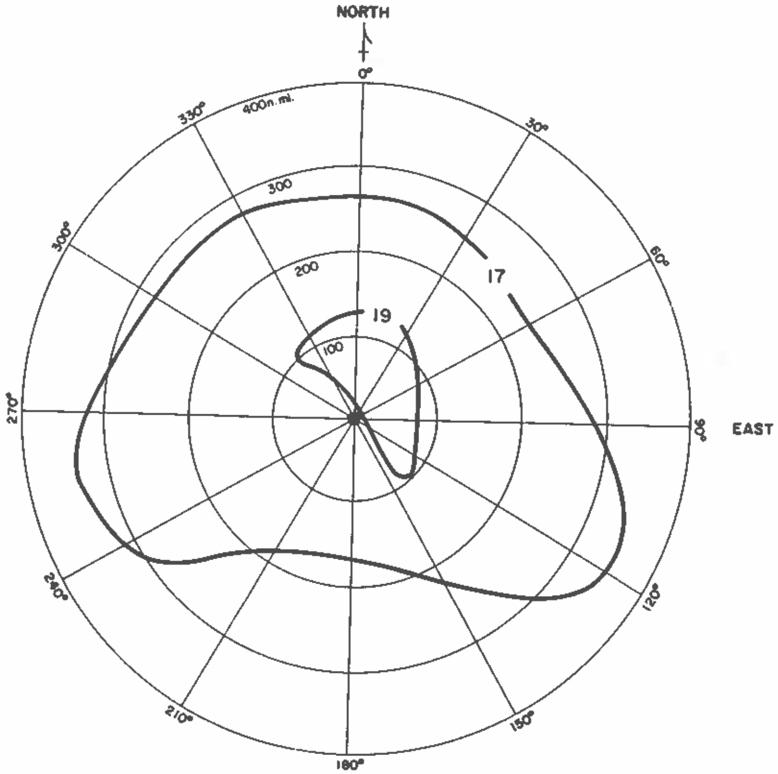

Fig. 28. Plan view of U. S. hurricanes without tornadoes. 850 mb temperature in ^{o}C. Hurricane centered.

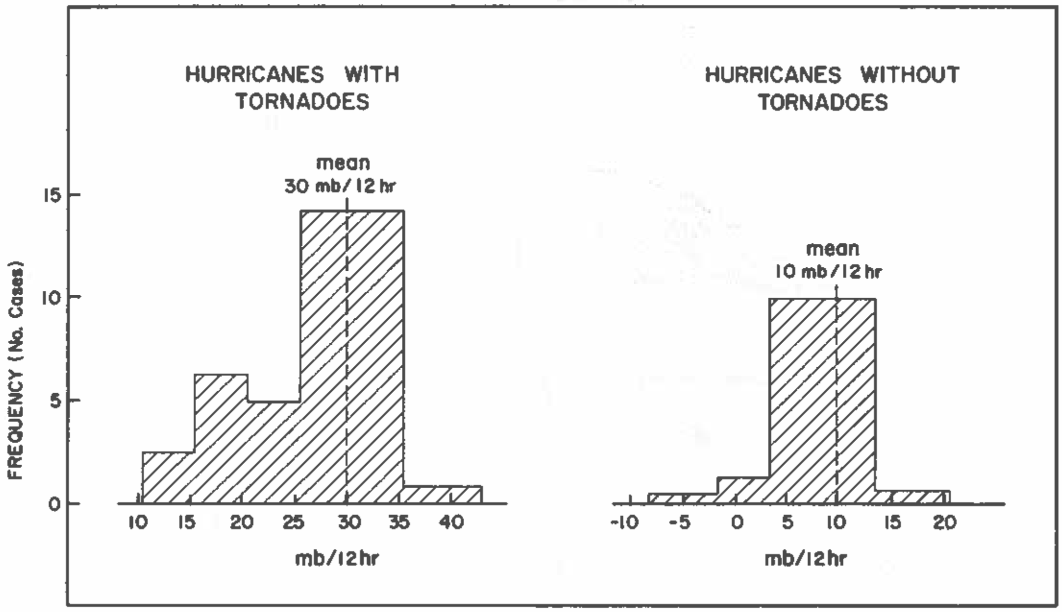

Fig. 29. Filling rates (mb/12 hr) for hurricanes with tornadoes in contrast with hurricanes without tornadoes.

10° from the surface to 850 mb and 33° from the surface to 500 mb (see Fig. 30). Japanese typhoons having tornadoes showed 10° and 38° of veering from the surface to 850 mb and 500 mb, respectively. This is in marked contrast to the tornado environment of the Great Plains which showed about 20° and 60° of veering from the surface to 850 mb, respectively (see Fig. 31).

Instability. One of the more surprising aspects of hurricane induced tornadoes is their lack of strong thermal instability. Kellerstrass (1962) discovered that Showalter index values in the tornado areas of hurricane Carla (1961) were positive. Figure 32 shows that the tornado cases are actually a little more stable on the average than the null cases but the difference between the two is very small. Note the similarity of the U. S. and Japanese cases.

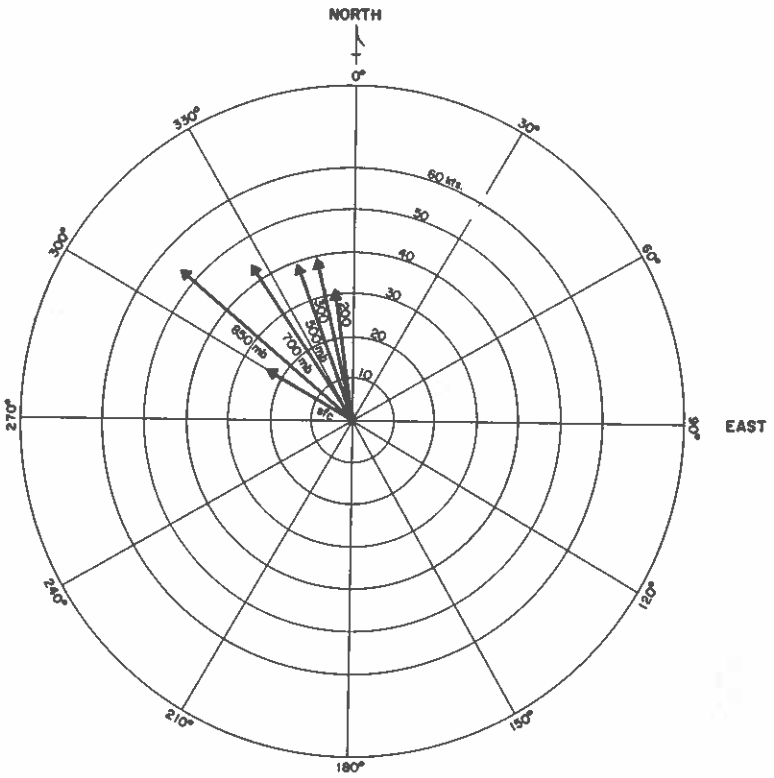

Fig. 30. Typical hodograph for proximity soundings of hurricane spawned tornadoes.

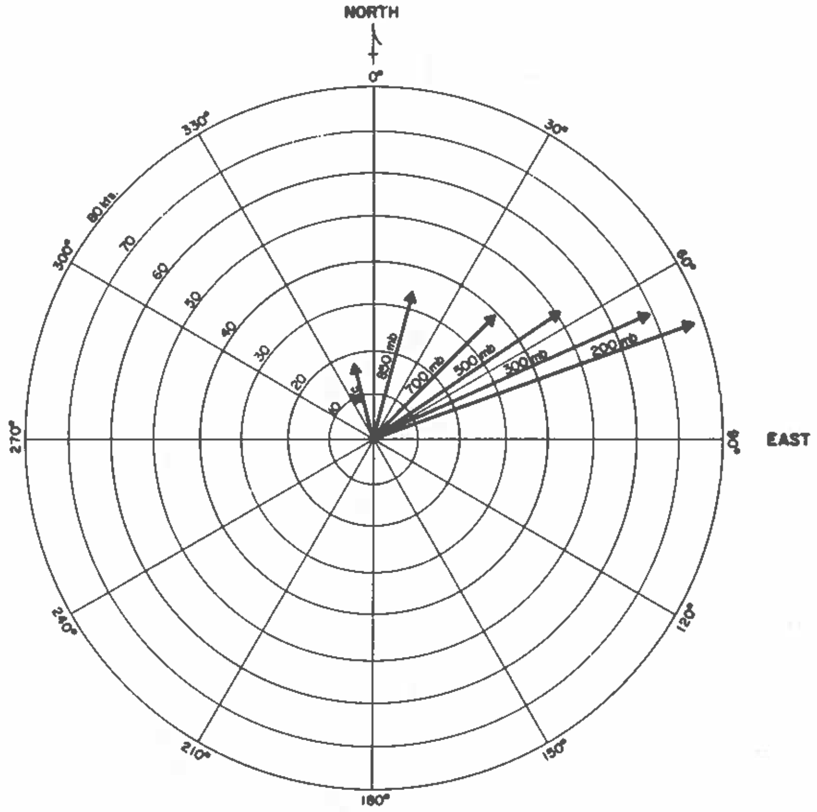

Fig. 31. Typical hodograph for proximity soundings of Great Plains tornadoes (Maddox, 1973).

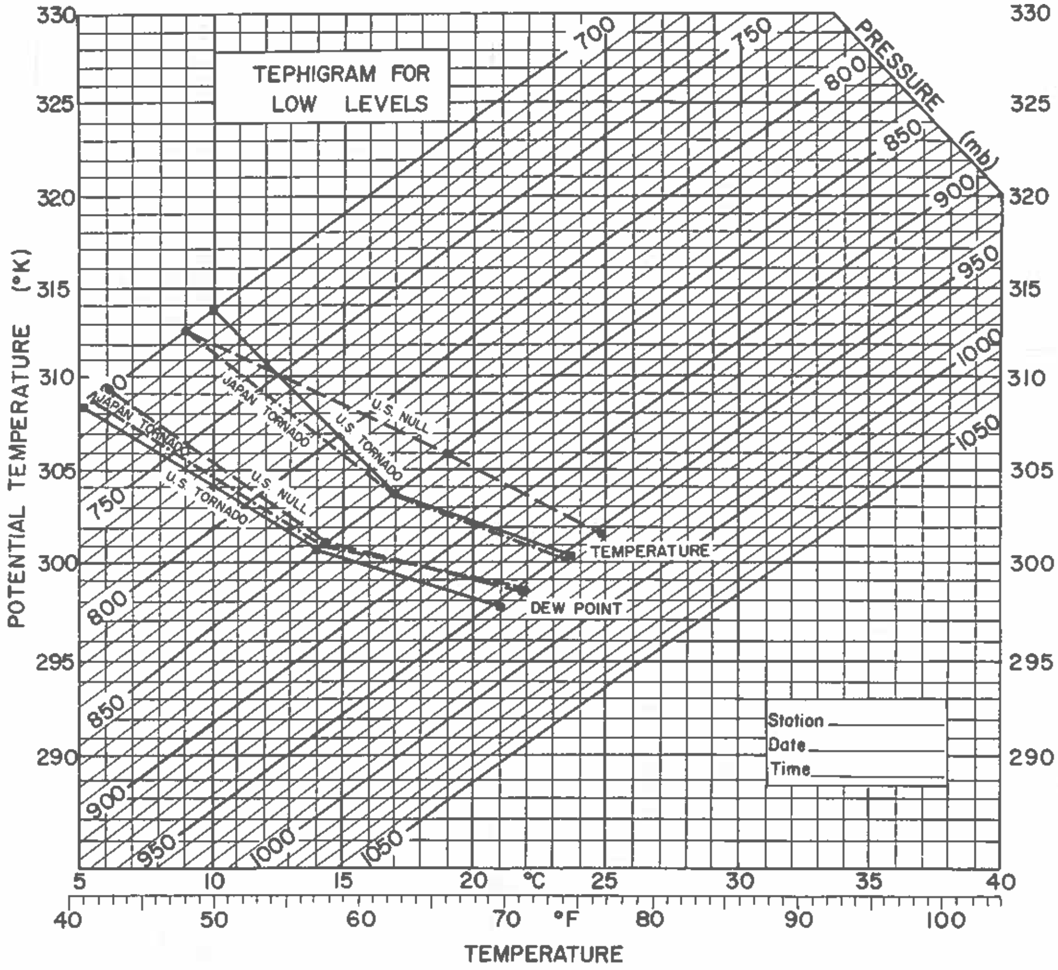

Fig. 32. Averaged proximity soundings for hurricane and typhoon tornadoes and right front quadrant soundings for U. S. hurricanes without tornadoes.

Goldstein (1968) concluded that hurricane tornadoes occur where the air is nearly unstable and differential advection at 850-700 mb and 700-500 mb of .5^{o}C/hr or more adds further instability to the low level environment. Tornadoes did not occur where there was no differential advection or where it occurred at a rate less than the above. He notes that in the tornado cases the lifted index changed from 0 to

-2 in 12 hours while in the non-tornado cases, the lifted index remained close to 0. Thus, there appeared to be only very small stability differences between hurricanes with and without tornadoes. It is hard to explain why previous authors have stressed instability as a primary genesis mechanism.

Table 4 compares the average parcel lifted index values for U. S. hurricanes without tornadoes, U. S. and Japanese storms with tornadoes, and the Great Plains tornadoes. Note the significant instability for the Great Plains cases. Again note the agreement between the U. S. and Japanese tornado cases. The null cases were slightly more unstable than the tornado cases on the average, but not significantly.

One might suspect that thermal instability would not have to play a dominant role in hurricane spawned tornadoes since strong rainband convection is greatly enhanced by the boundary layer frictional convergence over land associated with the large cyclone vorticity pattern. The low level frictional convergence would be much less without the hurricane.

Comparison Between Great Plains and Hurricane Tornadoes. As shown in Figs. 30 and 31 both the Great Plains and hurricane tornadoes exhibit large lower tropospheric wind shears averaging 40 knots. In the hurricane cases, this shear is concentrated between the surface and 850 mb, however. In Great Plains tornadoes, the shear is distributed through the entire surface to 500 mb layer with no lower level concentration. While directional shear in the hurricane cases is

Table 4

Average Parcel Lifted Indices for Tornado and Non-Tornado Hurricanes and Great Plains Tornadoes.

	Hurricanes Without Tornadoes (Right Front Quadrant)	Hurricane Tornado Cases		Great Plains Tornadoes (Maddox, 1973)
		U. S.	Japan	
Level	Lifted Index	Lifted Index	Lifted Index	Lifted Index
Surface to 850 mb	+2	+1	+1	+1
Surface to 700 mb	-1	+2	+1	0
Surface to 500 mb	0	+1	+1	-4

small between the surface and 500 mb (averages 30°), it is two to three times larger for the Great Plains tornadoes.

Hurricane induced tornadoes occur under more thermally stable conditions. They are not as intense as the typical Great Plains tornadoes. This is probably due to the fact that all the dynamics and instability of the hurricane tornado are concentrated in the low levels (700 mb and below). In the Great Plains tornado, the thermal instability is much larger and there are also upper tropospheric dynamic influences.

Conclusion. The most significant observational fact concerning the hurricane tornado is the presence of very strong low level wind shears from the surface to 850 mb (averaging 40 kts). There is little directional wind shear from either the surface to 850 mb (10° veering) or from the surface to 500 mb(30° veering). Those hurricanes associated with tornadoes dissipate rapidly over land and fill (>30 mb/12 hr) three times as fast as hurricanes without tornadoes.

Instability does not play a dominant role in these tornadoes. Differences in stability between hurricanes with and without tornadoes is slight. The hurricane tornado is typically less intense than its Great Plains counterpart.

IV. TORNADO GENESIS

Hurricane Dissipation Dynamics. While the hurricane is at full intensity at sea, the boundary layer air, dur to friction, spirals inward. As the air moves towards lower pressure, it loses sensible heat through expansion. This expansion cooling is compensated by sensible heat transport from the ocean. The typical formula for sensible heat gains (H) over the ocean as quoted from a number of sources by Priestly (1960) is:

$$H = \rho c_p K_T u (T_o - T_a) \tag{1}$$

where

ρ = density of air

c_p = specific heat of air

K_T = coefficient of eddy heat exchange $\sim 2 \times 10^{-3}$

u = surface wind

$T_o - T_a$ = temperature of the ocean (T_o) minus the temperature of the air (T_a)

As an example of this powerful heat source: for $T_o - T_a = 2^{o}C$, $u = 10$ m/sec, a boundary layer depth of 500 m can be warmed as much as $8^{o}C$/day.

Thus, the greater the wind and the difference between the sea surface temperature and air temperature, the greater the heat flux. The constant turbulent mixing of the ocean surface by the hurricane force winds allows for a continuous and rapid heat exchange from the ocean to the air. Over the ocean the air temperature is typically never more than 2°C cooler than the ocean temperature. In the typical hurricane over the ocean the boundary layer air spirals isothermally to the central core region. A typical vertical wind profile for a weak hurricane at sea is shown in Fig. 33.

Conditions for the hurricane over land are very different. Air spiraling inward over land is denied the heat source typicaly of the ocean. The specific heat content of the land is less than that of the ocean. The land surface cannot be turbulently mixed as the ocean can. The inward spiraling air over land receives only a small energy input from the surface. Under these conditions the boundary layer air can no longer move towards lower pressure and maintain its temperature. As it moves inward it cools. The inner region lapse rates become stable and convection is suppressed. The storm begins to weaken. It is for this reason that hurricanes only form over water and quickly weaken when they move inland.

The cylindrical thermal wind equation with the origin at the vortex center and pressure as the vertical coordinate (Gray, 1967), may be written as:

$$\overset{\text{(Shear)}}{\underset{2\times10^{-6}}{\left(f+\frac{2u}{r}\right)\frac{\partial u}{\partial p}}} = \overset{\text{(Baroclinicity)}}{\underset{1.9\times10^{-6}}{-\frac{R}{p}\left(\frac{\partial T}{\partial r}\right)_p}} \overset{\text{(Friction)}}{\underset{10^{-7}}{-\frac{\partial F_r}{\partial p}}} \overset{\text{(Acceleration)}}{\underset{10^{-8}}{+\frac{\partial}{\partial p}\left(\frac{dv}{dt}\right)}}, \qquad (2)$$

Relative values for the tornado-hurricane over land.

where

f = Coriolis parameter
r = distance from the storm's center
R = gas constant for dry air
p = pressure
u = tangential wind
v = wind component along r
T = temperature
F_r = horizontal frictional acceleration along r

A low level cold core system will tend to develop a vertical wind profile with definite wind shear between the surface and 850 mb as shown in Fig. 33.

Role of Vertical Wind Shear. As thermal instability does not seem to be a dominant factor in tornado genesis, one must look to other physically relevant parameters. It appears that the most important meteorological influence in hurricane tornado genesis is the surface winds of but 15-20 knots in association with 850 mb winds of 50-60 knots. This leads to a very large wind shear between the surface and 850 mb of 40-45 knots. Figure 34 illustrates the low level wind speed profiles for storms which produce tornadoes and those which do not. Surface to 850 mb vertical shears as high as 70-80 knots have on occasion been observed. These are remarkably high wind shears for the lowest 1 1/2 km. Even intense frontal systems do not experience such intense low level shear. Figure 35 shows an extreme case of large low level vertical wind shear.

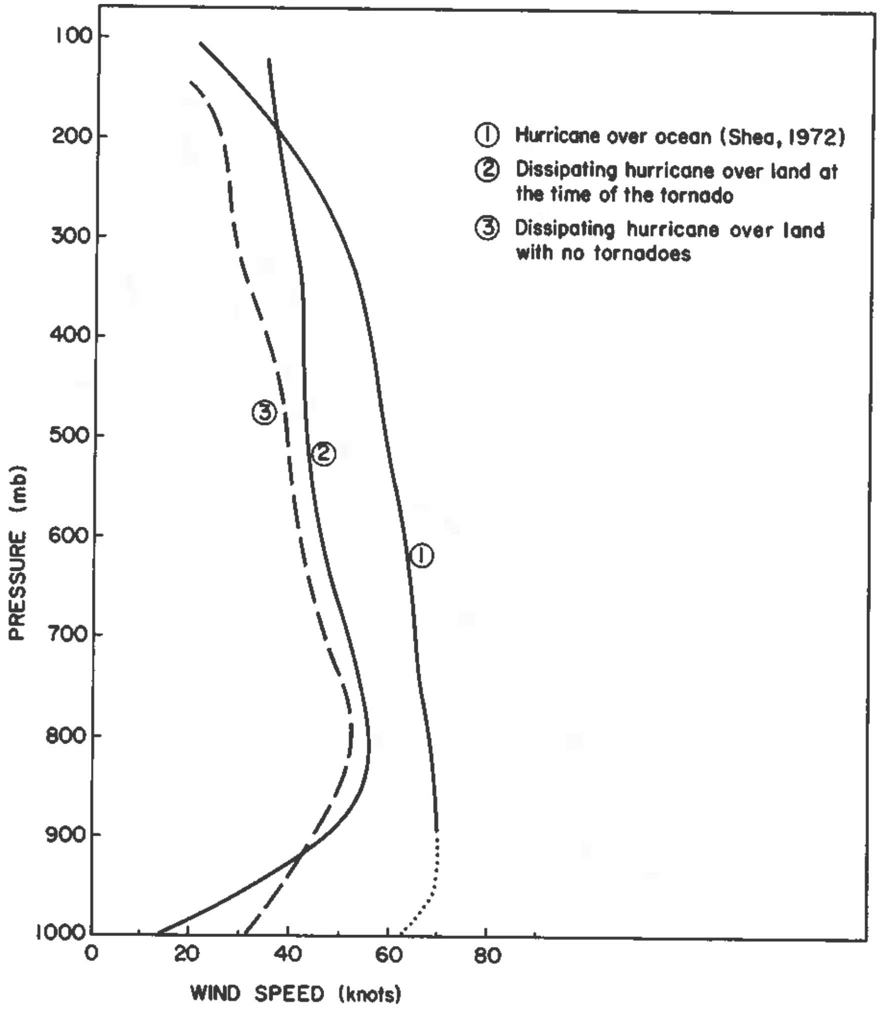

Fig. 33. Comparison of the right front quadrant vertical wind profiles at 30 n. mi. radius in the typical hurricane over the ocean with the vertical wind shears in the hurricane at 60 n. mi. radius over land for tornado and non-tornado cases.

The relative importance of the large low level vertical wind shear is probably to produce a large initial vorticity tendency ($10^{-4}/\text{sec}^2$) through the tilting term of the vorticity equation $\left(\frac{dw}{dx}\frac{dv}{dz} - \frac{dw}{dy}\frac{du}{dz}\right)$. In addition, it is quite likely that the strong upper level winds are effectively blocked by the updrafts (as discussed by Gray, 1969) and produce significant local horizontal convergence-divergence (i.e., the vorticity tendency comes through the divergence term). Both of

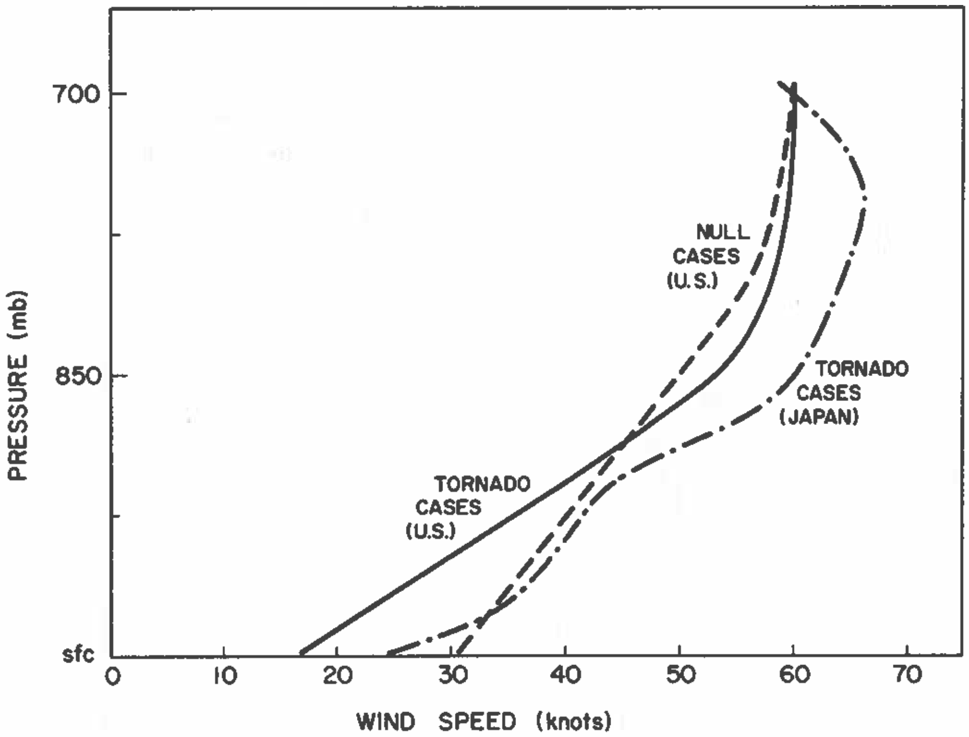

Fig. 34. Vertical wind profiles (right front quadrant) for hurricanes with and without tornadoes.

these hypotheses have yet to be established. Perhaps both mechanisms are at work to produce the large vorticity tendency as required for genesis in 15-20 minutes ($10^{-3}/\sec^{-2}$) (Gray, 1971). Recent investigations by Maddox (1973) suggest that these strong vertical wind shears aid in producing large localized horizontal wind shears in the boundary layer. We might speculate that in the hurricane tornado either through cumulus downdrafts or cumulus blockage of the 850 mb flow, winds of 50-60 kts at 850 mb are brought down to the surface where the environmental winds are but 10-20 kts. Large horizontal shears are produced. Maddox (1973) hypothesizes that these horizontal shears in turn produce a frictionally forced low level convergence

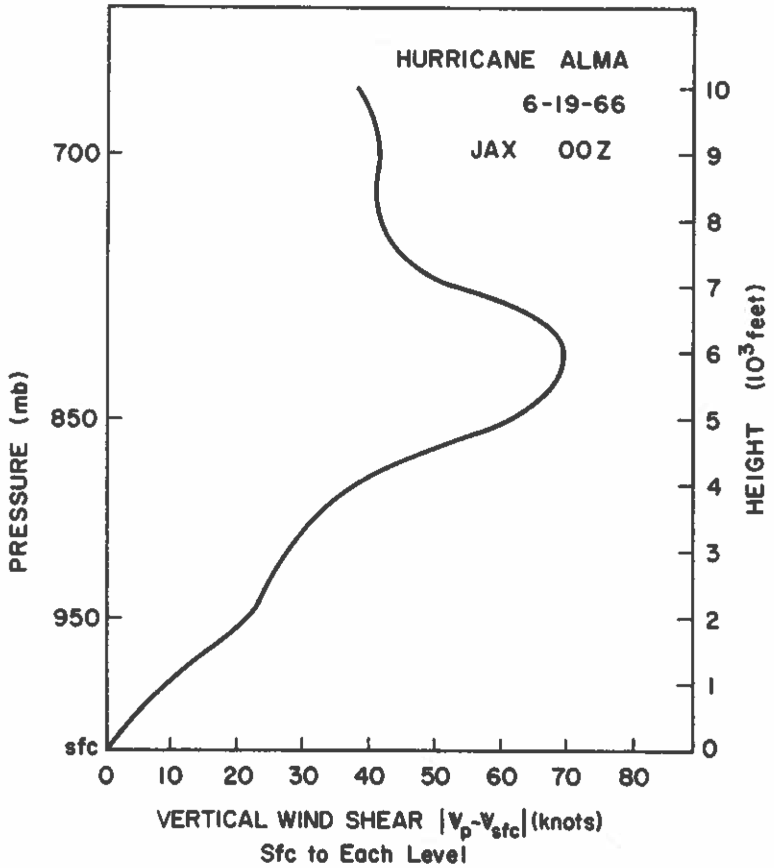

Fig. 35. Extreme vertical wind shear associated with the tornadoes in Hurricane Alma (1966). The magnitude of the vertical wind shear between any upper pressure level wind ($\mathbb{V}_p$) and the surface wind ($\mathbb{V}_{sfc}$) is shown.

due to Ekman type wind veering in a positive vorticity field. This convergence occurring in stable conditions can become very concentrated and intense. From angular momentum considerations, very rapid and intense small scale velocity concentrations result.

Hurricane tornadoes are often observed to be associated with the strongest convective elements on the active outer rainbands (Hill *et al.* 1966; Fujita, 1972). Often several tornadoes will occur on the same rainband (hurricane squall line). These rainbands are preferred areas for tornado development as the environmental values of convergence and vorticity gradients are typically strongest in their vicinity.

Right Front Quadrant. It is interesting to speculate why hurricane induced tornadoes are found most abundantly in the right front quadrant of the hurricane. Kellerstrass (1962) attributed this to the fact that the right front quadrant of the storm is more moist and unstable. Yet as mentioned previously, instability values are never very large and do not appear to play a dominant role.

It is the author's belief that the right front quadrant favors tornado development because this quadrant has the highest vertical wind shears and has also been shown by Riehl (1954) and B. I. Miller (1966) to contain the maximum low level convergence. It has the strongest convective activity. Figure 36 shows the largest vertical wind shears are present in the right front quadrant in comparison with the other storm quadrants. Wind shear is plotted relative to the surface wind.

As shown earlier in Fig. 11, hurricane tornadoes can often occur when the storm center is off shore and the right front quadrant spiral bands come on shore.

Conclusion. As hurricanes dissipate rapidly over land, they become cold core systems in the boundary layer first and develop large vertical wind shears (SFC-850 mb). This shear is strongest ($\geq$ 40 kts) where the baroclinicity is very concentrated for dying storms. These vertical shears may help establish large low level horizontal shears to produce the vorticity required for tornadoes.

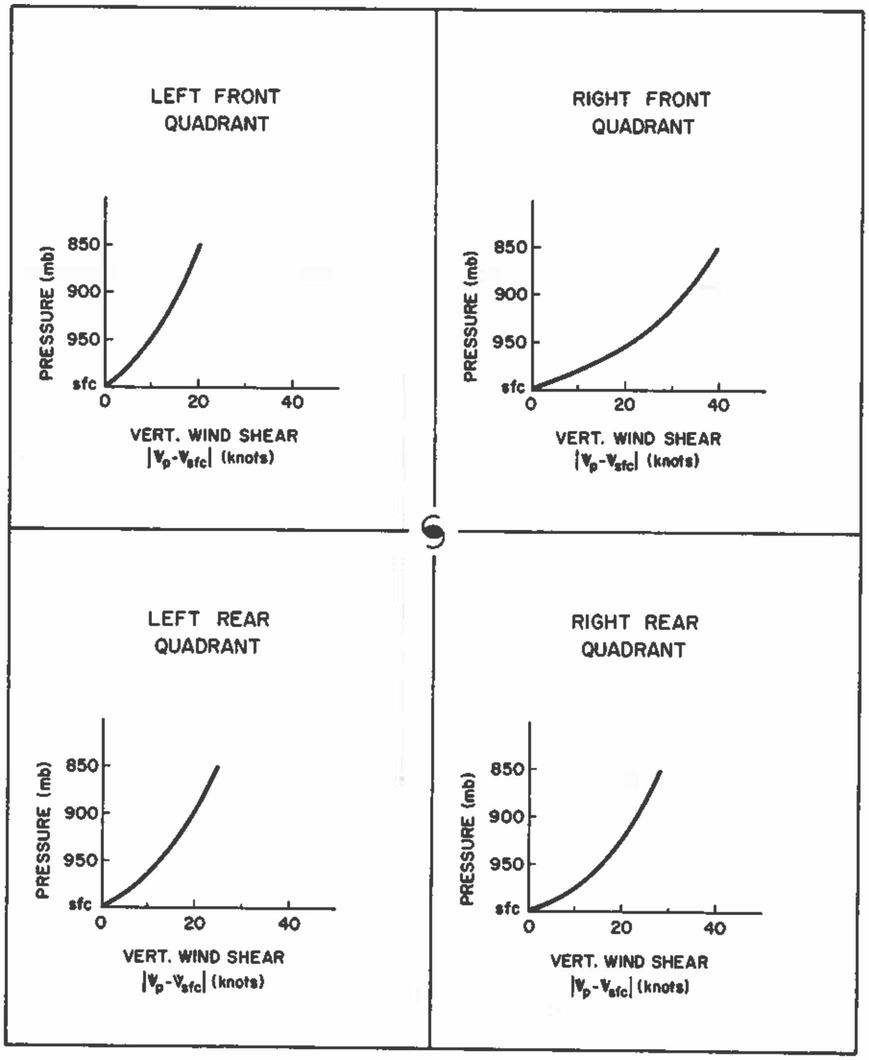

Fig. 36. Vertical wind shear by quadrants in hurricanes with tornadoes (at a radius of 100 n. mi. from the hurricane center). The magnitude of the vertical wind shear between any upper level wind ($\mathbb{V}_{p}$) and the surface wind ($\mathbb{V}_{sfc}$) is shown.

V. OTHER CHARACTERISTICS

Dry Air Intrusions. A notable thermodynamic feature associated with large family outbreaks of tornadoes (Audrey, 1957; Carla, 1961; Hilda, 1964; Beulah, 1967) has been the presence of pronounced dry air in the storm's right rear quadrant between 850 mb to 700 mb. Hill et al. (1966) and Grice (1967) have also made special mention of this middle level dry air. Grice's study of Beulah (1967) attributes the record tornado outbreak as primarily due to the presence of dry air between 850 mb to 700 mb and its advection into the right front quadrant. Figure 37 shows the Lake Charles, Louisiana sounding 200 miles from the storm center in the right rear quadrant during the time Beulah spawned some of her tornadoes over Texas. Both the actual moisture values for LCH along with a normal September LCH moisture sounding are shown. Note the pronounced middle level drying. The question of whether this middle level dry air is actually advected into the right front quadrant and is a major contributing feature to the tornado family outbreaks is open to further investigation. The mean soundings of the right front quadrant indicate that dry air advection is not a common characteristics of most hurricane tornado storms.

This pronounced drying was probably a result of the periphery substance from the hurricane itself and, as such, was not an independent environmental feature. It could, nevertheless, have had a feed-back influence.

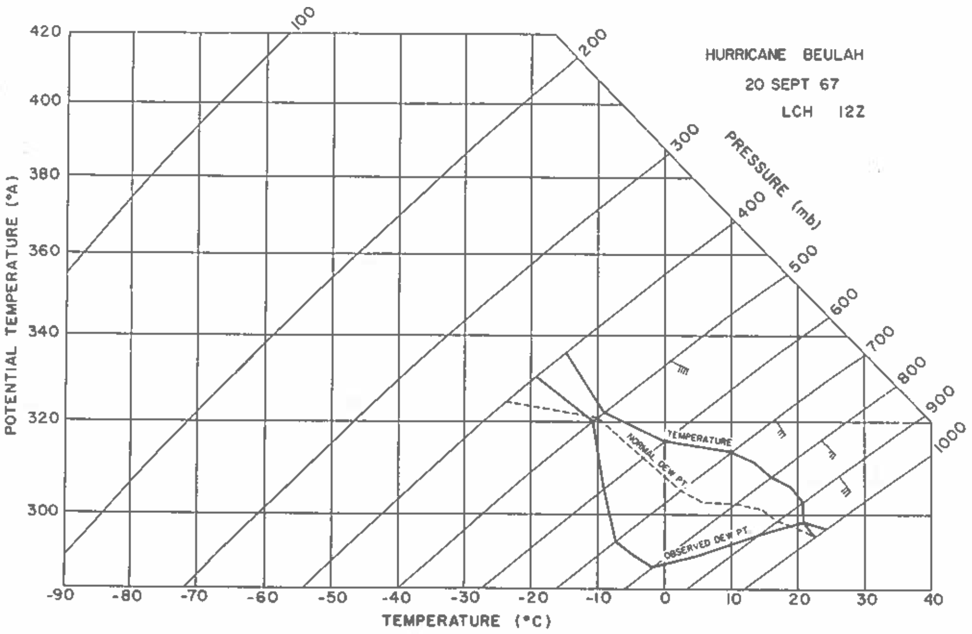

Fig. 37. Lake Charles sounding of 20 Sept 67 - right rear quadrant of Beulah.

Hurricane Donna (1960). One very notable exception to the conditions for hurricane spawned tornadoes was Hurricane Donna when she crossed over Southwest Florida. Despite the fact that she filled at the rate of about 20 mb per day and had 70 knots of vertical wind shear between the surface and 850 mb over Miami on September 9 (see Fig. 38), there were no tornado reports. The only Donna tornadoes reported were in North and South Carolina.

Donna was an extremely intense hurricane and caused a large population evacuation along with severe damage to communication facilities. This may explain that even if Donna did spawn tornadoes in Florida, they were not observed or not reported. There were, however, unusual small scale damage effects on the vegetation of the Everglades, (Dunn, 1961). Also, the possiblity remains that Donna spawned waterspouts at sea. Waterspouts may have occurred due to Donna's trajectory inland over southern Florida causing a large portion of the right front quadrant to be over the ocean. Nevertheless, despite the fact that Donna had filled rapidly while crossing Florida and had developed a cold core at the surface with large vertical wind shear, she remained quite unique in that her overall organization remained intact over Florida.

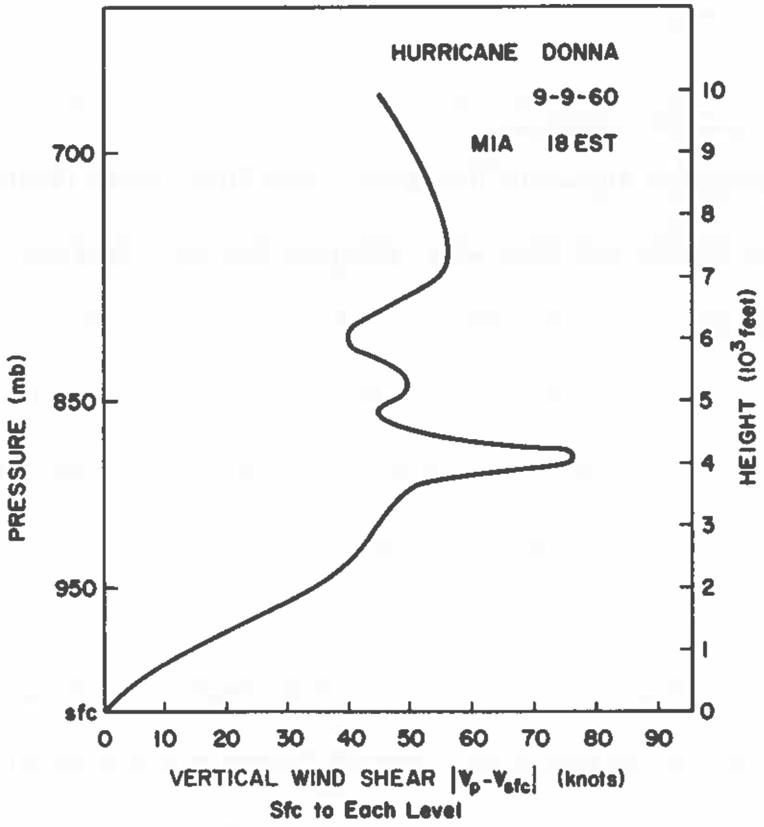

Fig. 38. Vertical wind shear profile over Miami in Donna (1960). The magnitude of the vertical wind shear between any upper level wind ($\mathbb{V}_p$) and the surface wind ($\mathbb{V}_{sfc}$) is shown.

VI. FORECASTING APPLICATIONS

On Duty Forecasting Aids. Better forecasting of hurricane tornadoes might help reduce the 10% total hurricane fatality figure. Several methods are evident which can aid the operational forecaster:

(1) The rate of hurricane filling should be determined from monitoring the teletype reports of sea level pressure from inland stations (particularly those stations close to the center) or by observing the sharpness and apparent intensity of the eye wall clouds on radar. Stations near the center should be required to report their sea level pressure, temperature, and wind every 30 minutes rather than every hour.

(2) Particular attention should be paid to the radar echoes of active squall lines (particularly the outer rainbands) which have strong convective cells. Several tornadoes may occur along one band.

(3) Special pibals could be taken as the hurricane moves inland or if the station is not equipped for pibals, the observer should be required to give an estimate of the wind velocity at cloud base height in his hourly Service A observation, particularly in areas showing surface winds of only 15-20 knots. Areas of strong convection with weak surface winds and fast low level cloud motion are very likely regions for tornado genesis.

(4) Significant dry air intrusions located in the right rear quadrant of the hurricane at 850-700 mb may serve as indicators for potential tornado "family" outbreaks.

(5) A tornado bearing hurricane will rapidly develop a cold core at the surface while still maintaining a warm core at the 850 mb level. A surface temperature map could be plotted from the teletype observations on an hourly or half hourly basis. Tornadoes should be forecast when the inner storm surface temperatures show significant cooling. In the average case of reported tornadoes the storm center temperature was 6°C colder than the temperature at 100 n. mi. from the center.

Practical Rule of Thumb. The theory presented in this paper might lend itself to applications on the layman's level. A practical rule of thumb for the public might be stated as follows: When a hurricane moves inland and starts to decay, persons located particularly in the right front section of the storm should be observant for surface winds of 15-20 mph while overhead the low level clouds appear to be moving with much greater velocities. These conditions signify tornado potential in the regions where cumulus convection is occurring.

Table 5 sums up these findings in a forecast work sheet.

Table 5

Hurricane-Tornado Forecast Work Sheet.

	Tornadoes Likely	Tornadoes Not Likely
1.	Intense hurricanes or those tropical cyclones increasing in intensity just before landfall.	Weak hurricanes or filling tendency just before landfall.
2.	After hitting land hurricanes fill at the rate of greater than 30 mb/12 hr.	After hitting land, hurricanes fill at the rate of less than 10 mb/12 hrs.
3.	Once on shore the center rapidly cools and becomes $6^{\circ}C$ colder than temperatures 100 n. mi. out from the storm center.	Only small central storm cooling.
4.	Vertical wind shear profiles surface to 5000 feet of 40 kts or more. Surface winds of only 15-20 knots.	Surface to 850 mb wind shears are less than 40 knots.

Recommended Tornado Watch Area

General area: Surface pressure is between 1004 to 1012 mb.

Specific area: Areas of vertical wind shear greater than 40 kts from the surface to 850 mb. Surface winds 15-20 kts.

Specific area: Within the "preferred sector": 60-250 n. mi. from the center of the hurricane and at an azimuthal range of 0° to 120° WITH RESPECT TO TRUE NORTH.

Specific area: Along strong radar observed rainbands, particularly the outer rainbands.

Begin Tornado Watch: When the center is 100-150 n. mi. off shore and the first rainbands start to come on shore.

Table 5 (cont'd)

Recommended Tornado Watch Area

End Tornado Watch/Warning:	When the rainbands begin to break up and the vertical wind shear (sfc-850 mb) falls below 40 knots.

Note: Significant dry air intrusions in the right rear quadrant indicate a potential for tornado "family" outbreaks.

VII. CONCLUSION

Hurricane spawned tornadoes are closely related to the presence of very strong low level vertical wind shear. In general, buoyant instability does not appear to play a major role in their formation. Thus the dynamic components appear to dominate over the thermodynamic ones. Hurricanes that come on shore and fill rapidly develop a surface cold core which establishes large low level vertical wind shear. This vertical wind shear is indespensible to the genesis mechanism. Cumulus downdrafts which occur with it help develop local areas of strong low level horizontal wind shear, which, from boundary layer frictional convergence arguments leads to intense small scale convergence, spin, and velocity concentration.

This study has offered a new observational look at hurricane spawned tornadoes that will hopefully prove useful in understanding and forecasting these storms.

ACKNOWLEDGEMENTS

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REFERENCES

Dunn, G. E., (1961): Hurricane season of 1960. Mon. Wea. Rev., 3, 89, 99-108.

Fendell, F. E. and G. F. Carrier, (1971): The decay of a tropical cyclone at sea and over land, tornado and hurricane thermo-hydrodynamics. Report prepared for U. S. Dept. of Commerce NOAA Environmental Research Laboratory, 48 pp.

Fujita, T. T., K. Watanabe, K. Tsuchiya, and M. Shimada, (1972): Typhoon-associated tornadoes in Japan and new evidence of suction vorticies in a tornado near Tokyo. J. of Meteor. Soc. of Japan.

Goldstein, M. G., (1968): Differential advection associated with tornadoes of tropical cyclone origin. M. S. Thesis, New York Univ., 32 pp.

Gray, W. M., (1967): Global view of the origin of tropical distrubances and storms. Mon. Wea. Rev., 10, 96, 669-700.

____________, (1969): Hypothesized importance of vertical wind shear in tornado genesis. Sixth Conference on Severe Local Storms, Chicago, Illinois.

____________, (1971): Research methodology, observations and ideas on tornado genesis. Seventh Conference on Severe Local Storms, Kansas City, Mo.

Grice, G. K., J. R. Scoggins, and R. A. Clark, (1967): An investigation of the tornadoes associated with hurricane Beulah. 26 pp.

Hill, E. L., W. Malkin, and W. A. Schulz, (1966): Tornadoes associated with cyclones of tropical origin--practical features. J. of Appl. Meteor., 5, 745-763.

Kellerstrass, E. J., (1962): Hurricane spawned tornadoes: A case study of Carla, September 11-13, 1961. M. S. Thesis, St. Louis University.

Maddox, R. A., and W. M. Gray, (1973): A frictionally driven model for tornado genesis with similarities to hurricane genesis. To be presented at the Eighth Conference on Severe Local Storms, Oct. 1973.

REFERENCES (cont'd)

Malkin, W., and J. G. Galway, (1953): Tornadoes associated with hurricanes. Mon. Wea. Rev., 81, 299-303.

Miller, B. I., (1958): The three-dimensional wind structure around a tropical cyclone. National Hurricane Research Project Report No. 15, 44 pp.

Orton, R., (1970): Tornadoes associated with Hurricane Beulah on September 19-23, 1967. Mon. Wea. Rev., 98, 541-547.

Pearson, A. D. and A. F. Sadowski, (1965): Hurricane induced tornadoes and their distribution. Mon. Wea. Rev., 93, 461-464.

Priestly, C. H., (1960): The evolution of energy gain by the atmosphere through contact with the ground or ocean in Studies in Weather Analysis and Forecasting. Severre Petterson, Air Force Cambridge Research Center - TR - 60232.

Riehl, H., (1954): Tropical Meteorology, McGraw-Hill Book Company, 392 pp.

Rudd, M. I., (1964): Tornadoes during hurricane Carla at Galveston. Mon. Wea. Rev., 92, 251-254.

Shea, D. J., (1972): The structure and dynamics of the hurricane's inner core region. Dept. of Atmos. Sci., Colo. State Univ., Res. Paper No. 182, 132 pp.

Smith, J. S., (1965): The hurricane-tornado. Mon. Wea. Rev., 93, 453-459.

Wills, T., (1969): Characteristics of the tornado environment as deduced from proximity soundings. Sixth Conference on Severe Local Storms, 8-10 April, Chicago, Illinois.

APPENDIX I*

Hurricane-Tornado Damage-Death Table

Year	Name	Damage 10^6 Dollars		Deaths	
		Hurr.	Tornado	Hurr.	Tornado
1948	Sep 21	12	.004		
1948	Oct 5	5	.2	42	0
1949	Aug	52	.2		
1950	Baker	3	.04	1	0
1952	Able	3	.06		
1953	Hazel	.3	.003		
1956	Flossy	25	.2	15	0
1957	Audrey	150	.8	390	20
1959	Cindy	.1	.65	1	0
1959	Gracie	14	.01	22	0
1959	Debra	7	.02	7	0
1960	Ethel	1	.05	0	0
1961	Carla	325	.41	41	14
1964	Isbell			6	0
1964	Hilda	100	5	38	22
1964	Dora			5	0
1964	Cleo			3	0
1965	Betsy	1420	11	75	0
1966	Inez			100	0
1967	Beulah	200	3	15	5
1968	Gladys			5	0
1968	Candy			0	0
1968	Abby			6	0
1970	Becky			0	0
1970	Celia			16	7
1971	Fern			0	0
1971	Edith			28	0
1971	Doria			0	0
1972	Agnes	3000	5	118	6
TOTAL		5305	26.6	934	95
			.5%		9.8%

* This represents the best possible estimate considering incomplete and missing data and different values quoted by different sources.