Hurricane-Spawned Tornadoes

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ABSTRACT

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 tornadoes.

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 appears to be required for tornado formation. It should be used as a forecast tool in hurricane tornado prediction.

1. Introduction

In this study, an updated climatology of hurricane tornadoes is presented from information gathered for United States 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 (NOAA storm data reports) than 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. In some cases the tornadoes account for most of the deaths.

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 vortices.

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. Goldstein (1968) discussed hurricane genesis in terms of differential temperature advection.

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.

2. Climatology

Table 1 lists all the hurricanes and tropical storms during the period from 1948 to 1972 that have come onshore in the United States. Of these 83 United States hurricanes and tropical storms, 25% spawned tornadoes (a total of 373). Hurricane Beulah (1967) had 141 tornadoes, accounting for 38% of all hurricane tornadoes. Excluding Beulah, the average hurricane which spawned tornadoes had ten. These tornadoes have

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TABLE 1. U. S. hurricanes with/without tornadoes. (Also see Hill *et al.*, 1966, for more detail on individual tornadoes.)

Hurricane name	Month	Year	Number tornadoes	% of tornadoes
Agnes	Jun	1972	17	5.4
Beth	Aug	1971	0	0
Doria	Aug	1971	1	0.3
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	0.3
Alma	May	1970	0	0
Greta	Oct	1970	0	0
Camille	Aug	1969	1	0.3
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	0.8
Beulah	Sep	1967	141	38.4
Doria	Sep	1967	0	0
Alma	Jun	1966	9	2.4
Inez	Oct	1966	1	0.3
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	0.5
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
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	0.3
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	0.3
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	0.3
Alice	Jun	1953	0	0
Florence	Sep	1953	0	0
Barbara	Aug	1953	0	0
Able	Sep	1952	3	0.8
How	Oct	1951	0	0
Baker	Aug	1950	2	0.5
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	Jul	1948	0	0
Unnamed	Sep	1948	2	0.5
Unnamed	Sep	1948	1	0.3
Unnamed	Oct	1948	2	0.5

occurred from May through October but most frequently in September. Note that very few hurricane tornadoes were reported until the middle 1950s.

Table 2 (Fujita *et al.*, 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 those for United States hurricanes.

TABLE 2. Japanese typhoons with tornadoes (summarized from Fujita *et al.*, 1972).

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

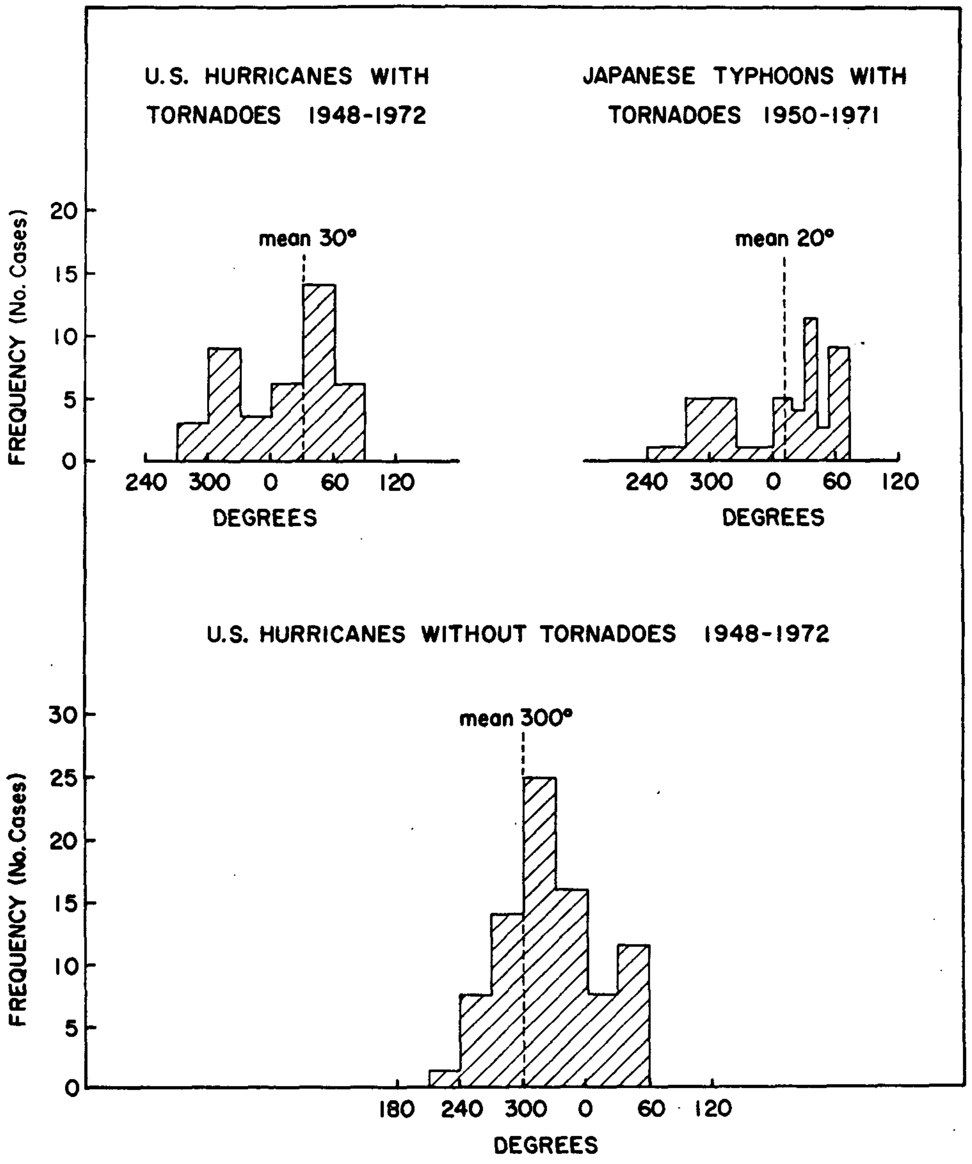

FIG. 1. Frequency diagrams of storm direction (in degrees) at landfall for U. S. hurricanes *with* and *without* tornadoes (1948–1972) and Japanese typhoons *with* tornadoes (1950–1971).

a. Tornadoes relative to hurricane direction

Most hurricane-typhoon tornadoes occur close to the time the storms cross land. Figure 1 is a histogram of hurricane and typhoon direction frequency at 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 United States cases. There were, however, 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.

b. Preferred sector of the hurricane

Figure 2 composites all the United States tornadoes in a plan view display with respect to true north and distance from the center of the hurricane in nautical miles. Orton (1970) has shown that a frame of reference with respect to true north was superior to one with

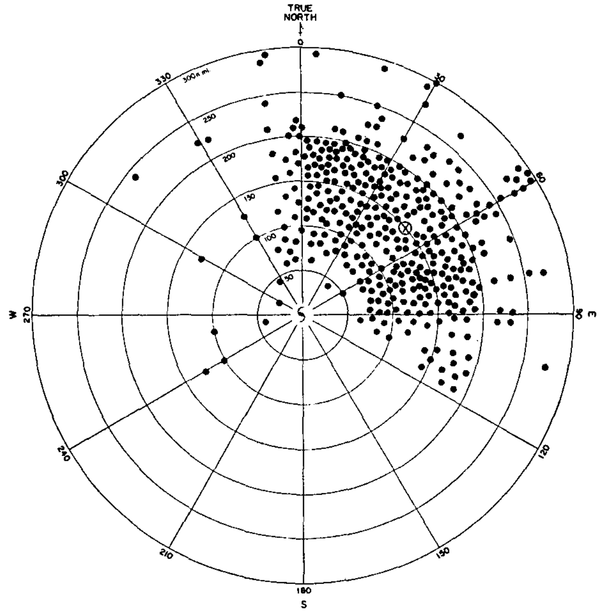

Fig. 2. Plan view display of 373 U. S. hurricane tornadoes (1948–1972) with respect to the hurricane center (S) and true north. The symbol ⊗ refers to the centroid of all cases, located at 50° azimuth, 150 n mi from the hurricane center.

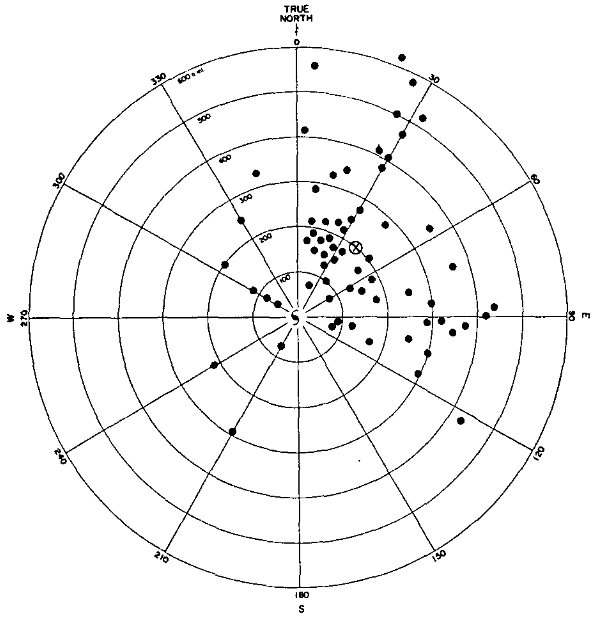

Fig. 3. Plan view display of 68 Japanese typhoon tornadoes (1950–1971) (Fujita *et al.*, 1972) with respect to the typhoon center and true north. The symbol ⊗ refers to the centroid of all cases, located at 40° azimuth, 200 n mi from the center of the typhoon.

respect to the directional heading of the hurricane. It can clearly be seen that there is indeed a preferred sector for hurricane tornadoes from 350° to 120° azimuth and 60–250 n mi out from the storm center (centroid point of 50°, 150 n mi). Figure 3, 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 4 is a composite of the United States tornadoes with respect to direction of cyclone 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. Hill *et al.* (1966) have also shown this. 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.

c. Time of day, hurricane speed, and distance from shore

Fujita *et al.* (1972) have noted a six-hour oscillation period for typhoon tornadoes and have 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 factor fundamental to understanding these vortices. Hurricane tornadoes can occur at any hour with a weak frequency peak around 1100 LST. Speed of the hurricane is likewise not a significant feature. Hurricanes

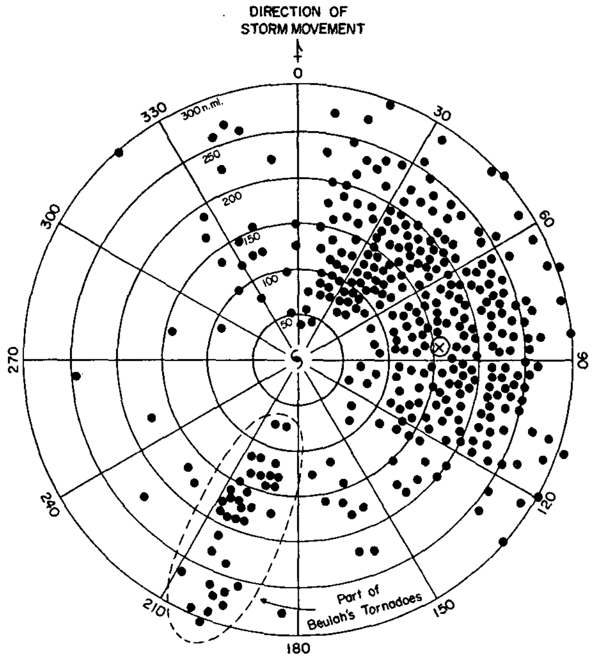

Fig. 4. Plan view of 373 U. S. hurricane tornadoes (1948–1972) with respect to the hurricane center and its direction of motion. The symbol ⊗ is the centroid point of all tornadoes, located at 80° azimuth, 150 n mi from the hurricane center.

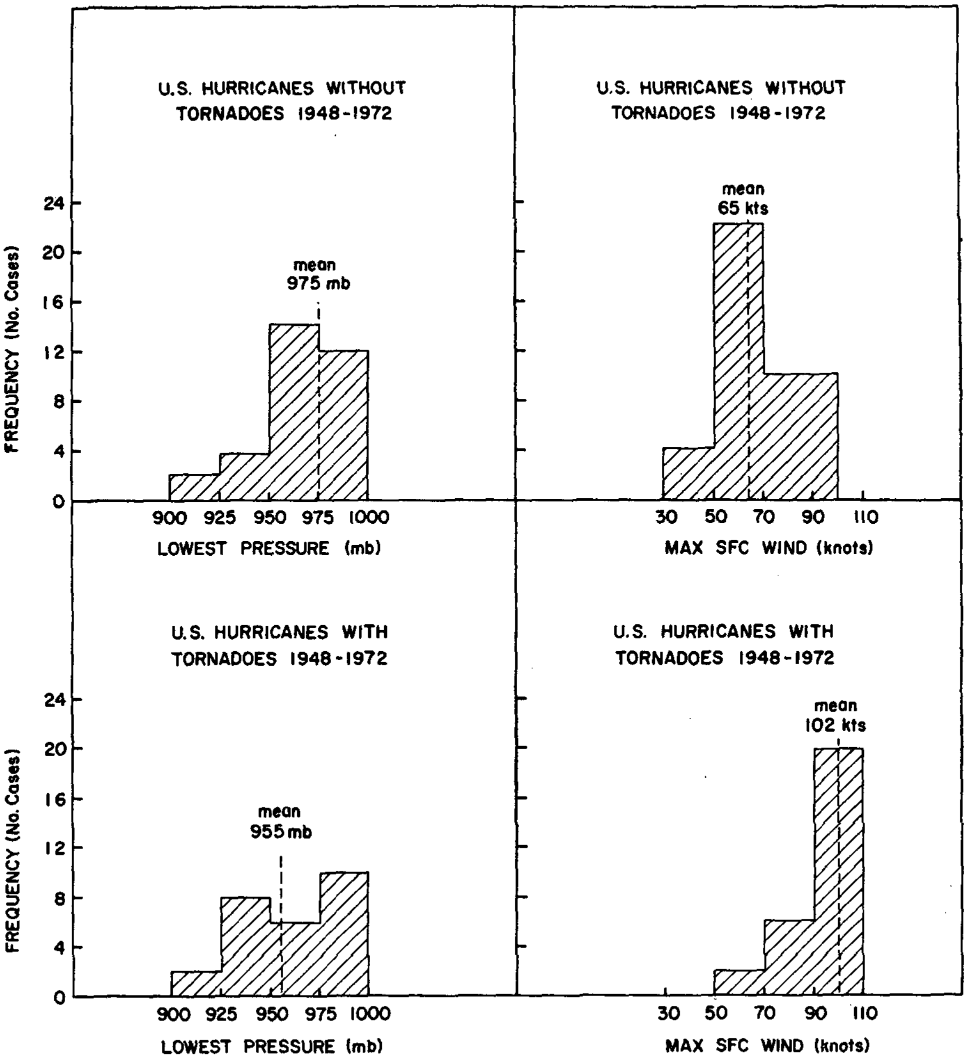

FIG. 5. A comparison of maximum surface winds and lowest sea level pressures for hurricanes *with* and *without* tornadoes at landfall. Mean values are indicated on each histogram.

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

d. 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) have 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 vortices. This study has verified Hill *et al.* findings. There appears to be a direct relationship between tropical cyclone intensity and tornado incidents. Figure 5 indicates that hurricanes with lower pressures and/or stronger maximum surface winds at landfall are more likely to produce tornadoes than other storms.

e. Tornado location inland

Figure 6 shows that the majority of hurricane-induced tornadoes were located on land within 100 n mi of shore. This demonstrates, as will be shown later, that tornadoes occur when the hurricane undergoes rapid dissipation as it first comes on shore.

f. Summary

Hurricane tornadoes are typically generated in the right front quadrant of the cyclone. They are directly related to the storm intensity as it strikes land. The

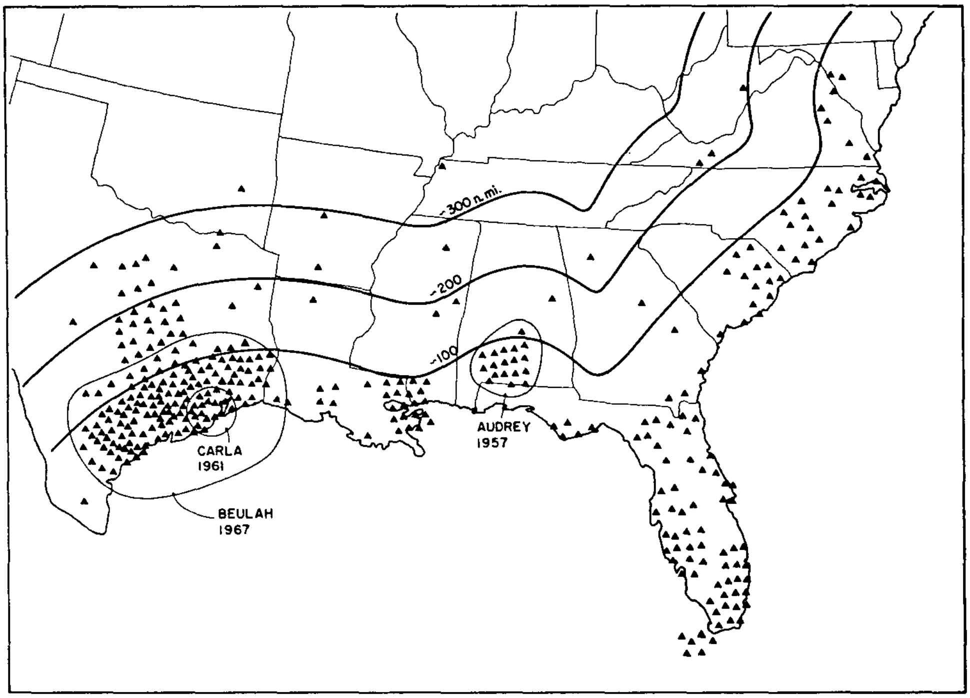

Fig. 6. Geographical distribution of hurricane tornadoes 1948–1972.

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 surface pressure of 1009 mb and at the time when the hurricane's center is 50 n mi inland.

3. 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. This criterion is not very restrictive, but was necessary to obtain a sufficiently large data sample. Seventy-five non-tornado or null-case soundings were selectively paired with the tornado ones, matching as closely as possible the same storm track, storm trajectory, distance from the storm center, and azimuth angle.

a. Vertical wind shear

A remarkable fact about tropical storm-spawned tornadoes is that while winds 4000–5000 ft above the surface average 55 kt and greater, the surface winds are relatively light, averaging only about 15–20 kt (Wills, 1969).

Figure 7 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 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 United States 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 4.

The maximum vertical wind shear in the Japanese cases is at a level about 2000 ft higher than in the United States vortices. This may be due to the greater topography of Japan. This difference is not felt to be physically significant.

Figures 8–15 result from compositing data in all the hurricane quadrants for both tornado and non-tornado hurricanes separately (United States cases 1948–1972). Note in Figs. 8 and 14 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. 7 (40-kt shear between the surface and 5000 ft), the cylindrical thermal wind equation requires the establishment of a cyclone center temperature between the surface and 850 mb which is ≈ 8C colder than the ambient air temperature 100 n mi out from

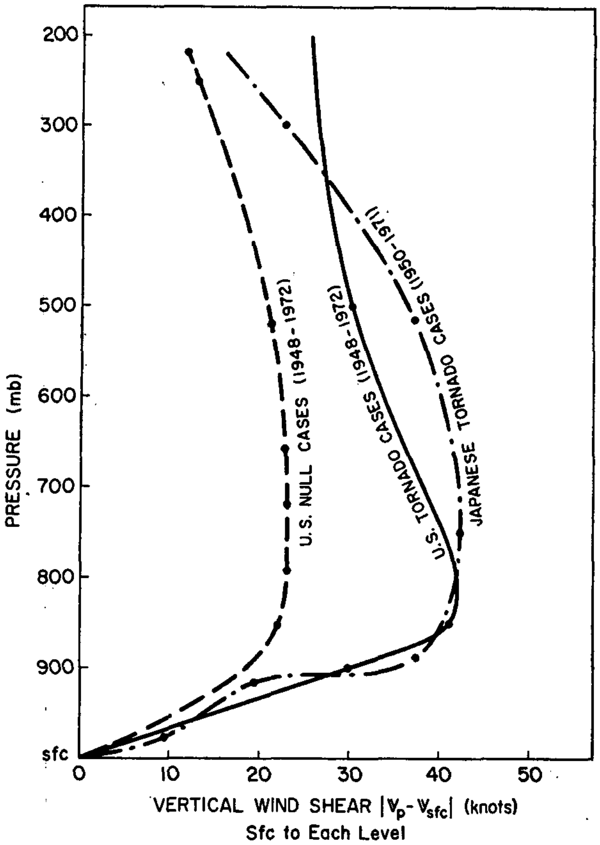

FIG. 7. Proximity vertical wind shear profiles for hurricane and typhoon tornadoes and right front quadrant wind shears for U. S. hurricanes *without* tornadoes. $V_p - V_{sfc}$ gives the magnitude of the vertical wind shear between any pressure level wind (V_p) and the surface wind (V_{sfc}).

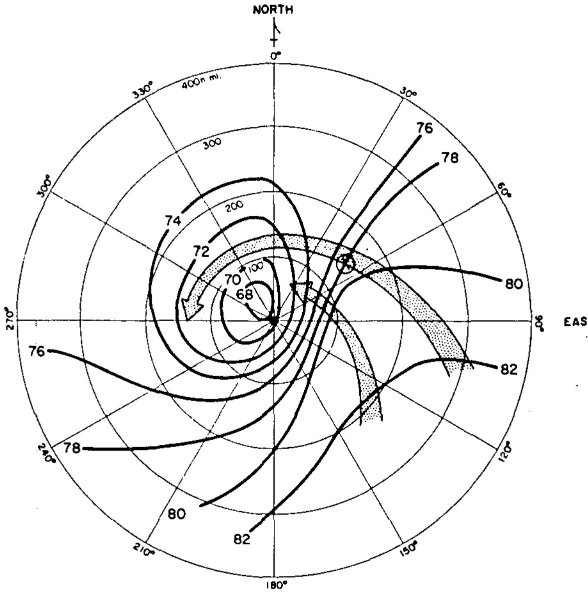

FIG. 8. Hurricane-centered plan view of U. S. hurricane *with* tornadoes. Surface temperature in °F. Note air spiraling toward a cold core. Compare with Fig. 9. The symbol ⊗ is centroid point for all tornadoes.

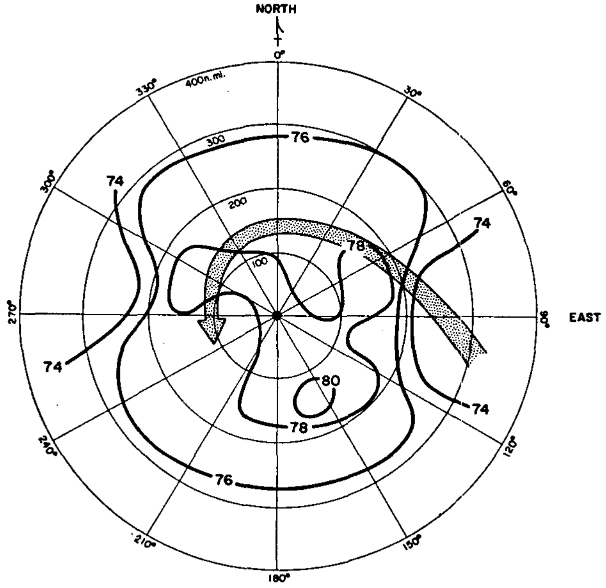

FIG. 9. Plan view of U. S. hurricanes *without* tornadoes. Surface temperature in °F. Note the warm center area in comparison with Fig. 8.

the center. Figure 8 shows that the observed temperature data approximately support this contention. Observed cyclone center surface temperatures average 6C colder than do the temperatures 100 n mi out from the center. The 850-mb temperature difference is less than is required. Nevertheless, the surface to 850-mb inner core cooling is well substantiated.

Figures 10–13 portray the available inner cyclone surface and 850-mb winds for hurricanes with and

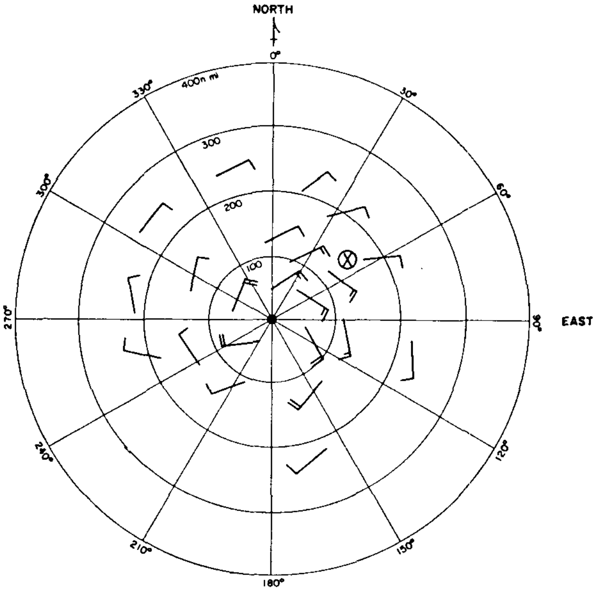

FIG. 10. Hurricane centered plan view of hurricanes *with* tornadoes. Averaged surface winds (knots). Note how weak the winds are around the centroid point for all tornadoes (⊗).

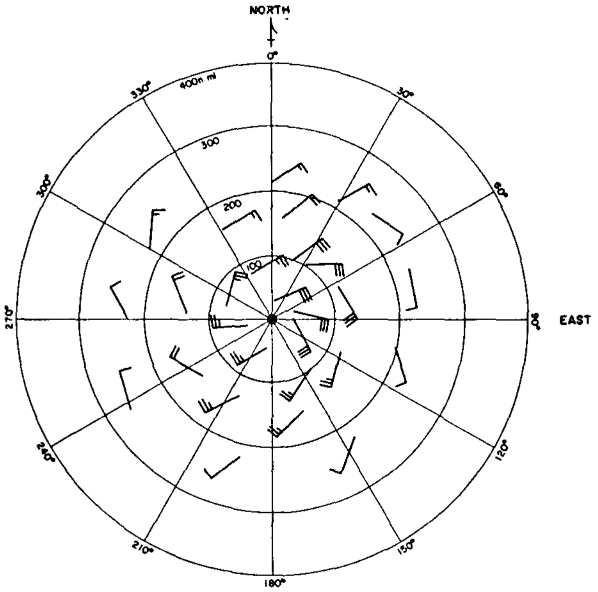

FIG. 11. U. S. hurricanes *without* tornadoes. Averaged surface wind (knots). Hurricane centered. Note that in the right front quadrant, 150 n mi out from the center, the winds are twice as high as the winds in Fig. 10.

without tornadoes. It is seen that hurricanes with tornadoes have substantially weaker surface winds. By contrast, the tornado and non-tornado 850-mb winds show no noticeable velocity difference. It is clear that the surface to 850-mb wind shear is significantly larger for the tornado cases. Figures 14–15 contrast the inner 850-mb temperature for the tornado and non-tornado cases. As expected, a more distinctive central core warming is observed in the non-tornado cases.

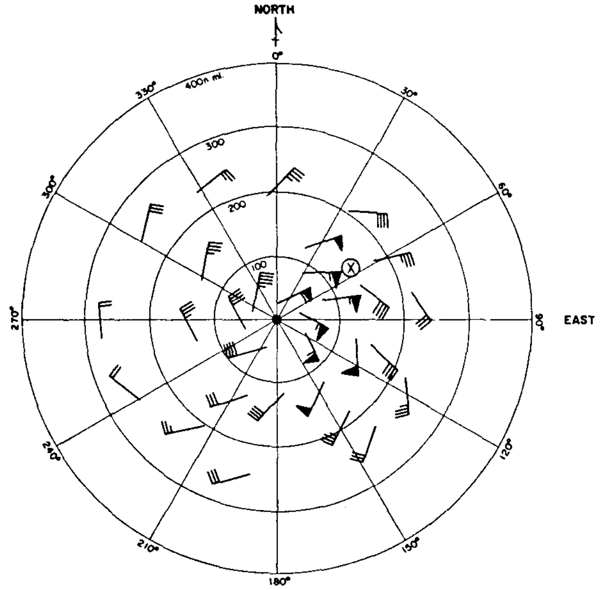

FIG. 12. U. S. hurricanes *with* tornadoes. Averaged 850-mb winds (knots). Hurricane centered. The symbol ⊗ is the centroid of all tornadoes.

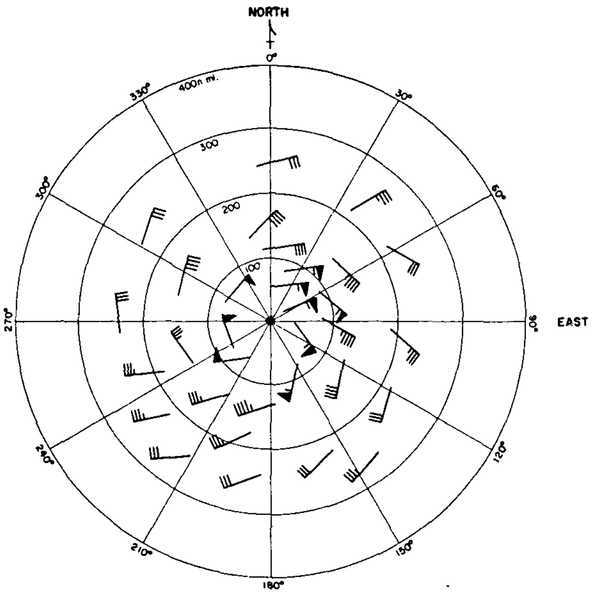

FIG. 13. Plan view of U. S. hurricanes *without* tornadoes. Averaged 850-mb winds (knots). Hurricane centered. Note the similarity to Fig. 12.

b. Filling rates

Figure 16 shows the very important result that hurricanes having tornadoes fill about three times as fast (average 30 mb/12 hr), as they undergo dissipation over land, as do the non-tornado hurricanes (average 10 mb/12 hr). Japanese typhoon cases that had tornadoes also were observed to fill, on the average, 30 mb/12 hr. This result agrees with the plan views in Figs. 8–15. Hurricanes that fill the fastest develop the

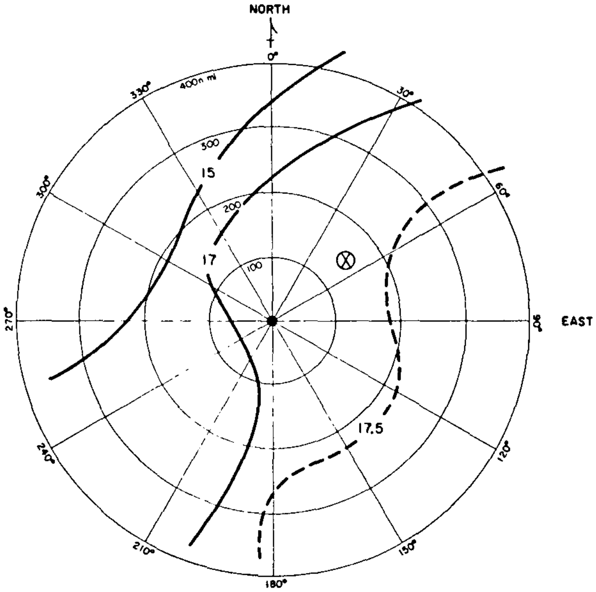

FIG. 14. Plan view of U. S. hurricanes *with* tornadoes; 850-mb temperature in °C. Hurricane centered. The symbol ⊗ is the centroid of all tornadoes.

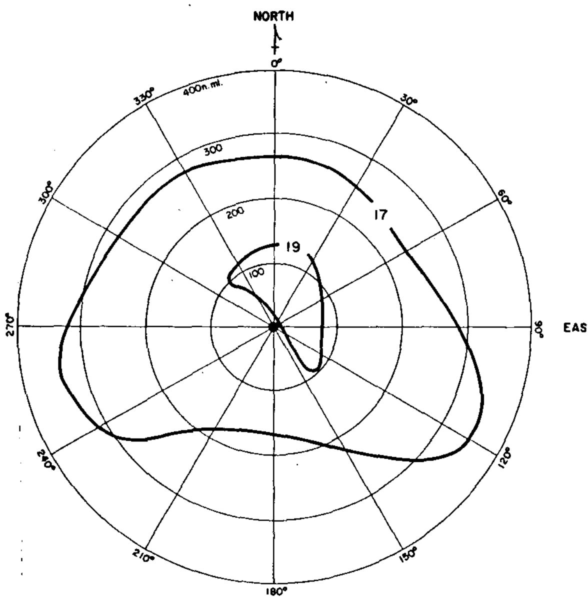

FIG. 15. Plan view of U. S. hurricanes *without* tornadoes; 850-mb temperature in °C. Hurricane centered.

most intense cold-core structure and produce the largest vertical wind shear (see Fig. 7). On the other hand, a slowly filling hurricane will not develop a strong low-level cold-core structure and intense vertical wind shear pattern.

c. 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 10° from the surface to 850 mb and 33° from the surface to 500 mb (Fig. 17). 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 and 500 mb, respectively (Fig. 18).

d. 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 19 shows that the tornado cases are actually a little more stable on the average than the null cases. Note the similarity of the United States and Japanese cases. Again note the agreement between the United States and Japanese tornado cases. The null cases were slightly more unstable than the tornado cases on the average. This inverse relationship of tornadoes and thermal instability was unexpected. This again emphasizes that tornado genesis cannot be explained by thermal stability arguments alone.

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.

e. Comparison between Great Plains and hurricane tornadoes

As shown in Figs. 17 and 18, both the Great Plains and hurricane tornadoes exhibit large lower-tropo-

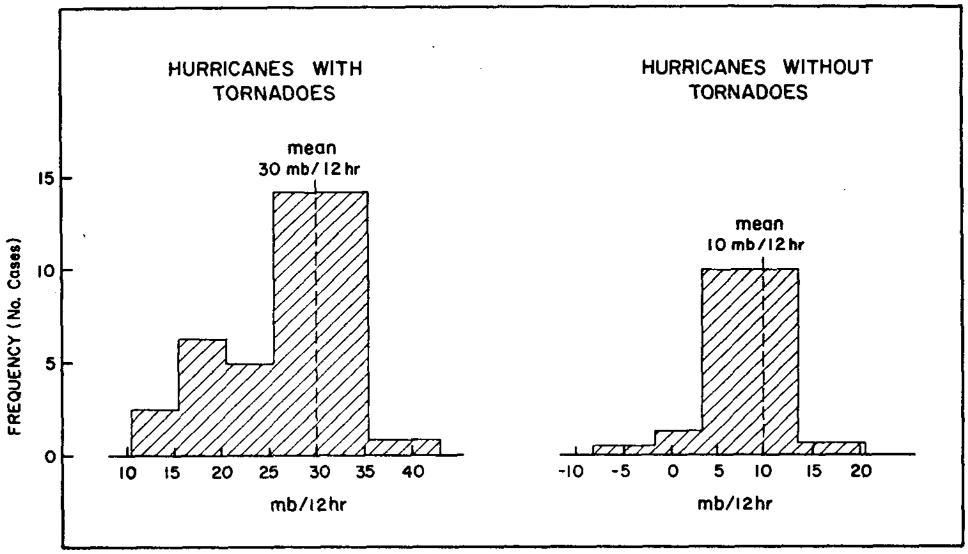

FIG. 16. Filling rates (mb/12 hr) for hurricanes with tornadoes in contrast with hurricanes *without* tornadoes.

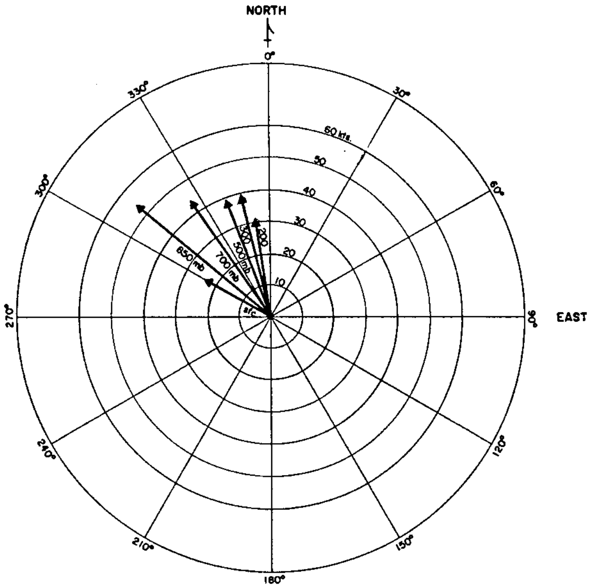

FIG. 17. Typical hodograph for proximity soundings of hurricane spawned tornadoes.

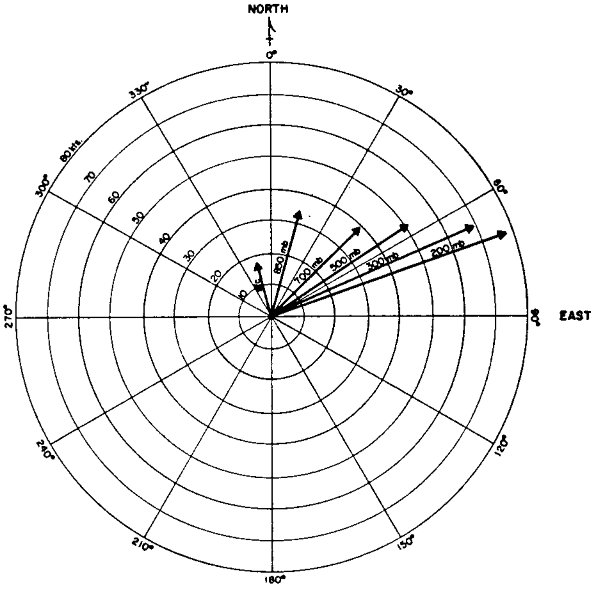

FIG. 18. Typical hodograph for proximity soundings of Great Plains tornadoes (Maddox, 1973).

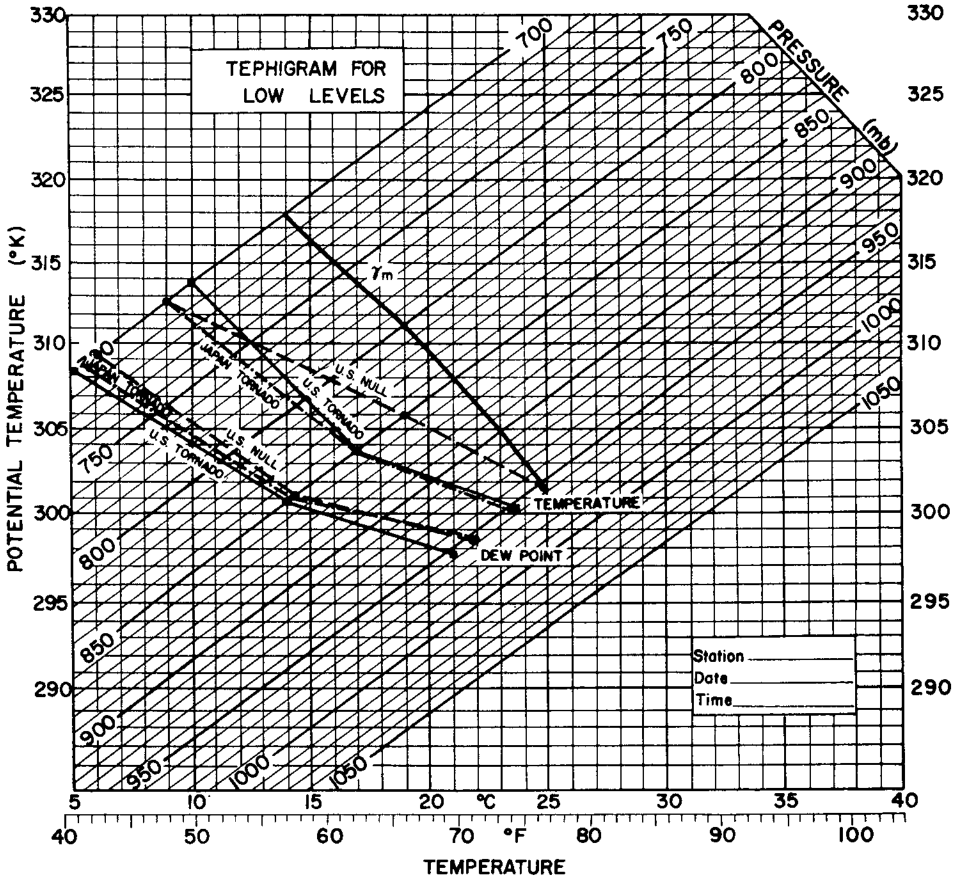

FIG. 19. Averaged proximity soundings for hurricane and typhoon tornadoes and right front quadrant soundings for United States hurricanes without tornadoes.

spheric wind shears averaging 40 kt. In the hurricane cases, however, this shear is concentrated between the surface and 850 mb. 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 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 low levels. In the Great Plains tornado, the thermal instability and vertical shear occur through a deeper layer.

4. Tornado genesis

a. Hurricane dissipation dynamics

While the hurricane is at full intensity at sea, the boundary layer air, due 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 Priestley (1960) is:

$$H=\rho c_p K_T V(T_0-T_a) \qquad (1)$$

where

ρ = density of air
c_p = specific heat of air
K_T = coefficient of eddy heat exchange $\sim 2\times10^{-3}$
V = surface wind
T_0-T_a = temperature of the ocean (T_0) minus the temperature of the air (T_a).

As an example of this powerful heat source: for $T_0-T_a=2\text{C}$, $V=10$ m sec^{-1}, a boundary layer depth of 500 m can be warmed as much as 8C day^{-1}.

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 2C cooler than the ocean temperature. In the typical hurricane over the ocean the boundary layer air spirals isothermally to the central core region.

Conditions for the hurricane over land are very different. As previously discussed by Bergeron (1954), Miller (1964), and Palmén and Newton (1969), air spiraling inward over land is denied the heat source typical 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:

$$\underset{\sim 1\times10^{-6}}{\overset{\text{Shear}}{\left(f+\frac{2V_t}{r}\right)\frac{\partial V_t}{\partial p}}}=\underset{\sim 1\times10^{-6}}{\overset{\text{Baroclinicity}}{-\frac{R}{p}\left(\frac{\partial T}{\partial r}\right)_p}}\ \underset{\sim 10^{-7}}{\overset{\text{Friction}}{-\frac{\partial F_r}{\partial p}}}\ \underset{\sim 10^{-8}}{\overset{\text{Acceleration}}{+\frac{\partial}{\partial p}\left(\frac{dV_r}{dt}\right)}}, \qquad (2)$$

where

f = Coriolis parameter
r = distance from the storm's center
R = gas constant for dry air
p = pressure
V_t = tangential wind
V_r = wind component along r
T = temperature
F_r = horizontal frictional acceleration along r. This acceleration was calculated from bulk aerodynamic stress formula with $C_D=3\times10^{-3}$. F_r was assumed to be half of the total friction.

A low-level cold-core system will tend to develop a vertical wind profile with definite wind shear between the surface and 850 mb. Note in Eq. (2) how the shear term is approximately balanced by the baroclinicity term for the hurricane over land with tornadoes. The low-level vertical wind shear thus has a reasonable explanation. The friction and acceleration terms are of lesser magnitude.

b. 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 kt in association with 850-mb winds of 50–60 kt. This leads to a very large wind shear between the surface and 850 mb. 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 kt at 850 mb are brought down to the surface where the environmental winds are but 10–20 kt. Large horizontal shears are produced. Maddox (1973) hypothesizes that these horizontal shears in turn produce a frictionally forced low-level convergence 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 *et al.*, 1972). Often several tornadoes 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.

c. *Summary*

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 kt) 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.

5. 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 established large low-level vertical wind shear. This vertical wind shear is indispensable 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, we hope, prove useful in understanding and forecasting these storms. A discussion of forecasting applications is contained in the Appendix.

For a more detailed discussion of this subject please see the Colorado State University Project report on this subject (Novlan, 1973).

APPENDIX

a. *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 min rather than every hour.
2) Particular attention should be paid to the radar echoes of active 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 kt. 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. Hill *et al.* (1966) have also discussed this.
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 tem-

TABLE 3. Hurricane-tornado forecast work sheet.

TORNADOES LIKELY	TORNADOES NOT LIKELY
1. Intense hurricanes or those tropical cyclones increasing in intensity just before land-fall.	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 hr.
3. Once on shore the center rapidly cools and becomes 6C colder than temperatures 100 n mi out from the storm center.	Only small central storm cooling.
4. Vertical wind shear profiles surface to 5000 ft of 40 kt or more. Surface winds of only 15–20 kt.	Surface to 850-mb wind shears are less than 40 kt.

RECOMMENDED TORNADO WATCH AREA

General area: Surface pressure is between 1004–1012 mb.
Specific area: Areas of vertical wind shear greater than 40 kt from the surface to 850 mb. Surface winds 15–20 kt.
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.
End tornado watch/warning: When the rainbands begin to break up and the vertical wind shear (sfc-850 mb) falls below 40 kt.
Note: Significant dry air intrusions in the right rear quadrant indicate a potential for tornado "family" outbreaks.

perature 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 6C colder than the temperature at 100 n mi from the center.

b. *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 3 sums up these findings in a forecast work sheet.

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