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REVIEW OF TORNADO
CONSIDERATIONS FOR FFTF

HANFORD ENGINEERING DEVELOPMENT LABORATORY

UNITED STATES ATOMIC ENERGY COMMISSION

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REVIEW OF TORNADO CONSIDERATIONS
FOR FFTF

D. E. Simpson
January 1971

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REVIEW OF TORNADO CONSIDERATIONS FOR FFTF

D. E. Simpson

INTRODUCTION AND SUMMARY

Design criteria adopted for the FFTF did not include requirements for protection against or sustaining the effects of tornadoes. This was consistent with past practice at Hanford and with AEC reactor licensing policy for the western U.S.

Late in 1970, in the course of AEC regulatory review, the AEC licensing policy was reconsidered, and the question was raised as to FFTF capability and requirements for tornado resistance. During the same period of time, similar questions were raised concerning the Jersey Nuclear Corporation's fuel manufacturing facility at Richland. W. L. Dotson of HEDL reviewed the likelihood and potential severity of tornadoes in the Hanford region; his discussion is included in this report as Attachment 1. A more detailed study of tornado occurrences in the Northwest was made by T. Fujita for Jersey Nuclear Corporation; his report is included as Attachment 2.

Dotson's and Fujita's work shows that tornadoes to which the Hanford region might be subject are of much lower severity than the 300 mph tornadoes commonly considered in reactor safety evaluation for the middle-Western and Eastern U.S.⁽¹⁾ Also, the indicated probability of being struck by a tornado at any point is approximately $2 \text{ or } 3 \times 10^{-6}$ per year, based on both Dotson's and Fujita's information.

Even though the tornado probability is extremely low, a margin of safety against such an event may be called for. A conservative assessment

- Temperature Lapse Rate - A measure of the rate of change of temperature with increasing height. Standard 3.6°F/1000 ft (decrease).
Unstable lapse rate is a greater decrease than standard with increasing height.
- Unstable Air - An atmospheric condition where the temperature lapse rate is greater than standard.
- Continental Tropical Air - A warm, moist (up to 5,000 ft above the surface), buoyant air mass.
- Upper Air Trough - An area of the atmosphere (above the surface) where isopleths of pressure are curved cyclonically.
- Wind Maxima - An isolated region of high winds imbedded within a larger region of significantly lesser flow rate.
- Shear - The vector difference in wind velocity between two contiguous air currents.

R. C. Miller⁽¹⁾ states that severe storms, of the type that occur in "Tornado Alley", require that very specific atmospheric conditions be present simultaneously in time and space. The "fuel" for this type of storm is very warm, moist buoyant air in the lower 5,000 ft of the atmosphere. This type of air mass has been termed "continental tropical". Additional requirements are: the availability of a very dry continental air mass upwind, a low level jet in the moist air, a strong band of winds near the area at or near 20,000 ft, strong vertical shear, significant cooling aloft, and explosive instability. The first and last of these items are unknown in the Pacific Northwest. The other conditions do exist in the Pacific Northwest, but seldom coexist. We see no reasonable route over which an unmodified tropical air mass (warm, moist, buoyant) could be transported into the Eastern Washington-Oregon area. The mountainous features that are present to the east, south and west of this region would deplete such an air mass of its moisture by orographic lift prior to its arrival. If the moisture is not available then the fuel is also not present. Further, the unavailability of the tropical air, in the lower atmosphere, also negates the possibility of an explosive instability.

The historical record of the period 1950 to present, within an area prescribed by a circle centered on the FFTF site with a radius of 60 miles, lists four storms that may be classified as tornadoes.

On May 9, 1956, a tornado was observed 10 miles southeast of Kennewick, Washington. No damage occurred with this storm. The path was estimated to be approximately 3 miles long and 100 yards wide. Hail, heavy rain and severe lightning accompanied this storm.

On April 30, 1957, a severe dust storm developed approximately 8 miles south of Yakima, Washington. Towering storm clouds were associated with this storm. There was some damage: the roofs of two garages lifted off their walls. This storm was tentatively classified as a small tornado. The estimated path length was 2 to 3 miles with a path width estimate of 150 yards. This storm has been included in the tabulation although definite evidence of its tornadic character has not been fully established.

On April 24, 1958, an off-duty weather bureau observer saw a funnel cloud about 20 miles northwest of Walla Walla, Washington. This (trained) observer did not see the cloud touch the ground. However, Federal Aviation Administration personnel at the airport said it touched the ground briefly. No path variable estimates are available. This storm was associated with heavy rain, heavy hail and strong linear winds.

On June 26, 1958, at Wallula Junction, Washington (approximately 32 miles southeast of FFTF) a small tornado was observed. Damage to two boats, a building and a state park (trees) was incurred. The path length of this storm was one-fourth mile and the path width was estimated to be 50 yards.

These storms, which may be classified as tornadoes with some credibility, have several common features. It is evident that each was associated with either a cold front or cold upper air trough. Thus the air column in which the storm occurred was cold and moist. The fact that only four storms occurred in a twenty-year period indicates that they are an infrequent phenomena. The reported estimates of path area indicate that the storm dimensions are small; an average diameter of 100 yards. Dergarabedian and Fendell⁽²⁾ report that the maximum wind velocities that may be expected

in these storms is a function of vortex radii. Their estimate indicates that the maximum wind speeds that should be expected in a Pacific Northwest storm is 106 mph. The work of R. C. Miller⁽¹⁾ also generally supports this view.

H. C. S. Thom⁽³⁾ has shown that the probability of a tornado event occurrence may be calculated for any geometric point in a geographic region if the mean path area, $\bar{z}$, and the mean frequency of occurrence, $\bar{t}$, are statistically determinable in a region of area, A. For the FFTF site we have chosen to consider a circular area with a radius of 60 miles (approximately one degree of latitude). This choice was made to provide a reasonable number of validated occurrences in a generally uniform orographic and climatological environment. Thom proposed a mean tornado path area of 2.8209 square miles. This is the value used in the SSAR calculations. A careful study of his paper reveals that this number was developed using sample data from the Iowa area. The intent of this paper was that mean path areas for the region to be studied would be used. This has been done in recalculating the tornado probability for FFTF. The average path area ($\bar{z}$) for the region is 0.1018 square miles. The mean frequency of occurrence is 4 in 20 years or 0.2. The study region has an area of 11309.7 square miles. Then from Thom's formula

$$p = \frac{\bar{z} \bar{t}}{A}$$

the tornado probability is 1.8×10^{-6} per year. Doan⁽⁴⁾ suggests that the plant life probability of a tornado event is the product of the yearly probability and the expected plant life. For FFTF, with an expected plant life of 40 years, the lifetime probability is 7.2×10^{-5} . Doan further states that typical yearly probabilities for high tornado frequency regions are about 10^{-3} , and 10^{-4} for east coast sites. These numbers, according to Doan, yield plant life probabilities of the order of 10^{-2} . In contrast the corresponding probabilities for FFTF are about 10^{-6} and 10^{-4} respectively.

In conclusion, there is no reasonable way that the necessary criteria for formation of a severe tornado (of the mid-west type) could be satisfied within the climatological and orographic characteristics of the Pacific Northwest. The possibility of occurrence of any tornado is low, of the order of 10^{-6} per year.

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27 October 1970

Mr. Leon Dotson
1447 Arbor Road
Richland, Washington 99352

Reference our telephone conversation on the 27th of October 1970 concerning the probable intensity and frequency of occurrence of a major destructive tornado in the Hanford, Washington area. I submit the following opinions based upon my 22 years of forecasting and post analysis of these storms.

Using the definition of a major destructive tornado you gave me, that is, a storm with a tangential wind speed of 300 mph, a translational speed of 60 mph, and a pressure drop of 3 psi in 3 seconds, I would consider the following synoptic conditions necessary.

1. The availability over the threat area of very warm, moist air in the lower 5,000 feet of the atmosphere. This air should be Tropical in nature such as that readily available east of the Rockies with the Gulf of Mexico acting as the source region.
2. The availability in the lower 10,000 feet of very dry Continental air upwind of the threat area and in a position to intrude into and across the low level warm, moist stream.
3. The presence of a low level jet or strong band of winds, 30 knots or greater within the warm, moist air.
4. The presence of strong bands of winds over and near the threat area in the middle troposphere, near 20,000 feet. These would include strong horizontal speed shear zones and branching jet patterns.
5. There must be strong vertical shear between the low level and mid-tropospheric winds. Significant cooling aloft is also most desirable.
6. The vertical structure of the air mass must be extremely unstable and susceptible to explosive overturning when triggered by such synoptic features as fronts, squall lines, synoptic lows, or other atmospheric features such as mesoscale or microscale lows and upper cold fronts. The vertical structure referred to is only noted in the Great Plains tornado sounding. This pre-tornadic air mass structure is the one most commonly associated with multiple outbreaks or family types of destructive tornados. A second type of air mass structure conducive to large tornados, but less to family type outbreaks, occurs primarily over the Gulf Coastal area from east Texas eastward through S. Carolina and Georgia and requires the presence of copious amounts of Tropical air to relatively high levels.

In determining the probability of such synoptic conditions existing in the Hanford area some modern statistics, for the period of 1955 through 1967, gathered and published by the National Weather Service (formerly the United States Weather Bureau) seem to provide some basis for judgement. During this period the two-state area of Washington and Oregon shows an average of less than one tornado day and less than one tornado per year, while the two-state area of Oklahoma and Kansas shows an average of nearly 80 tornados and 30 tornado days per year for the same period.

During this period of record no tornados were recorded in the one degree latitude square in which Hanford is located and only 11 tornados in the entire state of Washington. This compares with 101 tornados in the one degree latitude square centered at Oklahoma City, Oklahoma.

Clearly the conditions which are favorable for the formation of any tornado occur only rarely in the area concerned. The parameters described earlier, which produce a major destructive tornado simply do not occur in the North-Western portion of the United States. It is true that some of them are occasionally present. These include favorable upper and lower wind fields, cold air advection aloft and warm, moist advection in the low levels. However, the primary fuel - the explosive ingredients of Tropical, or even Modified Tropical air and lack of dry Continental air in juxtaposition simply do not occur based on my experience.

The tornados which do occur in this area are what we term Type 3, or cold air type tornados caused primarily by very cold 500 millibar temperatures in a deep cold, but high relative humidity, air column. That these tornados can, and have caused very localized damage is a matter of record. By their very nature their paths are very short, very narrow, and the funnel short lived. It is my opinion that they do not even remotely approach the destructive potential of the Great Plains and/or Gulf Coastal type storms. I cannot assign a value to their probable tangential wind speeds but I most certainly believe them to be radically less than the figures used for a major destructive tornado. I believe the translational speed would be more on the order of 20 to 30 knots and I seriously doubt they would produce a pressure differential on the order of 3 psi in 3 seconds.

ROBERT C. MILLER, Chief Scientist
Analysis & Forecasting DOC/AFGWC

JUSTIFICATION FOR LACK OF TORNADO PROTECTION

PROBABILITY OF OCCURRENCE OF ANY TORNADO IS VERY LOW.

PROBABILITY FOR A MATURE MID-WEST TYPE TORNADO OCCURRENCE IS VERY NEAR ZERO.

- PACIFIC-NORTHWEST TORNADO OCCURRENCES ARE ONE TO TWO ORDERS OF MAGNITUDE LOWER THAN AREAS EAST OF ROCKY MOUNTAINS.
- PACIFIC-NORTHWEST TORNADOES ARE "COLD-CORE" AND THUS MUCH SMALLER AND MUCH LESS SEVERE.

DEFINITIONS

- TORNADO - A VIOLENT ROTATING COLUMN OF AIR, FORMING A PENDANT, USUALLY FROM A THUNDERSTORM CLOUD AND TOUCHING THE GROUND.
- FUNNEL CLOUD - A VIOLENT ROTATING CLOUD NOT TOUCHING THE GROUND.
- TORNADO PATH AREA ($\bar{Z}$) - THE SURFACE AREA UNDER THE INFLUENCE OF TORNADIC CONDITIONS.
- TORNADO FREQUENCY ($\bar{f}$) - THE ARITHMETIC MEAN OF TORNADO OCCURRENCES OVER A SPECIFIED PERIOD OF TIME IN A SPECIFIED AREA.
- PROBABILITY - THE CHANCE, PER A PERIOD OF PRESPECIFIED TIME, OF OCCURRENCE OF AN EVENT.
- TORNADO PROBABILITY - THE CHANCE OF A TORNADIC EVENT OCCURRING AT A GEOMETRIC POINT WITHIN A SPECIFIED GEOGRAPHIC REGION. TIME IS USUALLY TAKEN TO BE A ONE YEAR PERIOD.

DEFINITIONS CONTD

- TEMPERATURE LAPSE RATE - A MEASURE OF THE CHANGE OF TEMPERATURE WITH INCREASING HEIGHT.
STANDARD (ADIABATIC) A DECREASE OF $3.6^{\circ}\text{F}/1000\text{ FT}$
UNSTABLE LAPSE RATE IS A DECREASE IN TEMPERATURE WITH HEIGHT GREATER THAN STANDARD.
- EXPLOSIVE INSTABILITY - AN ATMOSPHERIC CONDITION WHERE THE ATMOSPHERE IS SO UNSTABLE THAT ANY INITIAL VERTICAL MOTION WILL CAUSE A VIOLENT OVERTURNING OF THE ATMOSPHERE TO GREAT HEIGHTS.
- CONTINENTAL TROPICAL AIR - A WARM, MOIST (UP TO 5000 FT ABOVE SURFACE), BUOYANT AIR MASS.
- UPPER AIR TROUGH - AN AREA OF THE ATMOSPHERE (ABOVE THE SURFACE) WHERE ISOPLETHS OF PRESSURE ARE CURVED CYCLONICALLY.
- WIND MAXIMA - AN ISOLATED REGION OF HIGH WINDS IMBEDDED WITHIN A LARGER REGION OF SIGNIFICANTLY LESSER FLOW.
- SHEAR - THE VECTOR DIFFERENCE IN WIND VELOCITY BETWEEN TWO CONTIGUOUS AIR CURRENTS.

SEVERE STORM CRITERIA

- VERY WARM MOIST AIR IN LOWER 5000 FT.
- A WEDGE OF VERY DRY AIR, NEAR 10,000 FT, THAT COULD BE SUPERIMPOSED OVER THE LOWER WARM MOIST LAYER.
- LOW LEVEL WIND MAXIMA (30 KTS OR GREATER) IN MOIST AIR.
- STRONG WINDS NEAR 20,000 FT WITH STRONG HORIZONTAL SHEAR AND BRANCHING JET STREAM.
- STRONG VERTICAL SHEAR BETWEEN LOW LEVEL AND MID LEVEL WIND FLOW.
- COOLING OF MID-LEVEL AIR MASS.
- EXTREME INSTABILITY.

JUSTIFICATION FOR NO SEVERE STORMS

THE PRIMARY CONDITION (FUEL) FOR SEVERE STORMS IS TROPICAL AIR (VERY WARM AND MOIST) IN THE LOWEST 5000 FEET OF ATMOSPHERE. THE SOURCE FOR THIS AIR IS THE TROPICS. TROPICAL AIR CANNOT REACH THE WASHINGTON-OREGON AREA, EAST OF CASCADES, WITHOUT UNDERGOING MODIFICATION BY OROGRAPHIC LIFTING - AND MOISTURE DEPLETION.

TORNADO HISTORY 1950-1970 (CIRCLE 60 MILE RADIUS)

- MAY 9, 1956 - 10 MILES SOUTHEAST OF KENNEWICK
LENGTH 3 MILES, WIDTH 100 YARDS, 12:45 PM
HEAVY RAIN, HAIL, SEVERE LIGHTNING
- APRIL 30, 1957 - 8 MILES SOUTH OF YAKIMA
LENGTH 2 MILES, WIDTH 150 YARDS
- APRIL 24, 1958 - 20 MILES NORTHEAST OF WALLA WALLA
TOUCHED GROUND BRIEFLY
- JUNE 26, 1958 - WALLULA JUNCTION
LENGTH .25 MILES, WIDTH 50 YARDS, 6:00 PM

PACIFIC NORTHWEST CHARACTERISTICS

- OCCUR WITH COLD VERTICAL AIR COLUMN
- INFREQUENT OCCURRENCE
- DIMENSIONS ARE SMALL
- MAXIMUM SPEED (FUNCTION OF VORTEX SIZE)
~106 MPH

PROBABILITY CALCULATIONS FOR ANY TORNADO

$$\bar{Z} = 0.1 \text{ MI}^2$$

$$\bar{t} = 0.2/\text{YEAR}$$

$$A = 11310 \text{ MI}^2 \text{ (CIRCLE OF RADIUS 60 MI)}$$

$$P = \frac{\bar{Z} \times \bar{t}}{A} = 1.8 \times 10^{-6} / \text{YEAR}$$

IF PLANT LIFE OF FFTF IS 20 YEARS

$$PL = P \times 20 = 3.7 \times 10^{-5}$$

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SATELLITE & MESOMETEOROLOGY RESEARCH PROJECT

*Department of the Geophysical Sciences
The University of Chicago*

ESTIMATE OF MAXIMUM WIND SPEEDS OF TORNADOES IN THREE NORTHWESTERN STATES

by

T. Theodore Fujita
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SMRP Research Paper

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ESTIMATE OF MAXIMUM WIND SPEEDS
OF TORNADOES IN
THREE NORTHWESTERN STATES¹

by

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The University of Chicago

A b s t r a c t

In an attempt to estimate the maximum wind speeds of potential tornadoes expected in three Northwestern states, all tornadoes and funnel clouds reported in Storm Data during a 20 year period, 1950 through 1969 were examined. Each storm was reevaluated using the author's method of "tornado characterization" based upon the intensity and area of each storm. Combined analyses of the distribution of characterized tornadoes and hailstorms revealed the existence of tornado alleys and hail swaths in the three-state area. It was concluded that the maximum speed of inswath tornadoes ranges between 200 and 225 mph and that a maximum wind speed of 175 mph seems to be a conservative figure for tornadoes elsewhere. Expected maximum values of the pressure drop of 1.5 psi and time change of 0.5 psi per sec in pressure of 200-mph tornadoes were also estimated.

¹The research reported in this paper has been sponsored by the Jersey Nuclear Company, Richland, Washington. Basic research on characterizations of hurricanes and tornadoes and on foreign tornadoes has been sponsored by the National Hurricane Research Laboratory under NOAA Grant E-22-24-71(G) and National Severe Storms Laboratory under ESSA Grant E-22-69-70(G).

1. INTRODUCTION

Our meteorological environment consists of a large variety of circulation systems such as anticyclones, cyclones, hurricanes, squall systems, thunderstorms, tornadoes, etc. Each of these can be expressed by characteristic dimensions and wind speed. By choosing cross-sectional area and maximum wind speed as specific parameters, for instance, one is able to express quantitatively the size and intensity of each disturbance. Such an attempt may be called the "characterization".

Hurricanes are intense tropical storms with maximum wind speeds in excess of 73 mph. The maximum wind speed of the most intense hurricane can be as high as 225 mph, showing a 73 to 225 mph range in the maximum wind speed. The storm areas vary between 10,000 sq. miles and 1,000,000 square miles showing variation through two orders of magnitude. Both size and intensity variations of hurricanes as described above seem to be significant, but the range of the variation in hurricanes is far smaller than that of tornadoes. In fact, no other circulation systems in the atmosphere are characterized by a wider range of variation in area and intensity than tornadoes.

The maximum wind speed within severe local storms reported officially as tornadoes may vary from about 50 mph for a weak storm to about 300 mph for a devastating tornado. The range of maximum wind speed is thus about 250 mph. The range of areal variation is also extremely large. A small storm tabulated as a tornado may be no larger than a large dust devil, for instance, 30 ft in diameter or about 0.0003 sq. mile. Whereas a large tornado is known to be accompanied by a damaging wind inside a 3-mile radius, resulting in an instantaneous area of 7 sq. miles. The relative range of areal variation of instantaneous areas exceeds 20,000 to 1. Because a large tornado is likely to travel a longer distance than an extremely small one, the range of tornado-affected areas exceeds 100,000 to 1.

As a first step in estimating tornado probability in three Northwestern states, Fig. 1 was constructed based upon 6-year statistics by Wolford (1960); 10-year, by Thom (1963); and 13-year, by Pautz (1969). 20-year statistics from Storm Data

Fig. 1 Four examples of tornado-frequency charts showing the occurrences within one-degree squares

Fig. 2 Damaging wind situation of October 26 - 27, 1950

were compiled by the author to learn more about tornado activities in these states where frequencies are considerably smaller than those of Midwestern states. By examining tornado occurrences in each "one-degree square", one might conclude that the probability of tornadoes inside open "squares" is zero, implying that one may forget about the possible occurrences of future tornadoes. Unfortunately, this conclusion is not realistic, because tornadoes were not reported in these squares due to a relatively short period of data collection.

For the best possible assessment of tornado probability it is necessary to reevaluate past tornadoes by characterizing each by size and intensity distribution. A 20-year period between 1950 and 1969 was selected for this purpose, and all funnel and tornado reports in Storm Data were examined. Each was characterized according to the affected area and estimated intensity. The locations of all tornadoes were then plotted on the 3-state map.

Prior to the investigation of tornado damage, several cases of damaging straight wind were examined. Such an examination usually reveals the effect of a maximum wind speed upon structures scattered over the area under investigation. Shown in Fig. 2 is the isobaric pattern of October 26-27, 1950 when Northwestern states were under the influence of straight winds of about 55 mph. Not a single tornado or funnel cloud was reported from the area included in the chart. Since the period of the "fastest mile" is about 1 min, one may assume that a peak gust lasting for a few seconds would be 10 to 40% higher than 55 mph. Most of the damage described in the chart was caused, therefore, by a straight gust of 60 to 75 mph. This range of speed is classified by Fujita (1970b) as F 0 scale accompanied by a GALE (force) TORNADO.

2. NEW METHOD OF TORNADO STATISTICS

A. Characterization by Tornado-affected Area

In order to differentiate tornadoes according to their damage areas, Fujita (1970a) computed areas affected by each tornado within the entire United States for

1965, 1967, and 1969. It was pointed out that two of the smallest storms reported as tornadoes were characterized by areas of only 0.0002 square mile while some large ones, on the contrary, resulted in 10 to 50 square mile areas, concluding that a large tornado involves an area over 100,000 times larger than an extremely small one which is, nevertheless, reported as a tornado. An attempt was made to classify tornadoes into the following categories according to their individual area defined as the product of the length and the mean width of damage by each tornado. These categories are

- (GI) GIANT TORNADO: A tornado with its individual area equal to or larger than 10 square miles.
- (MA) MACRO TORNADO: A tornado with its individual area equal to or larger than 1 square mile but less than 10 square miles. This category had been identified as REGULAR TORNADO, but the term regular is so vague that it was changed to MACRO TORNADO.
- (ME) MESO TORNADO: A tornado with its individual area equal to or larger than 0.1 square mile but less than 1 square mile.
- (MI) MICRO TORNADO: A tornado with its individual area equal to or larger than 0.01 square mile but less than 0.1 square mile
- (DE) DECIMICRO TORNADO: A tornado with its individual area equal to or larger than 0.001 square mile but less than 0.01 square mile.
- (TR) TRACE TORNADO: A tornadic storm with its individual area less than 0.001 square mile identified as "trace".
- (FU) FUNNEL CLOUD: A funnel cloud which does not induce tornadic wind on the ground. If an evidence of tornadic wind damage on the ground is confirmed beneath the path of a funnel cloud, one should classify the storm as a tornado under a reasonable assumption that a vertical column of rotating air extended all the way to the ground.

The above categories are based upon orders of magnitude of tornado areas. The proper selection of the area category can easily be made based upon a rather

approximate estimate of damage provided the estimate does not deviate more than one order of magnitude. For example, when a tornado swath extends a distance of 10 miles with damaged houses and trees scattered along a very narrow swath, this storm is classified as a MESO TORNADO. In order to call a storm of the same path length a MACRO TORNADO about a one-block width is needed throughout the entire swath. An accurate damage area estimate can be made through detailed surveys, but both newspaper clippings and eyewitness accounts are good enough to permit a tornado area assessment with "one-order of magnitude" accuracy.

B. Characterization by Tornado Intensity

The destructive force of a tornado does not depend merely upon its horizontal dimension. Therefore, each storm should be evaluated by independent parameters related to both intensity and dimension. Since the possibility of measuring the maximum intensity or wind speed of all tornadoes by means of direct or indirect sensing is remote, it is necessary to undertake a coarse assessment based mainly upon damage characteristics.

For this purpose Fujita's (1970b) proposed scale for damaging wind, intended initially for hurricane and typhoon classification, can readily be applied. The proposed Fujita scale, 1 through 12, connects smoothly the beginning of hurricane wind speed or Beaufort scale 12 with Mach 1, the velocity of sound in the atmosphere (see Fig. 3). Because of the fact that most storm damage due to high wind occurs during the high gust period, though not with the peak gust, the duration of high wind necessary to produce various damage should also be included in the scale. We know that a 10-minute period used internationally for synoptic reports is too long a period of damaging wind. Even a 1-minute period used currently by the U.S. National Weather Service is too long to be applied for damage assessment.

A tornado with a 0.1-mile radius of maximum wind and moving at 30 mph will show a 25 sec time difference between two wind maxima at the front and the rear edge of the travelling storm's core. The duration of very high wind will, therefore, be only several seconds. The duration of "fastest mile" wind corresponding to 200 mph is 18 sec and at 300 mph, 12 sec. In light of the above example, the duration corresponding to a

tornado wind seems to be several times too long. With the option of future modifications, "fastest quarter-mile" periods were computed and included in the following Fujita scale. The following specifications of damage are not intended to be absolute criteria for scale determination. They are presented as visual guide lines for a standardized determination of F scale.

(F 0) GALE TORNADO, Light Damage

40-72 mph (22-13 sec mean)

Some damage to chimneys and TV antennae; breaks twigs off trees; pushes trees over.

(F 1) WEAK TORNADO, Moderate Damage

73-112 mph (12-8 sec mean)

Peels surface off roofs; windows broken; light trailer houses pushed or overturned; some trees uprooted or snapped; automobiles pushed off the road.

(F 2) STRONG TORNADO, Considerable Damage

113-157 mph (7.9-5.8 sec mean)

Roofs torn off frame houses leaving most strong upright walls; trailer houses destroyed; large trees snapped or uprooted; railroad box cars derailed; light object missiles generated; cars blown off highway.

(F 3) SEVERE TORNADO, Severe Damage

158-206 mph (5.7-4.4 sec mean)

Roofs and some walls torn off frame houses; trains derailed or overturned; steel framed hangar-warehouse type structures torn; cars lifted off the ground.

(F 4) DEVASTATING TORNADO, Devastating Damage

207-260 mph (4.3-3.5 sec mean)

Whole frame houses leveled, leaving piles of debris; steel structures badly damaged; small flying objects debark trees;

cars and trains thrown or rolled considerable distances, large missiles generated.

(F 5) INCREDIBLE TORNADO, Incredible Damage

261-318 mph (3.4-2.9 sec mean)

Whole frame houses tossed off foundations; automobile-sized missiles generated; incredible phenomena can occur.

(F 6) 319-379 mph (2.8-2.5 sec mean)

(F 7) 380-445 mph (2.4-2.1 sec mean)

(F 8) 446-513 mph (2.0-1.8 sec mean)

(F 9) 514-585 mph (1.7-1.6 sec mean)

(F10) 586-659 mph (1.5-1.4 sec mean)

(F11) 660-737 mph (1.3 sec mean)

(F12) 738-818 mph (1.2 sec mean)

The above description of damage characteristics can be used for identification of tornadoes according to their intensity or maximum wind speed. An enclosed sheet of damage photographs will be helpful in determining the levels of tornado intensity.

C. Characterization by both Intensity and Area

As a result of the above classification applicable to both area and intensity of tornadoes, it is now feasible to combine

TORNADO INTENSITY	and	TORNADO AREA
F 0 Gale Tornado		TR Trace Tornado
F 1 Weak Tornado		DM Decimicro Tornado
F 2 Strong Tornado		MI Micro Tornado
F 3 Severe Tornado		ME Meso Tornado
F 4 Devastating Tornado		MA Macro Tornado
F 5 Incredible Tornado		GI Giant Tornado

into a combination of 36 types of tornadoes. Each can be expressed with two adjectives, the first, expressing the intensity, and the second, the area; Strong Micro Tornado,

Fig. 3 Scale of damaging wind by Fujita(1970b). This scale is designed to connect smoothly Beaufort scale with Mach scale.

Fig. 4 Tornadoic storms in Seattle area. During a 20-year period, occurrences of 3 tornadoes, 2 funnel clouds, and 2 waterspouts, one of which landed as a tornado, were reported.

Devastating Macro Tornado, Gale Decimicro Tornado, Weak Giant Tornado, etc.

3. CHARACTERIZATION OF 3-STATE TORNADOES DURING A 20-YEAR PERIOD 1950-1969

A. Analysis of Seattle area storms (see Fig. 4)

As an application of tornado characterization introduced in Section 2, all tornadic storms in the Seattle area reported in Storm Data in the 20-year period 1950-1969 were analyzed. Since such an attempt is of extreme importance to the further development of statistical analyses in other parts of the United States as well as other countries, examples of storm evaluations are presented.

STRONG MICRO TORNADO of September 28, 1962 was a small tornado, the first ever observed in Seattle. The storm developed over the northeastern section of the city and moved north-eastward crossing the northern end of the Sand Point Naval Air Base and Lake Washington. The funnel struck the east shore of the lake in the vicinity of Juanita Point, damaging a few residences and trees before disappearing. In the View Ridge area, a roof of one residence was severely damaged, windows were broken and trees damaged within a very narrow path. The roof of one hangar on the Air Base was damaged extensively. A small waterspout formed as it moved across Lake Washington. Reported path length was 3 miles and width, 30 yards. This description implies that the intensity of this storm was either high F1 or low F2. Selecting a conservative figure, an F 2 and 0.05 square mile Micro Tornado category was adopted.

FUNNEL ALOFT of May 7, 1963 was a small funnel cloud observed over the north end of Lake Washington for a period of approximately 4 minutes. The funnel did not reach the surface.

WEAK MESO TORNADO of August 18, 1964 was a small tornado observed in the area east of Kent and in the vicinity of Lake Meridian. The funnel was visible for several minutes before dissipating in the vicinity of Lake Youngs. The funnel touched the ground in a forest area, picking up debris but caused very little damage. Reported

path length and width were 8 miles and 30 yards, respectively, resulting in an area of 0.16 square mile. This storm was, therefore, regarded as an F1 Meso Tornado.

FUNNEL ALOFT of September 11, 1966 was a small, well-defined funnel cloud approximately 10,000 ft in length with a diameter of 600 ft at the top and 150 ft at the base. This funnel remained 300 ft or more above the surface, travelling eastward over the city 3 miles north of the Seattle-Tacoma airport.

SEVERE MESO TORNADO of December 12, 1969 was described in Storm Data as the most damaging tornado to strike any area in the state of Washington. A forerunner of this storm was observed at 1400 PST as a waterspout over the East Passage near the southern end of Maury Island. This waterspout disappeared and a second one formed between Maury Island and Redondo Beach, moving inland as a tornado between Des Moines and Saltwater State Park. The tornado travelled to the north of Kent where it disappeared. The funnel, reported as two funnels, would touch the ground for a short distance, damaging or destroying buildings, then lift for a few blocks before touching the ground again, causing considerable damage. Roofs were damaged on several residences, windows blown out, garages and other buildings were destroyed. The most extensive damage occurred near the Green River in the Kent Valley. Almost all windows were blown out of a large greenhouse and power lines were down along a path 75 to 200 yards wide and 5 miles long. The above statement in Storm Data implies that this storm was either an upper F2 or low F3 at the most, classified as an F3 Meso Tornado.

B. Analysis of 20-year Tornadoes in Washington, Oregon, and Idaho

In an attempt to apply this new classification method to all reported tornadoes in three Northwest states in the 20-year period, each storm description from Storm Data was analyzed carefully to obtain the final results presented in Tables I through III.

Overall statistics show that there were 2 waterspouts and 49 funnel clouds. The intensity and area distributions are

Table 1. Tornadoes and funnel clouds in Northwestern states during 1950-69.
 Time is given in local standard time, area in sq. miles, width and length in miles, and damage as expressed in the code listed at the end of Table III.

Number	Year	Date	State	Time	F-scale	Area	Sq mi	Width	Length	Damage
1	1951	Oct 2	WA	1510	F 3	ME	0.16	0.02	8.	4 (s)
2		Dec 6	OR	1540	F 1	DM	0.009	0.029	0.3	3 (0)
3	1953	Aug 26	WA	1630	F 0	MI	0.08	0.08	1.	3 (3)
4	1954	Apr 28	ID	1220	Funnel					
5		Jun 9	ID	1310	Funnel					
6		Jun 9	ID	?	F 1	MI	0.01	0.04	0.25	4 (?)
7		Jun 15	WA	1330	F 1	MI	0.03	0.06	0.5	4 (0)
8		Jul 6	WA	2030	F 2	DM	0.0015	0.014	0.11	3 (0)
9		Oct 22	OR	1535	F 1	DM	0.005	0.01	0.5	0 (0)
10	1955	Mar 29	OR	1000	F 1	ME	0.5	0.2	2.5	3 (s)
11		Jun 15	ID	1030	Funnel					
12		Jun 29	ID	1342	Funnel					
13		Aug 25	ID	1300	Funnel					
14		Aug 25	ID	?	F 1	DM	0.001	0.02	0.05	3 (0)
15	1956	May 9	WA	1245	F 2	ME	0.15	0.05	3.	1 (1)
16		May 18	ID	p.m.	F 1	DM	0.003	0.03	0.1	3 (1)
17		Jun 1	ID	p.m.	F 1	TR				? (?)
18		Jun 3	ID	p.m.	F 1	DM				3 (?)
19		Jul 9	ID	1800	F 1	DM				? (?)
20		Aug 23	ID	0900	F 2	DM				3 (?)
21	1957	Apr 12	OR	1200	F 3	MI	0.08	0.03	2.5	3 (2)
22		Apr 12	OR	1230	F 2	MA	2.7	0.15	18.	2 (2)
23		May 6	WA	1225	Funnel					
24		May 6	WA	1358	F 0	TR				0 (0)
25		May 10	OR	1400	F 0	TR				0 (0)
26		Jun 5	ID	1445	F 1	DM				0 (0)
27	1958	Mar 23	OR	p.m.	F 1	ME	0.1	0.02	5.	4 (2)
28		Apr 24	WA	1515	F 0	TR				0 (0)
29		Jun 8	OR	1415	Funnel					
30		Jun 9	OR	1420	F 1	DM				1 (1)
31		Jun 26	WA	1800	F 2	MI	0.007	0.03	0.24	4 (?)
32		Jun 27	ID	1145	F 2	MA	1.15	0.23	5.	4 (3)
33		Jul 15	ID	1230	F 2	MI				2 (0)
34	1959	Mar 13	ID	1605	F 1	MI	0.024	0.06	0.4	4 (?)
35		May 17	ID	1640	Funnel					
36		May 27	ID	1200	Funnel					
37		May 28	ID	1100	Funnel					
38		Sep 26	ID	1700	F 1	DM				4 (0)
39		Oct 15	ID	1550	Funnel					

Table 11. Tornadoes and funnel clouds in Northwestern states during 1950-69.

Number	Year	Date	State	Time	F-scale	Area	Sq mi	Width	Length	Damage
40	1960	Mar 8	OR	1515	F 2	MI	0.03	0.03	1.	3 (1)
41		Apr 28	OR	1020	Funnel					
42	1961	May 1	WA	1500	Funnel					
43		Jun 2	ID	1414	Funnel					
44		Jun 2	ID	1430	Funnel					
45		Jun 2	ID	1530	F 0	TR				0 (0)
46		Jul 5	ID	1530	F 2	ME	0.15	0.03	5.	3 (4)
47		Jul 31	ID	1425	F 0	TR				? (?)
48	1962	May 8	ID	1500	F 2	ME	0.1	0.01	10.	4 (4)
49		May 19	OR	1200	F 1	DM	0.005	0.01	0.5	3 (2)
50		May 8	WA	1400	F 0	TR				0 (4)
51		Jun 2	OR	1650	Funnel					
52		Jul 30	ID	1434	F 1	DM				0 (0)
53		Jul 26	WA	1522	Funnel					
54		Sep 21	ID	1230	F 0	TR				0 (0)
55		Sep 21	ID	1230	Funnel					
56		Sep 28	WA	1657	F 2	MI	0.05	0.017	3.	5 (0)
57	1963	May 7	WA	1500	Funnel					
58		Jun 4	ID	1630	Funnel					
59		Jun 4	ID	1845	Funnel					
60	1964	May 26	ID	1530	F 2	MI	0.05	0.1	0.5	4 (0)
61		May 22	OR	1419	F 0	TR				0 (0)
62		May 22	WA	1335	F 0	TR				0 (0)
63		Jun 2	ID	1218	Funnel					
64		Jun 2	ID	?	F 0	TR				? (?)
65		Jul 8	ID	0900	F 2	MI				? (?)
66		Aug 28	ID	1100	Funnel					
67		Aug 18	WA	1045	F 1	ME	0.16	0.02	8.	0 (0)
68	1965	Apr 9	OR	0955	Funnel					
69		Jun 26	ID	1200	Funnel					
70		Jun 24	OR	1338	Funnel					
71		Jul 26	OR	1800	Funnel					
72		Nov 24	ID	1435	Funnel					
73		Nov 24	ID	1520	Funnel					
74		Nov 10	OR-WA	1455	F 1	MI	0.01	0.01	1.	3 (0)
75		Nov 10	WA	1500	F 2	MI	0.01	0.02	0.5	4 (0)
76	1966	Mar 14	WA	2330	F 2	DM				3 (0)
77		Mar 14	WA	2347	Funnel					
78		Jun 2	OR	2000	Funnel					
79		Jun 23	OR	1800	F 2	DM	0.008	0.03	0.25	2 (3)

Table III. Tornadoes and funnel clouds in Northwestern states during 1950-69.

Number	Year	Date	State	Time	F-scale	Area	Sq mi	Width	Length	Damage
80	1966	Jun 25	WA	1700	Waterspout					
81		Jun 25	WA	1709	Funnel					
82		Aug 25	OR	2010	F 3	ME	0.72	0.06	12.	4 (3)
83		Sep 11	WA	1306	Funnel					
84		Oct 20	OR	1530	F 1	DM	0.001	0.01	0.1	3 (1)
85	1967	May 11	ID	1115	Funnel					
86		May 11	ID	1700	Funnel					
87		May 9	WA	1900	F 0	TR				0 (0)
88		Jun 2	ID	1512	F 2	MI	0.05	0.01	5.	0 (0)
89		Jun 6	ID	1300	F 0	TR				0 (0)
90		Jun 8	ID	1330	F 0	TR				0 (0)
91		Jun 8	ID	1530	F 0	TR				0 (0)
92		Jun 8	ID	1720	F 0	TR				0 (0)
93		Jun 9	ID	1618	F 0	TR				? (?)
94		Jun 12	ID	1210	Funnel					
95		Oct 3	OR	1305	W F 2	MI	0.02	0.04	0.5	4 (1)
96	1968	May 25	OR	1330	Funnel					
97		Jun 6	ID	1320	Funnel					
98		Jun 20	ID	1500	F 2	MI				4 (0)
99		Jun 11	OR	1600	F 2	MA	6.	0.6	10.	7 (0)
100		Jun 28	OR	1300	Funnel					
101		Aug 9	ID	1830	Funnel					
102		Aug 18	ID	1635	Funnel					
103		Aug 20	ID	1049	Funnel					
104		Aug 20	ID	1130	Funnel					
105		Sep 11	ID	0600	F 2	MI	0.012	0.025	0.5	? (?)
106	1969	Jan 29	OR	1155	Funnel					
107		May 14	OR	1542	Funnel					
108		May 18	OR	1100	Funnel					
109		May 2	WA	2110	Funnel					
110		Jun 20	ID	1535	F 1	DM				0 (0)
111		Jun 20	ID	1535	Funnel					
112		Jun 11	OR	1500	Funnel					
113		Dec 12	WA	1400	Waterspout					
114		Dec 12	WA	1412	W F 3	ME	0.3	0.06	5.	5 (?)

W Waterspout

W F 2 F 2 tornado originated from waterspout

Damage categories 1, less than \$50 Property (Crop)

2, more than \$50

3, more than \$500

4, more than \$5,000

5, more than \$50,000

etc.

s, slight damage

I n t e n s i t y			A r e a		
F 0	17 storms	(27%)	TR	17 storms	(27%)
F 1	21	(33%)	DM	17	(27%)
F 2	21	(33%)	MI	17	(27%)
F 3	4	(7%)	ME	9	(14%)
F 4	none	(none)	MA	3	(5%)
F 5	none	(none)	GI	none	(none)

4. TORNADOES IN AUSTRALIA AND JAPAN

The foregoing analysis of the Northwest reveals that tornado intensity as well as area are much less than those observed and expected in the Midwest. It would, therefore, be profitable to compare Northwest tornadoes with those in other countries where tornadoes of comparable size and intensity are reported.

According to a comprehensive survey of Australian tornadoes by Clarke (1962), frequencies depend largely on population density. During a 12-year period there were 66 tornadoes within the city limits of 5 big cities, Perth, Adelaide, Melbourne, Sydney, and Brisbane, with a total area of 2,300 sq. miles. The frequency density corresponding to the area and the number was calculated to be 24×10^{-4} per sq. mi per year. This frequency density is higher than that of Oklahoma City where 21×10^{-4} per sq. mi per year is reported according to Pautz's (1969) statistics given in the form of tornado occurrences in latitude-longitude squares.

Within 15 miles from downtown Tokyo, there were reports of 6 tornadoes in 6 years between 1963-1968. This frequency density is 14×10^{-4} per sq. mi. per year, slightly more than one-half of the Oklahoma City frequency. But these Japanese storms were small in area and weak in intensity. These characterizations are:

Weak (F1) Micro Tornado (Jan. 19, 1963) in Kawasaki: Ripped the roofs off a new post office and a warehouse under construction.

Weak (F1) Meso Tornado (May 24, 1964) in Setagaya: Left a 3-mile long swath, damaging 471 residential houses. This storm, 60-90 ft in diameter, stirring up

a cloud of dust extending 1,000 ft high, travelled at the slow speed of 10 to 12 mph.

Strong (F2) Meso Tornado (Aug. 21, 1965) in Denenchofu: 110 commercial or residential houses were damaged. Roofs were ripped off and window glasses broken. A 25 ft pine tree, 1 ft in diameter, was uprooted. 6 were injured.

Two Gale (F0) Decimicro Tornadoes (Aug. 21, 1965) in Kawaguchi and Urawa: 8 roofs were torn off houses.

Strong (F2) Macro Tornado (Oct. 14, 1965) in Sinagawa: Left widespread damage within a 0.6 mi x 2.5 mi area along the bullet-train tracks. One house was demolished, roofs of 10 houses were torn off, and 100 houses were damaged. 4 people were injured.

These statistics show that 11 million people living in Tokyo do not worry about tornado occurrences as much as Oklahoma City residents do. In fact, the author has not heard about an issuance of either a tornado watch or warning in Tokyo.

With the exception of a 200 mph wind estimated by Hounam (Clarke, 1962) in his study of the Brighton tornado in Melbourne, February 2, 1918, the maximum wind speeds of Australian tornadoes are generally less than 120 mph which corresponds to F 2 (see 200 mph tornado in Table IV). Clarke (1962) tabulated a frequency analysis of published wind speeds in 62 Australian tornadoes.

Table IV. Frequency of 62 Australian tornadoes as a function of estimated wind speed. From Clarke (1962) table was modified into approximate range of F scale wind speed.

Wind speed (mph)	51 - 70	71 - 110	111 - 120	200
No. of Storms	31	27	3	1
Corresponding F-scale	F 0	F 1	F 2	F 3

The above statistics of both Australian and Japanese tornadoes reveal that their intensity and areal analyses are of vital importance in assessing the tornado risk and in establishing design criteria. In this respect, the study of tornadoes in other parts of the world will be helpful in understanding the nature of our U. S. tornadoes.

Presented in Fig. 5 are tornado occurrences in Australia consisting mostly of thinly populated areas and in Japan with one of the highest population densities in the world.

Fig. 5 Occurrences of Australian and Japanese tornadoes during 1950-1961 and 1964-1968 periods, respectively

5. TORNADO FREQUENCY IN RELATION TO HAIL AND POPULATION DENSITY

Tornado frequencies in Northwestern states are greatly dependent upon the density of population and damaging effects upon ground structure and vegetation. It should be noted, however, that the reported tornado frequency is not always proportional to the number of residents in an area, because a tornado reported by "many" observers is tabulated as "one" tornado.

Presented in Fig. 6 is the distribution of reporting communities, rather than individuals. A community of several people will probably report tornadoes as if it were a large town or city if only one attentive person makes careful observation of a passing storm. The size of the population centers in Fig. 6 was not drawn in proportion to the population, but was designed to show the density of storm reporting communities.

Knowing that the eastern half of the three-state area is characterized by more hail storms than tornadic storms and that hail and tornado occurrences are closely related to each other, distribution of hail in a 20-year period, the period of this tornado study, was investigated in detail. The result is shown in Fig. 7 which includes the locations of hail reports. The hail sizes were distinguished by using different sized black circles.

It is seen that more hail locations exist in the eastern parts of the analysis area, where population density is much smaller, than near the Pacific coast. This inverse relationship between hail and population density indicates that the patterns of hail swaths are quite realistic. For reference purposes, these hail swaths are identified as Medford swath, Spokane swath, Columbia swath, etc. Some of these swaths seem to originate from upwind mountains and peaks suggesting that orographic effects do play an important role in the initial development of hail-producing thunderstorms.

To learn detailed patterns of tornado occurrences in these three Northwest states, Fig. 8 was compiled from tornado data as given in Tables I, II, and III. All storms including funnels aloft and tornadoes were entered in the figure. The tornado symbols corresponding to the storms' area and density are shown in the upper right portion of the figure.

The overall distribution indicates that more tornado occurrences than hail occurrences are seen toward the Pacific coast suggesting that thunderstorms to the

west are tornado-oriented rather than hailstorm-oriented. In fact, the hail frequency near Seattle is practically zero, but the tornado frequency is relatively high.

There is a narrow band of tornado occurrences along the coast of the Pacific and Puget Sound. As stated in the section of tornado analysis in the Seattle area, most of these tornadoes move inland from the Pacific or open water. Due to unknown reasons these coastal tornadoes gain intensity after landing, thus reaching their maximum intensity several miles inland. It is suspected that a moderate friction within the lower boundary layer stimulates the inflow which is usually insignificant in the case of waterspouts. A number of Japanese waterspouts were reported to intensify shortly after coastline crossing. The maximum estimated wind speed inside such waterspout-originating tornadoes may be regarded as being less than the upper F 3 scale corresponding to 206 mph.

Each tornado alley as analyzed in Fig. 8 corresponds to a counterpart hail swath in Fig. 7. This does not mean that both hail and tornado are originated by the same parent storm. Some tornadoes may not be accompanied by hail, and hailstorms may not necessarily be associated with tornadoes.

The north-south valley extending between the Coast Range and the Cascade Range appears to be a factory for tornadoes with intensities up to F 3. Some of these storms travel eastward causing extensive damage to farms, orchards, and forests on the west foothills of the Cascades. Both Portland and Eugene alleys extend eastward, but the tornado intensity inside these alleys seems to decrease eastward, while hail frequency increases eastward.

We may thus conclude that the intensity of most tornadoes in the eastern half of the combined Portland-Eugene Alley is F 2 or smaller, practically eliminating the possibility of experiencing an F 3 tornado. In the light of the preceding analysis, the following figures may safely be used as the maximum wind speeds of tornadoes affecting specific areas within these three states. The maximum speeds include both rotational and translational speeds of tornadoes.

- a. Pacific Coast Alley:
175 mph probable, 225 mph maximum
- b. Portland-Eugene Alley west of Cascades:
175 mph probable, 225 mph maximum

- c. Portland-Eugene Alley east of Cascades:
150 mph probable, 200 mph maximum
- d. Medford Alley:
150 mph probable, 200 mph maximum
- e. Spokane Alley:
150 mph probable, 200 mph maximum
- f. Baker Alley:
150 mph probable, 200 mph maximum
- g. Caldwell Alley:
175 mph probable, 225 mph maximum
- h. Twin Falls Alley:
150 mph probable, 200 mph maximum
- i. Other areas in three states:
125 mph probable, 175 mph maximum

Fig. 6 Population density of three Northwestern states

Fig. 7 Distribution of hailstorms in 20-year period, 1950-69. The sizes of hailstones are identified with four-size black circles as well as open circles used for unknown size hailstones. All reports of damaging hailstorms in Storm Data were used in producing this hail distribution chart.

Fig. 8. Distribution of characterized tornadoes in 20-year period, 1950-69. Identification numbers next to each storm correspond to those in Tables I through III. Note that a storm is regarded as a tornado if area is larger than trace and intensity is higher than F 0.

6. MAGNITUDE OF PRESSURE VARIATION ACCOMPANIED BY A 200-MPH TORNADO

The central pressure of a rotating column of air is considerably less than the environmental pressure. If a vortex is described as a Rankine-combined vortex, the pressure drop from the far distant environment to the circle of the maximum wind is given by

$$P_{\infty} - P_m = \frac{1}{2} \rho V_m^2$$

where P_{∞} and P_m denote the static pressure at infinity and at the circle of the maximum wind V_m . The same amount of pressure drop is expected between the circle of the maximum wind and the vortex center. Thus, the total pressure drop by a Rankine vortex is

$$\Delta P = \rho V_m^2$$

where $\Delta P = P_{\infty} - P_o$, the total pressure drop.

If a vortex cannot be approximated as a Rankine vortex, a correction parameter, μ must be used. Thus we write

$$\Delta P = \mu \rho V_m^2$$

Statistics show that a 200 mph typhoon in the Western Pacific will show a central pressure of 891 mb, 119 mb or 1.7 psi lower than the environmental pressure of 1010 mb. This would result in

$$\mu = 1.25 \text{ for typhoons.}$$

A 200-mph hurricane in the Atlantic shows a statistical central pressure of 909 mb which is 101 mb or 1.5 psi lower than the environmental pressure which gives

$$\mu = 1.05 \text{ for hurricanes.}$$

The difference in μ is mostly a result of the horizontal dimensions of hurricanes which are statistically smaller than Pacific typhoons. The larger the storm the more the effect of the Corioli's force which deepens the central pressure for a given distribution of tangential wind speed.

There are no pressure measurements at the center of a 200-mph tornado. Due to the fact that the horizontal dimensions of tornadoes are too small to be affected by the Corioli's force, there are reasons to believe that the value of μ is even smaller than 1.00 according to author's latest calculation. Because of above evidences, we may

safely assume that the central pressure of a 200-mph tornado is about 95 mb or 1.4 psi lower than the environment. In this case, the translational speed is assumed to be zero in order to estimate the maximum possible pressure drop due to a 200-mph tornado.

Along the circle of the maximum 200-mph wind, the static pressure drop would be just about one-half of 95 mb, but the dynamic pressure will further lower the pressure around the corners or tops of buildings as much as half 95 mb. The total drop in pressure including the dynamic pressure induced by high wind would, therefore, be about 95 mb or 1.4 psi everywhere inside the circle of the maximum wind. It is recommended that a 95 mb or 1.4 psi be adopted as the pressure drop inside a 200-mph tornado. It should be noted that the amount of pressure drop will become even smaller since the maximum speed of damaging 200-mph wind includes the storm's translational velocity.

The horizontal pressure gradient inside a Rankine-type vortex reaches the maximum on the circle of the maximum wind. The gradient can be computed from

$$\frac{1}{\rho} \left(\frac{\partial P}{\partial r} \right)_{r_m} = \frac{V_m^2}{r_m}$$

where r_m is the radius of the maximum rotational wind, $V_m = 200$ mph. The gradient will, therefore, depend upon the diameter of the tornado core as tabulated below.

Table V. Pressure gradient on the circle of a maximum rotational wind of 200 mph tabulated as a function of core diameter in mile.

Core diameter (mile)	0.05	0.1	0.3	0.5	1.0
Gradient (mb/mile)	1900	950	320	190	95
Gradient (psi/mile)	27.6	13.8	4.6	2.8	1.4

In order to compute local variation of pressure produced by a tornado vortex, one should specify the translational speed in addition to the pressure gradient as expressed in Table V, because the local change in pressure is dependent upon both the pressure gradient and the translational speed of the system. Either monthly or seasonal

variation of tornado occurrences is useful for estimation of the translational speed of tornadoes because mid-summer tornadoes tend to move more slowly than spring and autumn storms. With this seasonal aspect of storm motion in mind, inference of storm motion from the monthly occurrences presented in Table VI is possible.

Table VI. Occurrence of 114 tornadic storms in three Northwestern States during 1950-69. Based upon characterized storms in Tables I through III.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Waterspouts	0	0	0	0	0	1	0	0	0	0	0	1	2
Funnel	1	0	1	3	12	19	2	6	2	1	2	0	49
Gale (F 0)	0	0	0	1	6	7	1	1	1	0	0	0	17
Weak (F 1)	0	0	3	0	2	7	2	2	1	2	1	1	21
Strong (F 2)	0	0	2	1	3	6	4	1	2	1	1	0	21
Severe (F 3)	0	0	0	1	0	0	0	1	0	1	0	1	4
Total	1	0	6	6	23	40	9	11	6	5	4	3	114

This table indicates that both funnel clouds and gale tornadoes, the weakest storms in the author's intensity category, show the highest frequency in May and June. As storm intensity increases to strong category, the maximum frequency shifts toward June. But severe tornadoes (F 3) occurred one each in April, August, October, and December. Such a seasonal variation of severe tornado occurrences cannot be used in limiting the translational speed of 200-mph tornadoes within a narrow range. Thus, the speed range of Table VII was varied between zero and 60 mph. The computation was made by keeping the sum of rotational and translational speeds constant.

Table VII. Rate of pressure change by a tornado with a maximum speed of 200 mph including the translational speed. Pressure change in psi per sec.

Core diameter (mile)	0.05	0.1	0.3	0.5	1.0
Stationary storm	0.00	0.00	0.00	0.00	0.00
10 mph speed	0.07	0.04	0.01	0.01	0.00
20 mph speed	0.12	0.06	0.02	0.01	0.01
30 mph speed	0.18	0.08	0.03	0.02	0.01
40 mph speed	0.20	0.09	0.03	0.02	0.01
50 mph speed	0.21	0.10	0.04	0.02	0.01
60 mph speed	0.22	0.11	0.04	0.02	0.01

The table indicates that the rate of pressure change of 200-mph tornadoes reaches certain maxima as the travelling speeds increase beyond 40 mph. It is because the rotational speed decreases as the travelling speed increases in order to keep the sum of both speeds constant, that is 200 mph.

It should be noted, however, that the dynamic effects of gusty wind induce a low pressure in the order of $\frac{1}{2} \rho V_m^2$ during the period of gust, lasting for few seconds. If an overestimated value of 1 psi is applied to the dynamically-induced pressure drop, a few tenths psi per sec of pressure change must be added to the pressure change due to the tornado as a whole (see Table VII). Thus, a combined rate of 0.5 psi per sec seems to be sufficient.

7. CONCLUSIONS

Careful analysis of the distribution of hail, tornadoes, and population in three Northwestern states revealed that the storm-reporting communities are scattered densely enough to establish a reasonable pattern of storm occurrences. This evidence by no means implies that all tornadic and hail storms are reported. But the pattern of storm distribution is distinct enough to determine preferable regions of tornadoes and hailstorms which are identified as "tornado alleys" and "hail swaths" in this paper.

Through careful "characterization" of tornadoes in a 20-year period in three Northwestern states, it was concluded that the maximum wind speed, including both translational and rotational speeds, of tornadoes in alleys generally falls between 200 mph and 225 mph depending upon characteristics of alleys.

The amount of pressure drop due to a tornado vortex as well as high winds inside a tornado of 200-mph maximum rotational speed was estimated to be up to 1.5 psi.

Time change in the pressure caused by a fast-moving tornado vortex of a 200-mph combined speed was also computed to be up to about 0.2 psi per sec. A dynamic pressure change of a few tenths psi must be added to obtain the maximum total pressure changes. Thus, a 0.5 psi per sec may be regarded as the maximum pressure change outside a structure under the influence of tornadoes under consideration.

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FUJITA SCALE FOR DAMAGING WIND

Scale	mph	Expected Damage
F 0	(40- 72)	Light Damage
F 1	(73-112)	Moderate Damage
F 2	(113-157)	Considerable Damage
F 3	(158-206)	Severe Damage
F 4	(207-260)	Devastating Damage
F 5	(261-318)	Incredible Damage

TORNADO MISSILE CALCULATION

D. E. Simpson

TORNADO MISSILE CALCULATION

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The aerodynamic wind force which could act to lift an object and retain it within a tornado vortex is a lift force which may be expressed as

$$F_L = C_L \frac{\rho A}{2} (v_a - v_o)^2$$

where

C_L is a coefficient determined by object shape and attitude

A = object projected area (ft^2)

ρ = mass density of air;

$$\left(\frac{\text{lb-sec}^2}{\text{ft}^4} \right) (= 2.5 \times 10^{-3})$$

v_a = wind speed (ft/sec)

v_o = object speed (ft/sec)

Two forces exist tending to cause the object to escape from the vortex, these being gravity and centrifugal force.

$$F_G = W$$

$$F_{CF} = \frac{W v_o^2}{g R}$$

where

W = object weight (lb)

g = acceleration of gravity

v_o = object tangential velocity (ft/sec)

R = radius of maximum tornado wind speed.

The maximum object velocity which can be achieved is that at which the vector sum of the escape forces equals the possible lift force.

Thus

$$C_L \frac{\rho}{2} A (v_a - v_o)^2 = W \left[1 + \left(\frac{v_o^2}{gR} \right)^2 \right]^{1/2}$$

This equation has been solved to find the maximum object velocity as a function of $\frac{W}{A}$ for two sets of tornado characteristics:

a) First case

$$v_a = 220 \text{ ft/sec (150 mph)}$$

$$R = 100 \text{ ft}$$

b) Second case

$$v_a = 440 \text{ ft/sec (300 mph)}$$

$$R = 225 \text{ ft}$$

The results are shown in Figure 1, with C_L as a parameter for each case.

Some objects which have been considered as potential tornado missiles, and estimated approximate characteristics, are listed below:

<u>Object</u>	<u>Car</u>	<u>3" Pipe</u>	<u>4 x 12</u>	<u>2 x 12 or 2 x 8</u>	<u>3/4" Plywood</u>	<u>Steel Siding (20 ga)</u>
W/A	30	30	10	5	2	1-3/4
C_L	<1/4	<1/4	1/2	1/2	1	1
V_o - <u>mph</u>						
300 mph tornado	<55	<55	120	140	225	230
150 mph tornado	None	None	40	55	90	90

MAXIMUM OBJECT VELOCITY VS. WEIGHT/AREA RATIO