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SATELLITE & MESOMETEOROLOGY RESEARCH PROJECT

Department of the Geophysical Sciences
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TYPHOON-ASSOCIATED TORNADOES IN JAPAN AND NEW EVIDENCE OF SUCTION VORTICES IN A TORNADO NEAR TOKYO

by

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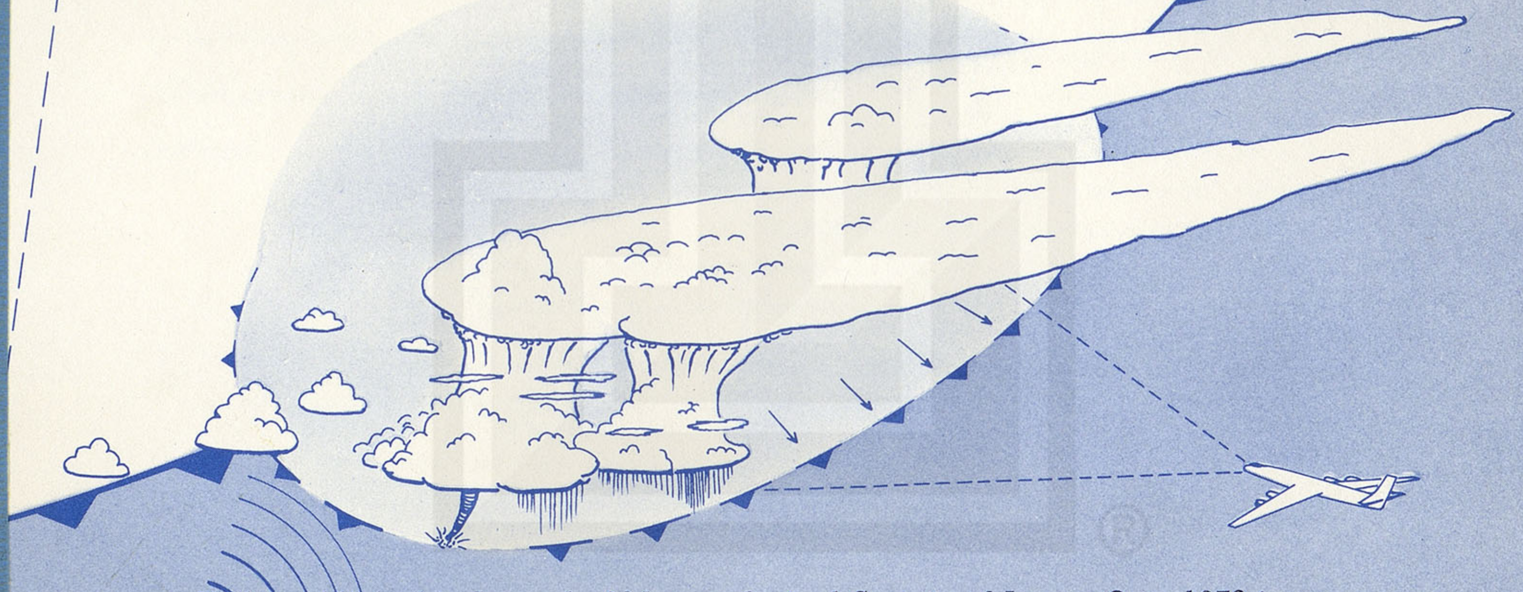

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TYPHOON-ASSOCIATED TORNADOES IN JAPAN AND NEW EVIDENCE OF SUCTION VORTICES IN A TORNADO NEAR TOKYO

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TYPHOON-ASSOCIATED TORNADOES IN JAPAN AND NEW EVIDENCE OF SUCTION VORTICES IN A TORNADO NEAR TOKYO[1]

by

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Kiyoshi Tsuchiya and Moriya Shimada

Abstract

Typhoon-associated tornadoes during a 22 year period, 1950-71, were investigated in relation to hurricane-associated tornadoes studied by Hill et al. (1966). It was found that most tornadoes of this type spawn in the right front quadrants of the parent tropical storms. A significant 6-hr variation in the tornado frequencies was found through Fourier analyses. Damage areas of Omiya tornado of July 7, 1971, associated with tropical storm Ivy, were surveyed both from the air and the ground. Two types of suction-vortex swaths which have not been known in the U. S. were found in an open field. One was characterized by a pattern of cyclonic vortex depicted by the orientations of sweet potato vines stretched in the direction of the strong winds. The other left a clear indication of a rotating column of dirt which spattered maple saplings. A deposit of dirt somewhat like a narrow dirt road was

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left in a plowed field along the path of this suction-vortex center. Detailed meso-analysis revealed the existence of a mesocyclone and a mesojet in the immediate vicinity of the spawning ground of the Omiya tornado, thus solving, in part, the mystery of the tornado formations to the right of tornado-cyclone centers commonly observed in the United States. Finally, the four scales of circular motion, cascading down from typhoon, tornado cyclone, tornado, to suction vortex, were emphasized to stimulate future investigations of similar phenomena in Japan, the United States and elsewhere.

1. INTRODUCTION

Tornadic phenomena have long been assumed to be unique to the United States, occasionally giving the false impression that similar but less pronounced phenomena in other parts of the world might be significantly different from typical U.S. tornadoes.

The word tatsumaki, consisting of two Chinese characters - tatsu, dragon, and maki, whirl - has been used in Japan to designate both waterspouts and tornadoes. Funnels aloft over water are often identified by tatsumaki aloft. Because most of the literature on tatsumaki is written in Japanese, tatsumaki stories have not been evaluated properly in relation to tornadoes and waterspouts in the United States.

Although the history of early tatsumaki in Japan is not known very well, historical records date back as early as 1147 A.D. when a tatsumaki was reported in Kyoto. A tatsumaki of August 12, 1721 started at 2 AM with a rumbling noise, somewhat like that of an earthquake, and was followed by tremendous winds, trees were uprooted and stones started flying. When the storm ended most houses in one village had received damage while the neighboring villages experienced only heavy rain. Some thought that the local disturbance was caused by a dragon as he ascended up into the storm cloud. On June 30, 1899 a tornado hit a speeding train, overturning 5 passenger cars. The incident occurred only several blocks from the present location of the New Tokaido Line south of Nagoya City. Some 30 years ago, November 1941, a giant tatsumaki (waterspout) near Toyohashi, Aic. picked up 10 boats at the landing site, then continued traveling inland destroying houses, schools, factories and trees along an 8-km (5-mile) path; 12 were killed, 177 were injured and 1350 houses were damaged.

In recent years, more reliable statistics have been obtained by a number of meteorologists. The sources of tatsumaki data vary with researchers but the main source is Kishoyoran (Japanese Storm Data), published monthly by Japan Meteorological Agency, which includes the most confirmed tornado data. There are always possibilities that additional data might be found in the local weather bureau reports and in various newspapers. Listed in Table 1 are frequencies of tatsumaki as reported by these researchers.

Table 1. Frequency of Tatsumaki in Japan. Since tatsumaki includes both waterspout and tornado, known tornado frequencies are given in parenthesis. Prorated annual frequencies were computed by multiplying 21, the area ratio of U.S. and Japan, excluding Alaska where tornado frequency is negligible.

Authors and (year published)	Sekiya (1949 and 1957)	Ibaraki and Tanaka (1961)	Shimada (1967)	Mitsuta (1968)	Shimada (1969)	Fujita (1971a)
Period	1926 - 48	1948 - 59	1955 - 64	1955 - 64	1955 - 65	1950 - 69
No. of Years	23	12	10	10	11	20
No. of Storms	*89	57	(76)	(72)	122	(156)
Per Year Freq.	*3.9	4.8	(7.6)	(7.2)	11.1	(7.8)
Prorated Freq.	*84	101	(160)	(152)	233	(164)

* includes 19 tatsumaki in Ryukyu, 5 on China coast and 2 in Caroline Island.
( ) exclude tatsumaki which stayed over water.

This evidence leads to an initial conclusion that tatsumaki can be classified into 3 sub-categories, tornadoes, waterspouts, and funnels aloft, each of which may be treated as the counterpart category of U.S. storms. Of course, their intensity, path length, path width, and other parameters are subject to further investigation.

The main objectives of this paper are (1) to investigate typhoon-associated Japanese tornadoes in a manner similar to that of Hill et al. (1966) who investigated hurricane-associated U.S. tornadoes and (2) to study in detail a specific tornado of July 7, 1971 which caused major damage in Omiya, 25 km (15 mi) NNW of downtown Tokyo.

As the first step of this research, various data on typhoon-associated tornadoes were collected from all possible sources in Japan for a 22-year period, 1950-71. A total of 68 tornadoes appearing in the initial list were classified based on the Fujita-Pearson Tornado Scale (1972). Meanwhile, literature on both U.S. and Japanese tornadoes was reviewed in an attempt to compare their characteristics.

The detailed structure of the Omiya tornado and its environment was investigated. An unusual amount of local meteorological data was collected in order to perform mesometeorological analyses of the tornado environment. Both aerial and ground surveys of the tornado affected areas were made in which color pictures were made to record damage along the 6.2-km (3.9-mile) path originating in Urawa City and ending in Iwatsuki City.

2. CLASSIFICATION OF TORNADOES IN JAPAN BASED ON FUJITA-PEARSON TORNADO SCALE - F P P SCALE

In order to evaluate typhoon-associated tornadoes in Japan a tornado scale proposed recently by Fujita and Pearson (1972) was used. The scale, abbreviated as F P P scale, consists of three numbers expressing the scales of damaging wind (F), path length (the first P), and path width (the second P).

The scale of damaging wind as presented in Fujita's (1971a) original article is expressed by

$$V = 6.30\,(F+2)^{\frac{3}{2}} \text{ m/sec} \qquad (1)$$

where V denotes the speed of the F-scale damaging wind or the fastest 1/4-mile wind corresponding to the F scale. It should be noted that the F1 speed corresponds to Beaufort force 12 and that F12 corresponds to the speed of sound, Mach 1 at -3°C. The F scale will thus permit us to assess the range of damaging wind speed of tornadoes as F1 (B12), F2, ... F12 (M1). Nonetheless, the occurrences of F6 or stronger tornadoes in the U.S. and F4 or stronger ones in Japan are most unlikely, although there are possibilities that an extraordinary storm might cause unexpected damage.

To perform quick F-scale assessments of the tornado damage, an F-scale damage chart (see Fig. 1) was made from a collection of damage pictures taken after the Omiya tornado. Damage specifications corresponding to each F scale were completed also based on a number of wind estimates such as that of Segner (1960), Mitsuta (1968) and Ishizaki et al. (1971a and 1971b). For further explanation of the F scale damaging wind, refer to Shimada's (1971) article in Japanese.

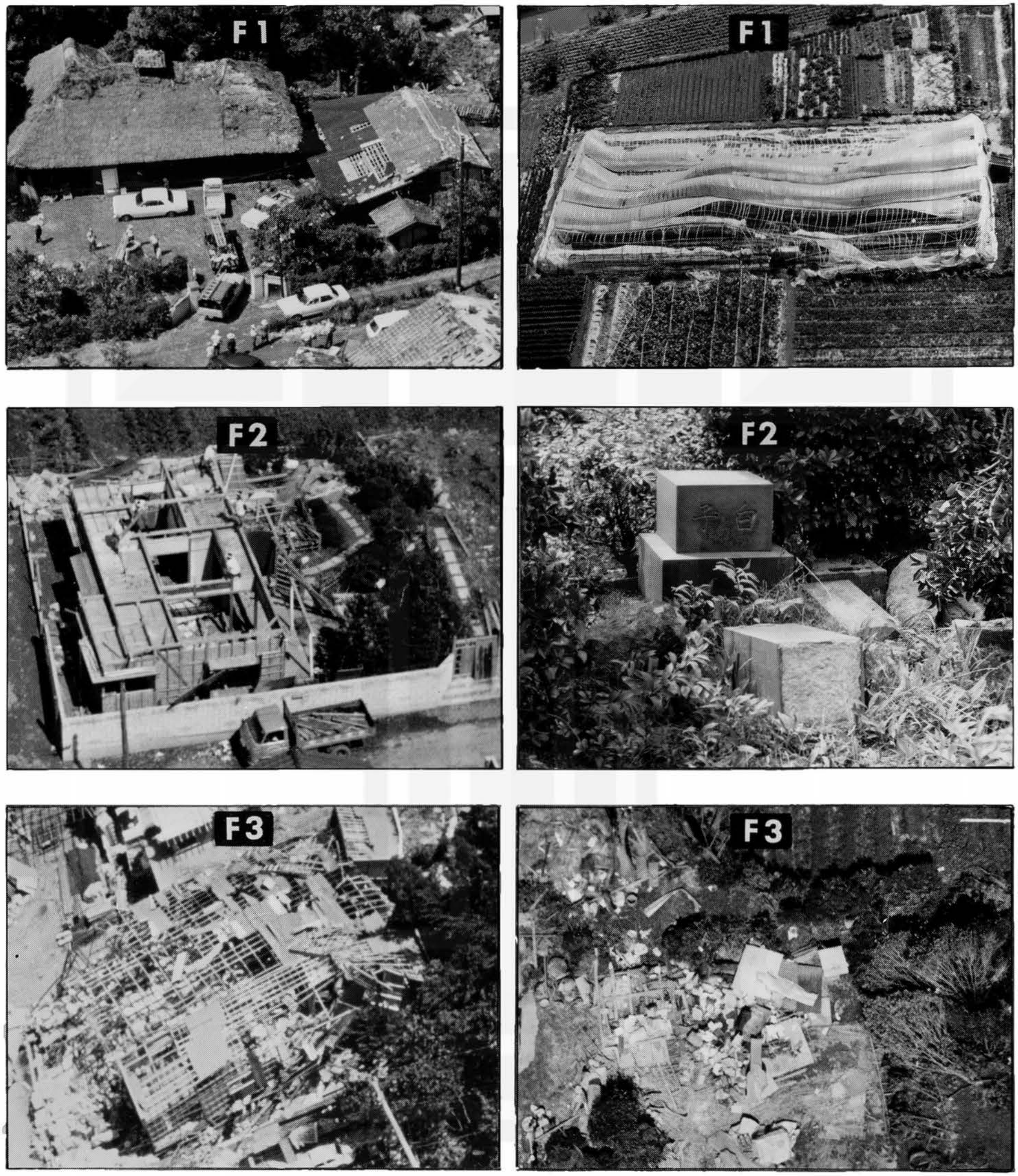

Figure 1. Fujita-scale damage pictures applicable to tornadoes in Japan. A similar collection of F 1 through F 5 damage pictures in U. S. is presented by Fujita (1971a).

Table 2. Ranges of Fujita-scale Wind Speeds

F Scale	Speeds in m/sec	Damage Categories in English and Japanese	
0	17.8 - 32.6	Light Damage	Keibina Higai
1	32.7 - 50.3	Moderate Damage	Namino Higai
2	50.4 - 70.3	Considerable Damage	Kenchona Higai
3	70.4 - 92.5	Severe Damage	Gekijinna Higai
4	92.6 - 116.6	Devastating Damage	Kohaiteki Higai
5	116.7 - 142.5	Incredible Damage	
6 or larger	142.6 -	Inconceivable Damage	

F-scale Damage Specifications

(F 0) 17-32 m/s, LIGHT DAMAGE (Keibina Higai)
Some damage to chimneys and TV antennae; breaks twigs off trees; pushes over shallow rooted or weak trees.

(F 1) 33-49 m/sec, MODERATE DAMAGE (Namino Higai)
Peels tiles off roofs; straw roofs damaged; weak windows broken; vinyl green houses disturbed and damaged; small cars overturned by lateral wind. F 1 begins with the typhoon wind speed.

(F 2) 50-69 m/sec, CONSIDERABLE DAMAGE (Kenchona Higai)
Roofs torn off residential houses leaving strong upright walls; weak non-residential houses demolished; large trees snapped or uprooted; railroad cars pushed over by lateral wind; cars blown off road by lateral wind; tombstones shifted or blown off foundations.

(F 3) 70-92 m/sec, SEVERE DAMAGE (Gekijinna Higai)
Roofs and some walls torn off residential houses; steel-framed structure destroyed; some non-residential houses blown off foundations; trains overturned; cars lifted off the ground; most trees in forest uprooted, snapped or leveled.

(F 4) 93-116 m/sec, DEVASTATING DAMAGE (Kohaiteki Higai)
Whole residential houses leveled to the ground, leaving piles of debris; steel-framed structure blown down; trees debarked by small flying debris; cars and trains thrown some distance or rolled considerable distance; large flying objects generated.

(F 5-12) 117 m/sec to sonic speed, INCREDIBLE DAMAGE
It is very unlikely that tornadoes of this intensity occur in Japan.

The tornado path length and path width to be identified as Pearson scale are computed from

$$L = 1609 \times 10^{\frac{1}{2}(P_L - 1)} \text{ meters} \quad (2)$$

$$W = 1609 \times 10^{\frac{1}{2}(P_W - 5)} \text{ meters} \quad (3)$$

where L is the path length measured along the tornado track, P_L, Pearson-scale path length, $\overline{W}$, the damage width averaged over the entire path, P_W, Pearson-scale path width. The coefficient 1609 resulted from the conversion of miles into meters.

Table 3. Ranges of Pearson-scale path lengths and path widths

P Scale	Path Lengths	Path Widths
0	less than 1.6 km	less than 16 m
1	1.6 - 5.0	16 - 50
2	5.1 - 16.0	51 - 160
3	16.1 - 50.8	161 - 490 m
4	50.9 - 160	0.5 - 1.5 km
5	161 - 508	1.6 - 5.0
6 or larger	509 or longer	5.1 km or wider

The longest path length and the widest path width of historical Japanese tornadoes is not known to the authors at the present time. It is very likely, however, that scale 3 would be the largest P P number. This means that most Japanese tornadoes are characterized by F P P scales ranging between 0,0,0 and 3,3,3. In the United States the range would be between 0,0,0 and 5,5,5.

3. TYPHOON-ASSOCIATED TORNADOES IN JAPAN

It is known that tornadoes often spawn within cyclones of tropical origin in their tropical storm, hurricane or typhoon, dissipating and redevelopment stages. These tornadoes have been identified by various authors who used terms such as "tornadoes associated with cyclones of tropical origin" by Hill et al. (1966), "tornadoes associated with hurricanes" by Malkin and Galway (1953), "hurricane-tornado" by Smith (1965), "hurricane-induced tornadoes" by Pearson and Sadowski (1965), "tornadoes associated with hurricane" by Sadowski (1962), and "tornadoes with hurricanes" by Sadowski (1966). These terms designate tornadoes spawned within the area of cyclones of tropical origin which often develop into hurricanes. In Japan these storms may grow into typhoons instead. Two simple terms, "typhoon-associated tornadoes" and "hurricane-associated tornadoes," are used in this paper with the understanding that typhoons and hurricanes include tropical-storm stages of cyclones of tropical origin.

In their study of 57 tornadoes in Japan during 1948-59, Ibaraki and Tanaka (1961) pointed out that 4 tornadoes occurred inside typhoons or tropical storms as they approached the southern coast of Japan. Further investigation of 76 tornadoes during 1955-64 by Shimada (1967) revealed that the right front quadrant of a typhoon is favorable for tornado occurrences. Two years later Shimada (1969) confirmed 6 tornadoes that spawned inside the right front quadrant of a typhoon traveling along the south coast of Japan. Wakita and Kinowaki (1968) compiled statistics of 28 tornadoes spawned in Miyazaki Prefecture during a 31-year period, 1934-64, finding that 17 occurrences (61%) were associated with typhoons. The locations of tornadoes were limited over the plain within 20 km (13 mi) from the Pacific coast of Miyazaki Prefecture covering only 60 × 130 km (40 × 80 mi) area.

An exhaustive search for typhoon-associated tornadoes was made by the authors, ending up with a table of 68 storms during a 22-year period, 1950-71. Table 4 was prepared following the format of 136 hurricane-associated tornadoes by Hill et al. (1966). In the 6th column we added the F P P scale along with the identifier of tornadoes originating from waterspouts which consist of 24% of the tabulated storms.

Geographical distribution of typhoon-associated tornadoes in Table 4 is presented in Fig. 2. Tornadoes are identified with F0 through F3 symbols as well as their

Table 4. List of typhoon-associated tornadoes in Japan during a 22-year period, 1950 through 1971. Time of storm occurrence is in Japan Standard Time which is GMT + 9 hr. Location includes the township and 3-letter prefecture identifier. AZ-RA combination denotes azimuth and range of tornado relative to the center of tropical storm; F P P, Fujita-Pearson tornado scale; D/I, deaths and injuries; P_e – Dir, environmental pressure and direction of tornado; and P_c – Dir, central pressure and direction of tropical cyclone.

ID	Date	Time	Location	AZ-RA	F P P	D/I	P_e – Dir	P_c – Dir
1	09-03-50	1410	7 ESE Toyohashi, Aic.	116- 210	1,1,0	0/14	1001 ---	962-031
2	10-14-51	0720	Aoshima, Mzk.	036- 690	2,1,0	0/64	999 NNW	930-021
3	10-14-51	0930	Kawaminami, Mzk.	036- 720	1,0,0	0/5	1001 NNW	930-020
4	08-06-53	1620	Handa, Aic.	339- 400	0,0,0	0/3	1011 W	990-029
5	08-17-54	2100	8 S Fujieda, Siz.	059- 910	0,2,2	0/0	1003 N	950-051
6	08-18-54	2100	9 WSW Toyohashi, Aic.	069- 360	0,0,0	0/0	993 ---	970-061
7	09-07-54	0900	Miyazaki, Mzk.	358- 270	0,0,0	0/0	1005 ---	950-003
8	09-12-54	1125	Takanabe, Mzk.	350- 550	*1,1,0	0/0	998 WNW	940-350
9	09-12-54	1300	Miyazaki, Mzk.	350- 550	0,0,0	0/0	998 SW	940-350
10	09-13-54	0900	Miyazaki, Mzk.	022- 280	0,0,0	0/0	980 ---	945-012
11	09-17-54	21xx	Fujieda, Siz.	028- 720	1,2,1	x/x	1009 ---	970-360
12	09-29-55	0920	Miyazaki, Mzk.	017- 380	1,1,0	0/22	1004 W	940-004
13	09-29-55	0930	Saito, Mzk.	016- 410	0,0,0	0/0	1005 ---	940-004
14	08-16-56	0630	Makurazaki, Ksi.	043- 470	*1,1,1	x/x	1006 NNW	965-030
15	09-07-56	0930	Kunitomi, Mzk.	001-1070	1,2,1	0/2	1011 WNW	940-323
16	09-09-56	1330	Yatsushiro, Kum.	051- 330	0,0,0	0/x	994 ---	940-007
17	09-10-56	0730	Shizuoka, Siz.	096- 730	2,2,2	2/44	1008 NNE	950-025
18	08-23-57	1510	Shingu, Wak.	033- 500	0,0,1	0/3	1008 NE	998-006
19	09-16-58	0030	9 WSW Saito, Mzk.	360- 550	0,0,2	x/x	1003 NW	945-035
20	09-17-59	0430	Nishinoomote, Ksi.	119- 440	*1,0,0	x/x	1002 NE	935-032
21	09-17-59	1940	7 NNW Tanabe, Wak.	138- 510	1,1,1	0/3	1003 NE	970 041
22	08-26-60	1530	30 N Obihiro, Hok.	240- 380	0,1,2	0/0	1006 ---	997-021
23	09-15-61	0740	Miyazaki, Mzk.	025- 490	0,0,0	0/1	1013 WNW	920-036
24	09-15-61	1015	Obu, Aic.	044-1040	1,2,1	0/14	1006 NNE	920-040
25	10-02-61	2250	Miyazaki, Mzk.	026- 750	0,0,1	0/0	1007 ---	938-280
26	08-25-62	15xx	Fuchu, Tyo.	030- 560	1,0,0	1/x	1017 ---	950-351
27	08-26-62	0400	Hamamatsu, Siz.	095- 190	*2,2,2	0/18	1007 NW	980-012
28	08-26-62	0410	Maisaka, Siz.	095- 180	*1,2,1	0/x	1006 NW	980-012
29	08-26-62	0700	Ami, Iba.	074- 420	0,0,1	0/x	1017 NW	985-010
30	08-26-62	0825	Omaezaki, Siz.	076- 300	*1,0,1	0/x	1012 NNE	985-010
31	08-27-63	1145	Kawaminami, Mzk.	331- 200	0,0,0	x/x	1009 ---	975-050
32	08-29-63	1750	Hamamatsu, Siz.	260- 550	0,0,0	x/x	1006 ---	985-066
33	08-01-64	1030	6 S Takanabe, Mzk.	350- 310	1,0,2	0/0	1000 WSW	965-305
34	08-20-64	0335	6 S Takanabe, Mzk.	360- 580	0,0,1	0/0	1000 SW	960-310
35	08-21-65	0915	Denenchofu, Tyo.	019- 510	2,1,1	0/7	1010 ---	945-305
36	08-21-65	1430	Sarushima, Iba.	025- 600	1,1,1	0/0	1010 ---	950-304
37	08-21-65	1500	Urawa, Sai.	020- 550	0,0,0	0/0	1009 ---	950-304
38	08-21-65	1900	Ami, Iba.	028- 530	0,0,0	0/0	1009 ---	950-300
39	07-19-67	16xx	Iizuka, Fuo.	340- 770	0,0,0	x/x	1004 SW	1003-270
40	10-28-67	0205	Kamogawa, Cba.	083- 270	*3,2,2	0/x	998 N	970-040
41	10-28-67	0233	Togane, Cba.	073- 300	2,1,2	2/x	998 N	970-040
42	10-28-67	0312	Iioka, Cba.	072- 340	*3,2,2	0/x	998 N	970-040
43	08-28-68	12xx	Kochi, Kch.	037- 660	0,0,0	x/x	1004 ---	980-030
44	09-24-68	1530	Miyazaki, Mzk.	045- 220	1,2,2	0/x	1005 NNW	955-040
45	09-24-68	1725	4 S Takanabe, Mzk.	045- 220	*2,0,2	0/15	1005 NW	955-040
46	09-24-68	1905	Takanabe, Mzk.	052- 160	*3,1,2	0/x	1001 WNW	955-040
47	09-24-68	1920	Takanabe, Mzk.	052- 160	*2,1,1	0/x	1001 NW	955-040
48	09-24-68	1930	Kawaminami, Mzk.	051- 170	2,x,x	1/0	1001 ---	955-040
49	08-22-69	1502	Yufuin, Ota.	345- 110	1,1,2	0/2	992 WSW	965-067
50	08-23-69	0930	Sarushima, Iba.	069- 200	3,3,2	2/107	998 NNW	986-064
51	08-23-69	1015	Kamogawa, Cba.	110- 190	*2,1,1	0/4	998 NNE	986-064
52	08-23-69	1045	Hachijojima, Tyo.	157- 310	*1,1,1	0/1	1001 NE	986-064
53	08-23-69	1050	Oyama, Tgi.	062- 160	3,2,2	0/23	993 NW	986-064
54	08-23-69	1130	Asou, Iba.	086- 170	*1,1,2	0/3	993 N	986-064
55	08-23-69	1420	Iwaki, Fus.	050- 90	1,0,1	0/0	987 ---	986-064
56	07-07-70	02xx	Fukue, Nki.	155- 330	0,1,0	0/3	999 ENE	997-225
57	08-21-70	1110	Tsumanuma, Sai.	068- 650	2,2,1	0/0	1016 NNE	970-350
58	07-07-71	0800	Omiya, Sai.	049- 640	3,2,2	1/12	1006 NNE	990-035
59	08-28-71	1420	Shimizu, Kch.	010- 530	*0,0,0	0/2	1008 WNW	945-303
60	08-31-71	03xx	Hamamatsu, Siz.	068- 240	0,x,x	0/x	991 ---	985-070
61	08-31-71	0330	Shimizu, Siz.	066- 290	1,1,1	0/x	993 ---	985-071
62	08-31-71	0715	Kamogawa, Cba.	074- 370	*1,1,1	0/x	995 N	985-072
63	08-31-71	075x	Kugayama, Tyo.	060- 340	1,0,0	0/x	994 W	985-073
64	08-31-71	0800	Honhaneda, Tyo.	063- 330	0,0,0	0/0	994 ---	985-073
65	08-31-71	0905	Chiba, Cba.	066- 330	2,2,2	1/16	993 NNE	985-076
66	08-31-71	1050	Iioka, Cba	066- 340	*1,1,1	0/1	995 N	986-077
67	09-08-71	02xx	Iioka, Cba.	325- 80	2,x,x	0/x	994 SW	975-044
68	09-08-71	04xx	Oohara, Cba.	235- 145	1,x,x	0/x	1002 ---	975-047

*Tornado originating from waterspout

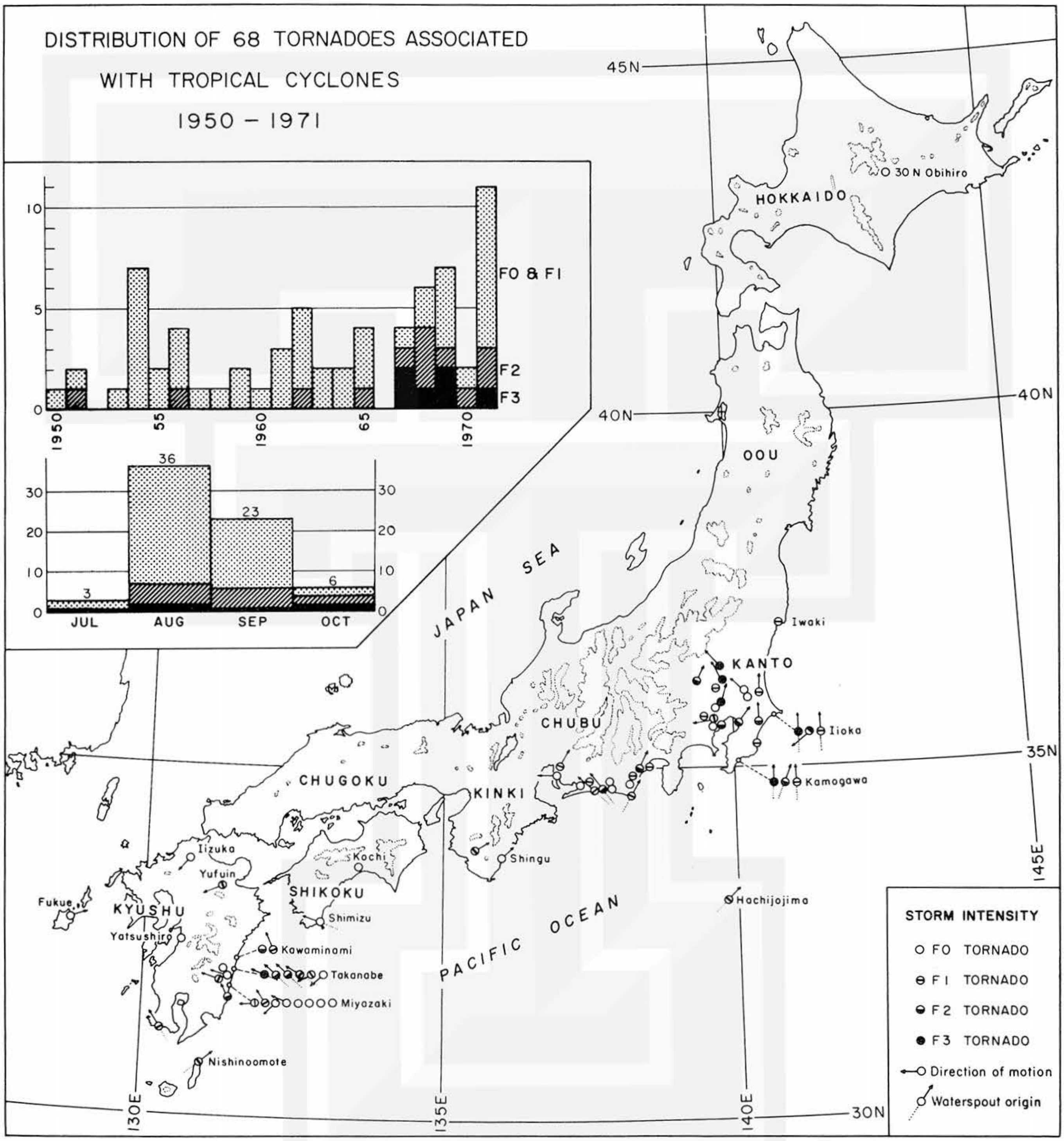

Figure 2. Distribution of typhoon-associated tornadoes during a 22-year period, 1950-71. Tornadoes are identified with F-scale intensity as well as their direction of motion and waterspout origin whenever applicable.

direction of motion and the origin, waterspout or not. It will be found that most tornadoes occurred inside low-level plains along the southern coast of Japan just north of Kuroshio current which is the counterpart of the Gulf stream. A large plain in Kanto appears to be very popular for tornado formation. Five tornadoes rated as F 3, two of which are of waterspout origin, are found there. A number of storms are seen within the narrow coastal plain along the Pacific coast of Chubu. Fast trains with 210 km/hr (130 mph) speed are operated every few minutes both ways along this tornado alley. Another concentration of 20 typhoon-associated tornadoes is seen in Miyazaki Prefecture where waterspout-originated tornadoes are the worst ones.

Due mainly to the typhoon season in Japan being July through October, the maximum frequency of all tornadoes took place in August. Strangely enough, F 3 tornadoes were more or less distributed uniformly during the 4-month typhoon season. In fact, the F 3 tornado in Omiya occurred in July as a big surprise to Fujita who happened to be in Tokyo without expecting such a severe tornado only 15 miles away.

The annual frequencies of typhoon-associated tornadoes have increased rather steadily since the early 1950s when only one or two were reported annually. Immediately after 1966 when there were 7 typhoons that landed in Japan and spawned no tornadoes, the typhoon-associated tornadoes increased both in number and intensity. This fact is probably attributed to the reporting and damage survey systems which have been improving in recent years. Meanwhile, we should not underestimate the influence of the economical growth of Japan, resulting in an expansion of urban areas around the cities of all sizes. Such an expansion will help proper assessment of tornadoes by local residents. The apparent increase of this tornado frequency in Japan may well correspond to that of the United States during early 1950s when the reported frequencies increased almost 3 times, from about 200 to 600 per year. During the past several years, 600 to 900 tornadoes were reported annually.

F P P distributions of tornadoes in Fig. 3 were made from Table 4. Note that tornadoes of waterspout origin are stippled. It is of interest to find that tornadoes of waterspout origin are stronger on the average than those originated over land. The averaged F scale for the former is F 1.6 while the latter is only F 0.8. In reading Japanese storm data, the authors noticed quite often that the storm circulation intensifies immediately after waterspout crosses rather flat coastline to become a tornado. This is probably because the right amount of friction within the shallow boundary layer

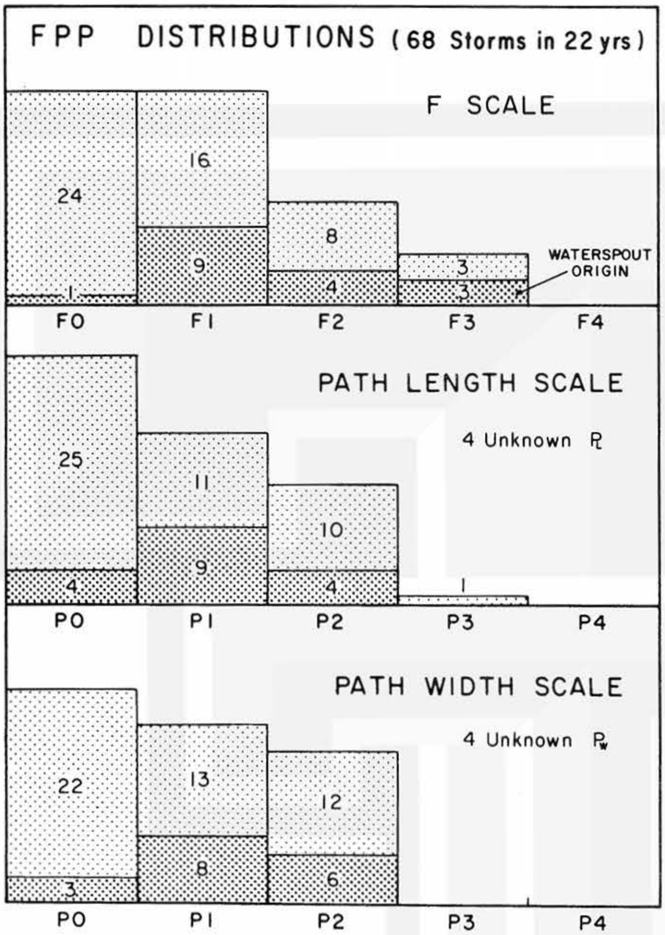

Figure 3. Distribution of FPP scale of typhoon-associated tornadoes in Japan. Based on 68 tornadoes in Table 4.

just above the surface could act as medicine to stimulate frictional inflow into the storm immediately after its landing. The radial inflow into a waterspout could be inhibited due to the lack of proper amount of friction.

The above statistics reveal that some tornadoes of waterspout origin within typhoons could be very dangerous. Recent studies of Florida waterspouts by Golden (1969 and 1971), based on aerial photogrammetry, reveal the occurrences of damaging waterspouts in southern Florida. He concluded that wind speeds increase to about 40 kt (F 0.1) at the outer edge of the spray vortex above the sea surface and that the wind speeds of large intense waterspouts may reach as high as 130 kt (F 2.8).

An intense waterspout of February 7, 1971 which landed near Pensacola at 4:18 AM causing $3,000,000 damage was rated as an F 4 tornado by the Climatologist for Florida. On December 12, 1969 a waterspout traveled over Puget Sound for several miles, changing into an F 3 tornado upon landing just south of Seattle, Washington, 47.4°N latitude. The above evidence implies that some tornadoes of waterspout origin could be as intense as F 4.

Tornado frequencies for both path-length and path-width scales decrease almost exponentially. The maximum path-length scale was P 3 while no path width with P 3 or larger scale has been found so far.

Distributions of hurricane-associated tornadoes relative to the parent storm have been studied extensively in the United States. Malkin and Galway (1953) stated that tornadoes associated with hurricanes have, to date, been observed only in the forward semicircle or along the periphery of the tropical storm. Smith (1965) concluded that 56% of his 93 tornadoes during 1955-62 occurred within the significant sector between 30° and 120° to the right of the hurricane movement. No hurricane-associated tornado occurred in 1963. This might correspond to the zero frequency in Japan in 1966. Based on the 39 tornadoes in 1964, Pearson and Sadowski (1965) located the frequency center as being on the 30° line relative to the hurricane motion, which is in the right front quadrant of the parent storm. Since then Hill et al. (1966) tabulated 136 tornadoes which are predominantly located to the right of the hurricane motion with the frequency center located inside the right front quadrant about 30° to the right (see Fig. 4).

In order to compare the preferable locations of typhoon-associated tornadoes relative to the typhoon center and the direction of motion, 68 tornadoes in Table 4 were plotted in Fig. 4 in which tornado intensities are expressed in F scale. A circle in the diagram, which may be called the significant frequency circle, includes five out of six F 3 tornadoes as well as a large number of weaker tornadoes. The significant frequency circle drawn for hurricane-associated tornadoes appears to be very close in the relative position, implying that the preferable locations of hurricane- and typhoon-associated tornadoes may be considered identical. Outside the circle, tornadoes in typhoons spread far inside the forward sectors while those in hurricanes spread to the rear sectors. This is probably because many typhoons travel along the southern coast of Japan while most hurricanes move inland without following the coastlines for an extended period of time.

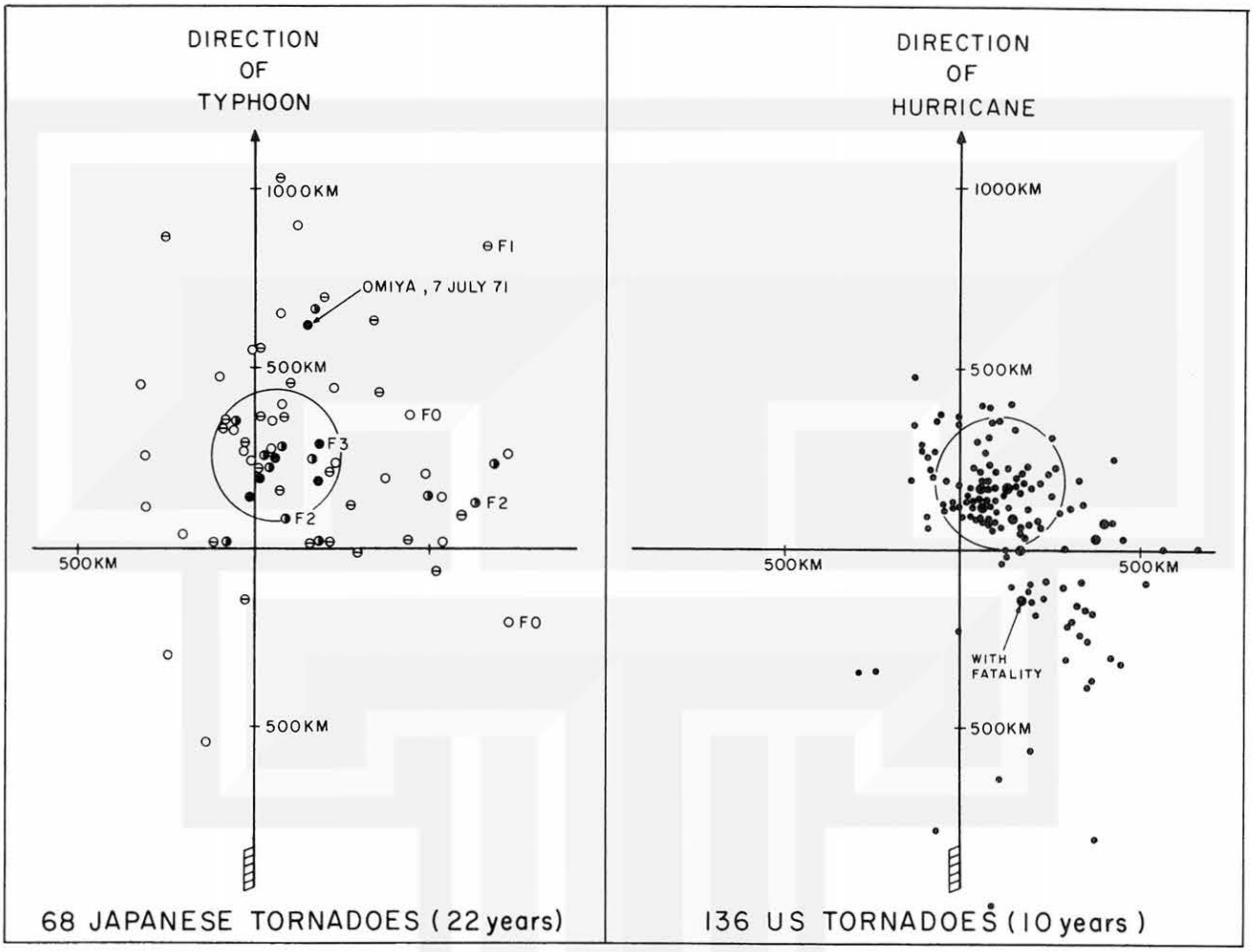

Figure 4. Comparison of the preferable locations of tornadoes associated with typhoons and hurricanes. 68 Japanese tornadoes are from Table 4 and 136 U.S. tornadoes from Hill et al. (1966).

Diurnal Variation of Tornado Frequency

Initial analysis of the diurnal variation of a typhoon-associated tornado revealed a striking 6-hour period oscillation with an amplitude somewhat larger than that of the expected 24-hour period. A Fourier analysis was performed to determine the corresponding amplitudes up to wave number n = 4. Namely, the amplitudes and phase angles were computed from

$$A = \bar{A} + \sum_{n=1}^{n=4} (a_n \cos n\omega t + b_n \sin n\omega t) \qquad (4)$$

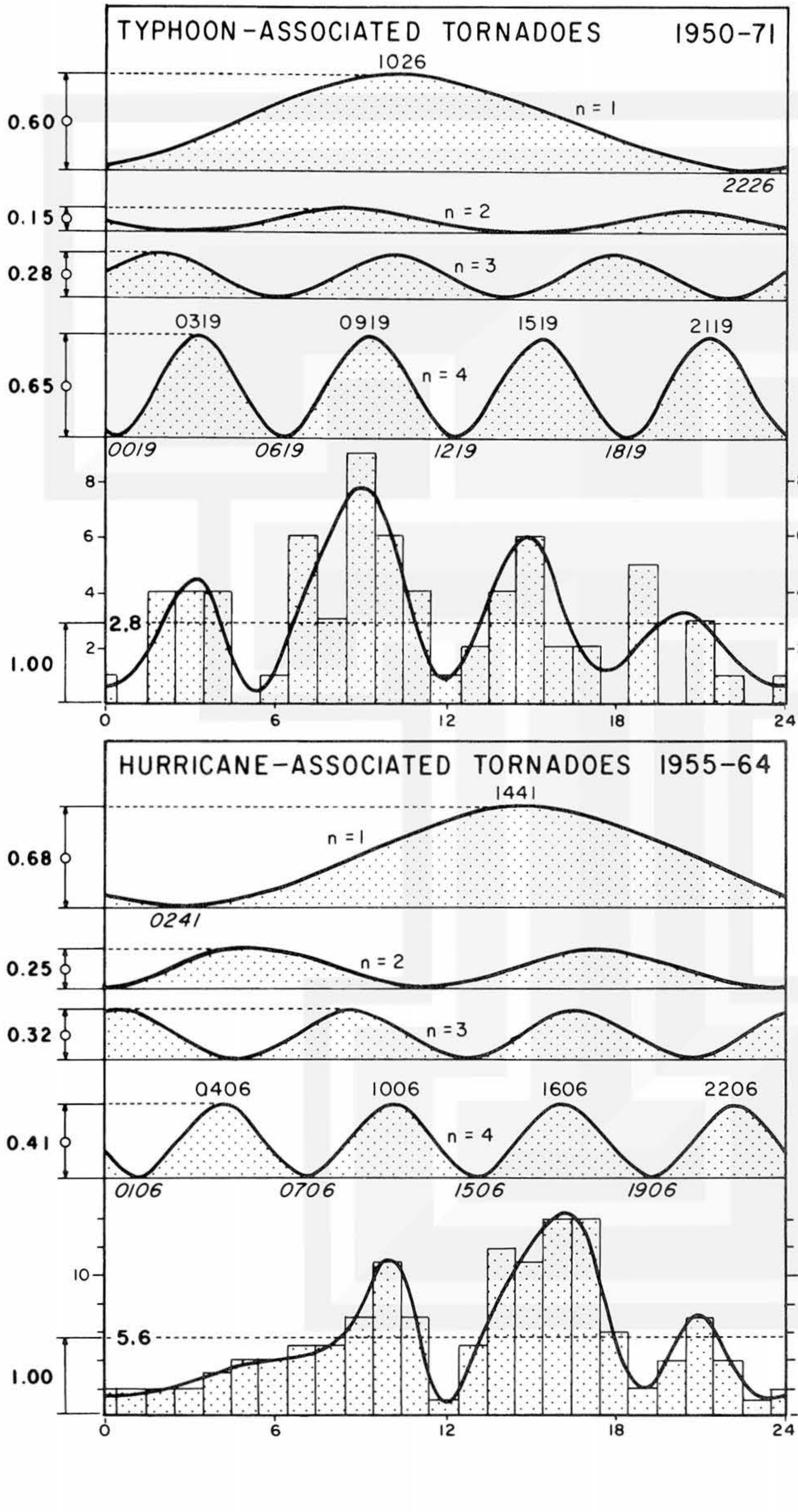

Figure 5. Fourier analysis of 68 Japanese and 136 U. S. tornadoes associated with typhoons and hurricanes, respectively. Despite the fact that the times of the 24-hour maxima are quite different, both amplitudes and phases of 6-hr variation are very similar in both cases, suggesting strongly that tornado frequencies are affected by 6-hr variation of meteorological parameters.

where A is the hourly tornado frequency, $\overline{A}$, the mean frequency averaged over the 24 hour period, n, the wave number, ω, the angular velocity of the earth, and a_n and b_n, the cosine and sine component of the amplitude, respectively.

Results shown in the top diagram of Fig. 5 reveal that the mean hourly frequency is 2.8 per hour during the 22-year statistical period. The amplitude of the 6-hr variation is 65% of the mean value, $\overline{A}$, while that of 24-hour amplitude is 60%. The phase angle of the 6-hr variation results in the maximum frequencies at 03h 19m, 0919, 1519, and 2119 JST while the maximum frequency of the 24-hr variation occurs at 1026 JST. Both wave numbers 2 and 3 are characterized by insignificant amplitudes.

It is reasonable to assume that the 24-hr variation is closely related to the rate of change in the incoming solar radiation which reaches a maximum during the early morning hours. Wave number 2 or 12-hr variation is very small but in phase with the semi-diurnal pressure variation. Wave number 4 or the 6-hr variation is by far the most mysterious one.

A similar 6-hr variation has been found when Fourier analysis was performed based on 136 hurricane-associated tornadoes tabulated by Hill et al. (1966). The maximum time of 24-hr variation for these storms is 1441 local standard time which corresponds to that of maximum surface temperature (see lower chart of Fig. 5). It should be noted that the maximum time of 24-hr variation of typhoon-associated tornadoes is 1026 local standard time which is 4hr 15min earlier. It would be necessary to perform statistical analyses of the diurnal variations of both pressure and temperature over Japan and coastal U.S. areas in relation to the air mass modification due to land and water distributions. Despite the difference in the maximum times of these 24-hr variations, the maxima of 6-hr frequencies of both typhoon- and hurricane-associated tornadoes are very close to each other. The phase difference is only 47 min which may be regarded as being identical in view of the differences in local apparent time applicable to each tornado location. An attempt of relating these mysterious 6-hr periods with a possible pulsation of hurricanes and typhoons might not be fruitful because similar but less pronounced 6-hr period variations were found by House (1963) for tornadoes in the Gulf states and by Shimada (1967) for tornadoes in Japan, each of which included all reported storms in respective areas.

4. SYNOPTIC SITUATIONS OF OMIYA TORNADO OF JULY 7, 1971

It is known that tornadoes are likely to spawn along hurricane rainbands. Specific research by Hill et al. (1966), Rudd (1964), and Sadowski (1962) revealed that tornadoes are frequently associated with either inner or outer rainbands in which convective activities are significant. Little was known about the tornado-rainband relationship within typhoons until Shimada (1969) put together tornado locations with rainband patterns as seen in Mt. Fuji radar and ESSA 8 pictures. He concluded that outer rainbands are the most favorable locations for tornado occurrences.

In light of the above evidence, an attempt was made to determine the location of the Omiya tornado in the APT picture received at Japan Meteorological Agency. The picture was taken at 0957 JST about 2 hours after the tornado (see Fig. 6). The location of the tornado is surrounded by a large mass of bright clouds. Nevertheless, the tornado appears to be located on the northern extension of the outermost rainband seen along 140° E.

The surface map at 0900 JST includes the tornado location and the path of tropical storm Ivy along with her 3-hourly positions. The tornado was located 640 km (400 mi) distance and 049° azimuth from the Ivy center (see Fig. 7). Large cold areas over the eastern half of Japan were covered with a massive cloud, suggesting that a shallow warm-front was in existence along the Pacific coast to the south of the cold areas.

A time cross-section from Tateno (646) located 50 km (30 mi) northeast of the tornado (see Fig. 8) indicates the presence of a 45-kt southwesterly jet extending up to about 600-mb height. At 530 mb the temperature appeared to be relatively cold with an indication of cold advection aloft centered about this height. The temperature deviation ΔT, defined as the air temperature above 293° K moist adiabat was computed at 6-hourly upper air observation time. Depicted in Fig. 8 is a significant cold pocket over the tornado location, suggesting strongly that the cold advection played an important role in decreasing the lifted index, resulting finally in the development of intense cumulonimbus convection.

Thermal wind generated by the cold advection aloft added a significant vertical shear to the underlying southwesterly producing a 62-kt mid-level jet. The horizontal extent of this mid-level jet over Tateno (646) was learned to be very narrow. As shown in the 530-mb map with APT cloud patterns in Fig. 9, Tateno wind is the strongest of

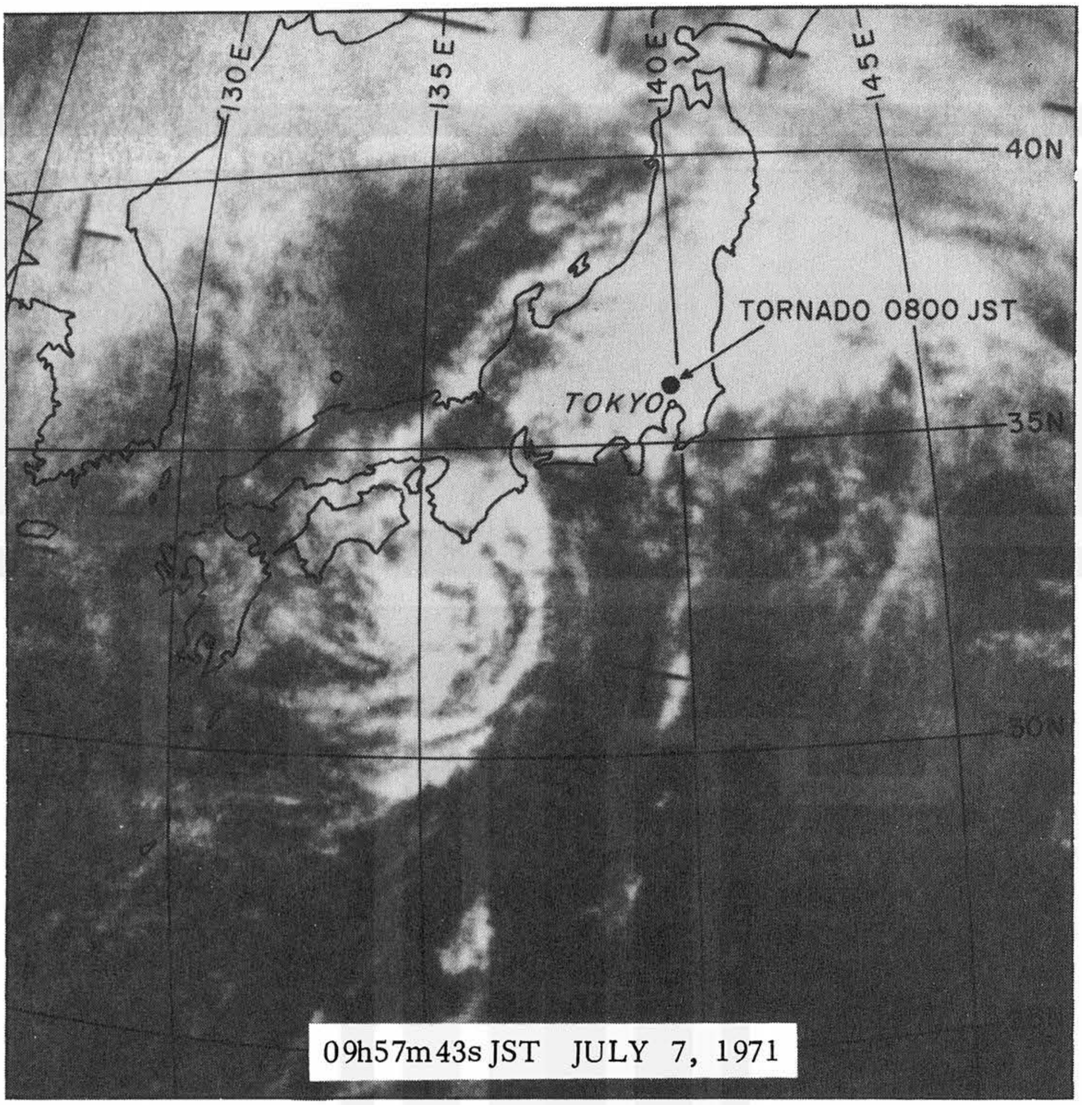

Figure 6. APT picture of ESSA 8 received in Tokyo. The picture time was about 2 hours after the Omiya tornado given by a black circle just north of Tokyo. An outer rainband can be followed southward from the tornado location.

all reported winds inside the map area. Although the extent of the mid-level jet toward the east cannot be estimated from existing data, it is very likely that a chain reaction of the cooling aloft and the induced thermal wind initiated a mesoscale mid-level jet over the area of the tornado development. Isotach analysis reveals that this mid-level jet is contributed by the outflow from Ivy but it is characterized

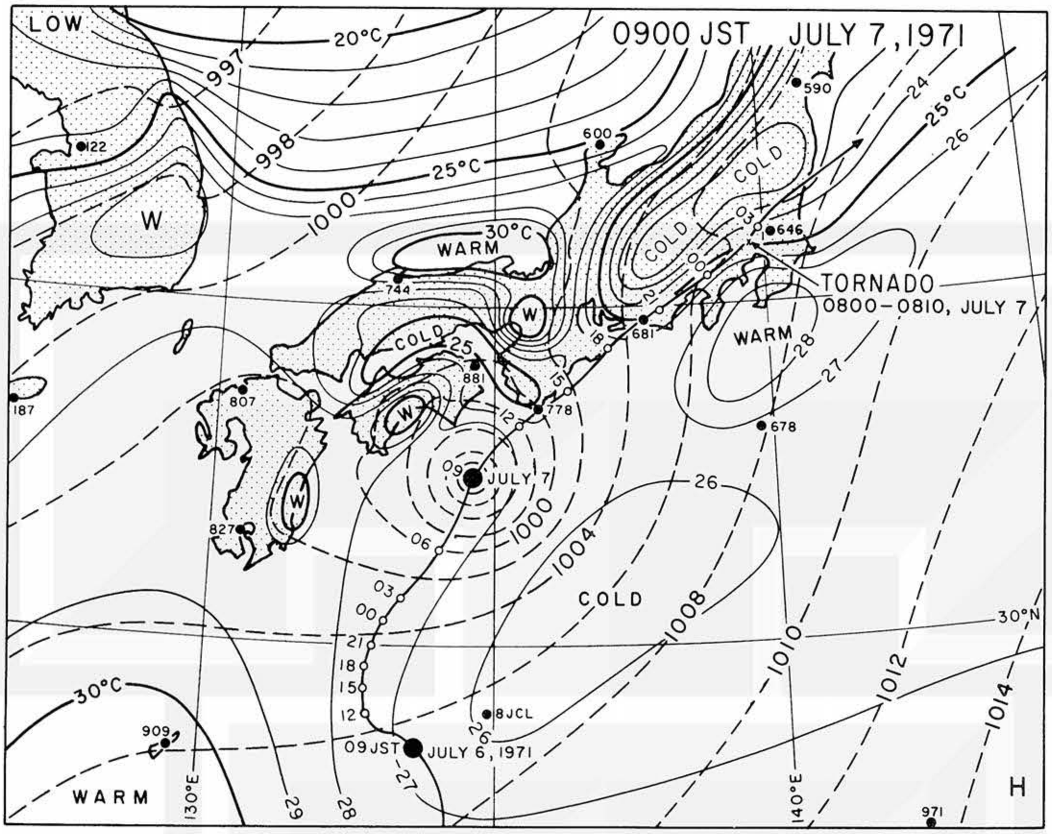

Figure 7. Surface map of tropical storm Ivy at 0900 JST, July 7, 1971. Isobars and isotherms are drawn for every 2 mb and 1° C, respectively.

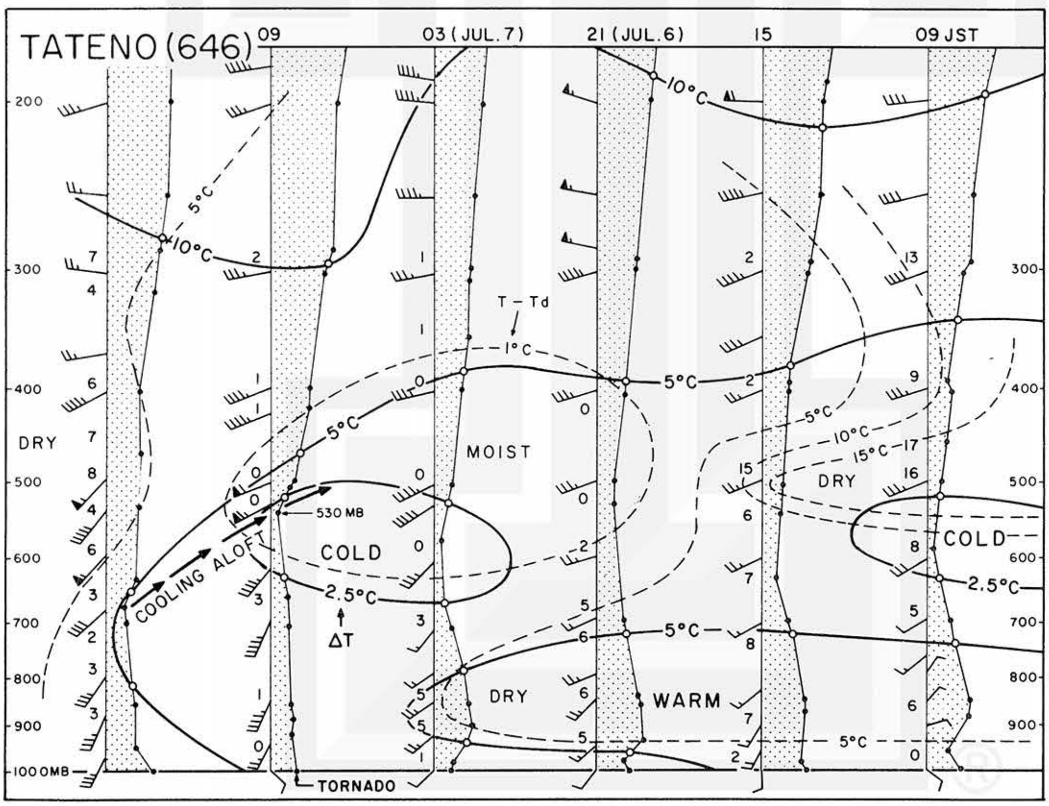

Figure 8. Vertical time-cross section of 6-hourly upper air soundings from Tateno (Station 646). Isotherms of the temperature deviations from a specific moist adiabat are drawn with heavy lines. Dashed isotherms are drawn for the dew point depression indicated in °C to the left of 6-hourly vertical lines. Note that the Omiya tornado occurred when 530 mb level was relatively cold and very moist.

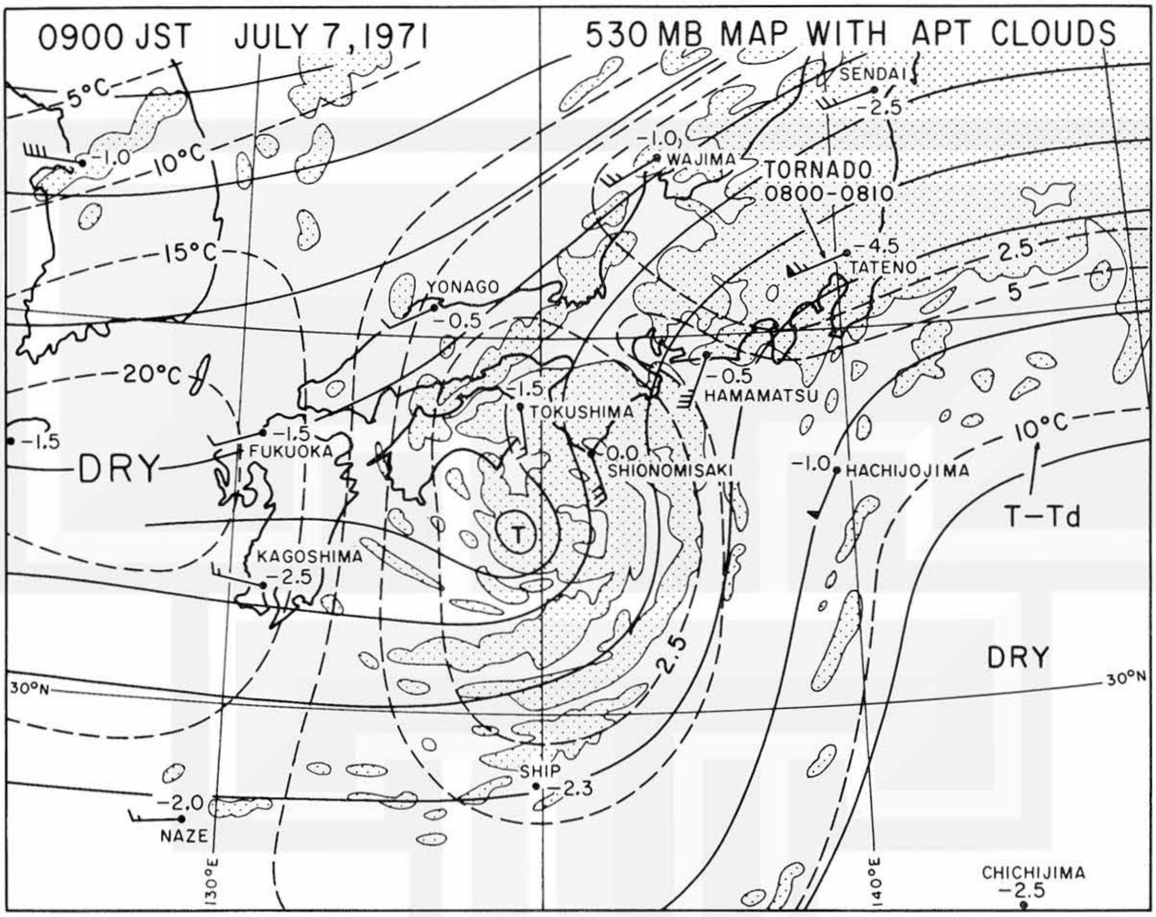

Figure 9. A 530-mb chart including APT cloud patterns. The western portion of tropical storm Ivy is drying up while moist air is transported north-eastward from the area of rainbands. A mid-level jet is seen over Tateno.

by a maximum jet speed near the tornado area. The isotherms of dew-point depression at 530 mb suggest that the western half of Ivy is drying up rather quickly, while near-saturation air is transported from Ivy toward the northeast and finally to east-northeast. The vertical distribution of the increasing dew-point depression is seen in Tateno sounding as early as 1500 JST, July 7 when the Ivy center was near Shionomisaki (778). The mid-level atmosphere over Tateno was quite moist between 21 JST, July 6 and 09 JST, July 7, some 18 to 24 hours before the passage of Ivy over Tateno area. A large mass of cloud appearing in the satellite picture of Fig. 6 corresponds to this moist area at the middle level.

5. MESOANALYSIS OF OMIYA TORNADO CYCLONE

For the purpose of learning the mesoscale atmospheric conditions giving rise to the formation of the Omiya tornado, meteorological data were collected from all available stations operated by JMA, the military, local fire stations, schools, train stations, prefecture offices, city halls, and public heath services.

The overall mesoscale map of Fig. 10 covering the Kanto plain reveals that the average station distance is no more than 15 km (10 mi) which is dense enough to carry out a detailed mesosynoptic analysis of the tornado situation of July 7, 1971. There are three centers of 24-hr precipitation ending at 09JST over mountains just west of the plain. The fourth one, extending diagonally through the center of the map, cannot be caused by orographic effects because Kanto plain is practically flat in this area.

Seen in the 09JST map are the boundaries of mesoscale outflow from the areas of heavy rain occurring early in the morning hours. A small mesocyclone seen near the center of the map was found to be the tornado cyclone in which the Omiya tornado spawned just about one hour earlier. This mesocyclone, only 15 km (10 mi) in affected diameter, can be traced back to the southwestern tip of the isohyet pattern 40 km (25 mi) to the west-southwest of Tokyo.

A very similar relationship between isohyetal patterns and tornado location was established by Shimada (1967) in his detailed mesoanalysis of the Yoshino Valley, Fui., tornado of April 2, 1961. It is of interest to find that this tornado occurred some 40 km (25 mi) behind a cold front and that the tornado was accompanied by a tornado cyclone with an outermost diameter of 30 km (20 mi). Both Omiya and Yoshino Valley tornado cyclones appear to have developed under entirely different meteorological conditions. Their similarity, nonetheless, presents questions regarding the mesoscale environments giving rise to the development of Japanese tornadoes.

Hourly mesoanalysis of this mesocyclone was performed over a smaller area for the hours 06 to 09JST (see Fig. 11). The 0600 map depicts the formative stage of the mesocyclone characterized by three mesoscale air masses. They are the southerly maritime air from the outer area of Ivy, the rain-chilled outflow from the highland to the west, and the cold air produced inside the mesohigh to the north of the mesocyclone. Rainfall amounts and isohyets are for the one-hour precipitation prior to the map time.

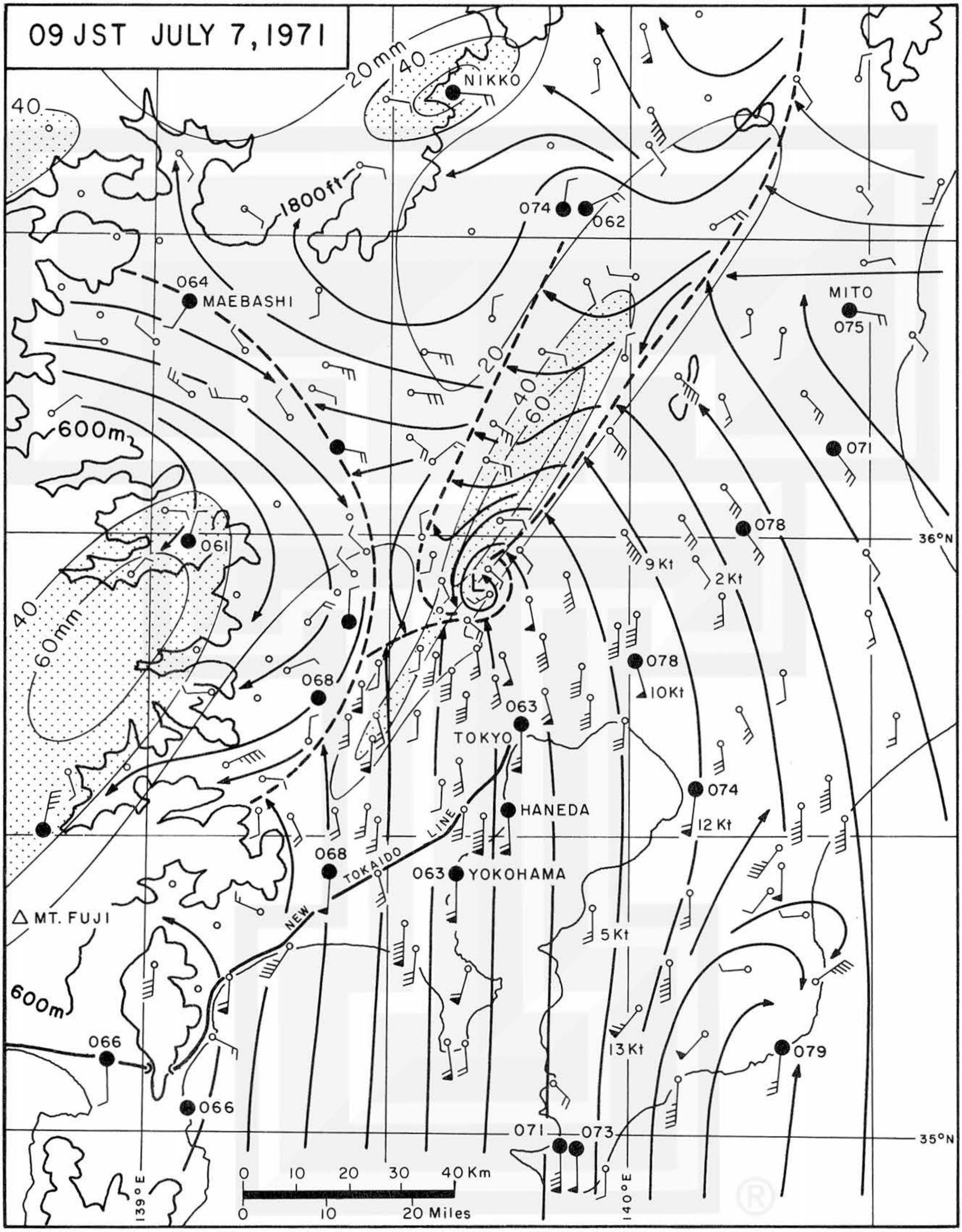

Figure 10. Overall mesoscale map covering the Kanto plain. 24-hr precipitation amounts measured at the map time are shown by isohyets drawn for every 20 mm (0.8 inch) intervals. To emphasize mesoscale flow patterns, one wind barb and a flag were plotted to represent 2 kt and 10 kt speed, respectively.

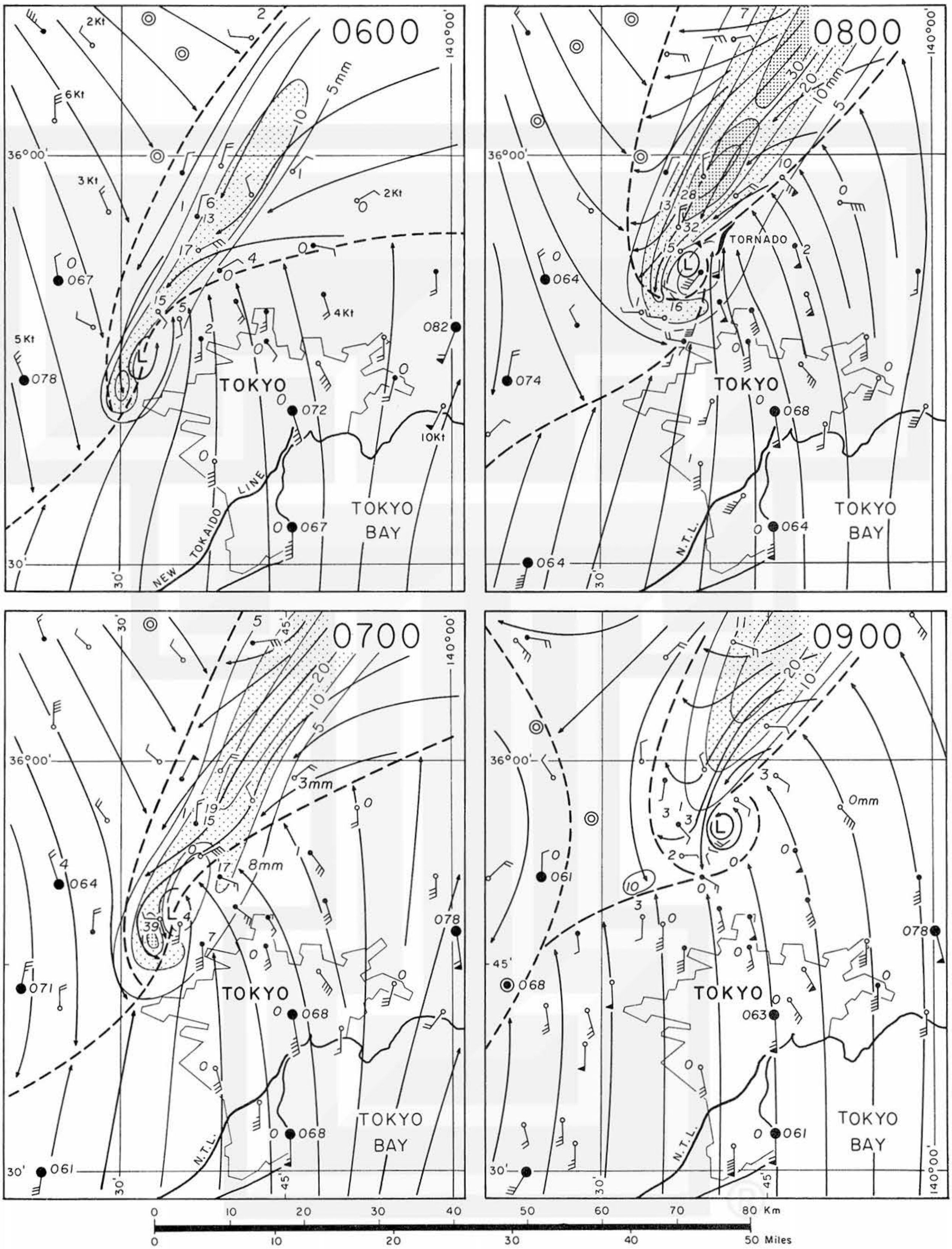

Figure 11. Hourly mesoanalysis maps showing the mesocyclone which produced an F3 tornado, 15 miles to the north-northwest of Tokyo. Hourly precipitation amounts are given in one-mm (0.25-inch) unit.

By 0700, the mesocyclone developed slightly, being characterized by $70 \times 10^{-5} sec^{-1}$ convergence averaged over the 15-km (10 mile) diameter. Limited hourly precipitation data imply that the mesocyclone at this time was accompanied by an incomplete ring of precipitation similar to that studied by Browning (1964) and Fujita (1965).

The mesocyclone reached its maximum intensity at 0800 when a tornado occurred to the right of this center. Technically, the name of a mesocyclone should be changed to "tornado cyclone" whenever it produces one or more tornadoes.

Within about one hour after the dissipation of the tornado, the mesocyclone weakened considerably. Meanwhile, the heavy rain moved to the northeast leaving the cyclonic storm behind. As seen in the 0900 map, the southerly flow over Tokyo and vicinity continued without initiating new rainfall areas inside the maritime warm air.

At 0900, Ivy was moving northeast, heading toward Shionomisaki (778). Thereafter, she kept moving toward Kanto passing directly over the tornado damage area at 0200 JST, July 8, some 18 hours later. By then, the parent storm had become so weak that no one in the area even noticed the passage of Ivy. In his study of typhoon-associated tornadoes, Tsuchiya (1971) mentioned that a typhoon is likely to move toward the location of tornadoes that she produced. After all, Ivy spawned only one tornado which turned out to be one of the most intense tatsumaki.

After confirming the existence of the Omiya tornado cyclone, further investigation of its structure in relation to the initiation of the F 3 tornado was undertaken. The authors were surprised to find 10 wind recording stations within about 15 km (10 mi) of the tornado-cyclone center. These stations were established and operated by various agencies to meet their own requirements, without realizing that these stations are ideally distributed for mesometeorological studies of the Omiya tornado cyclone.

Shown in Fig. 12 are these 10 wind recording stations. In addition to these recording stations there are a number of hourly observing stations indicated by open circles. A total of 25 winds from these stations are entered with heavy vectors accompanied by wind speed in kt. 24-hr precipitations, ending at 09 JST, are also plotted and contoured with isohyets at 20-mm (0.8-inch) intervals. Most of the 24-hr rainfall that occurred was associated with the tornado cyclone which traveled north-northeast almost parallel to the 50 mm (2-inch) isohyet.

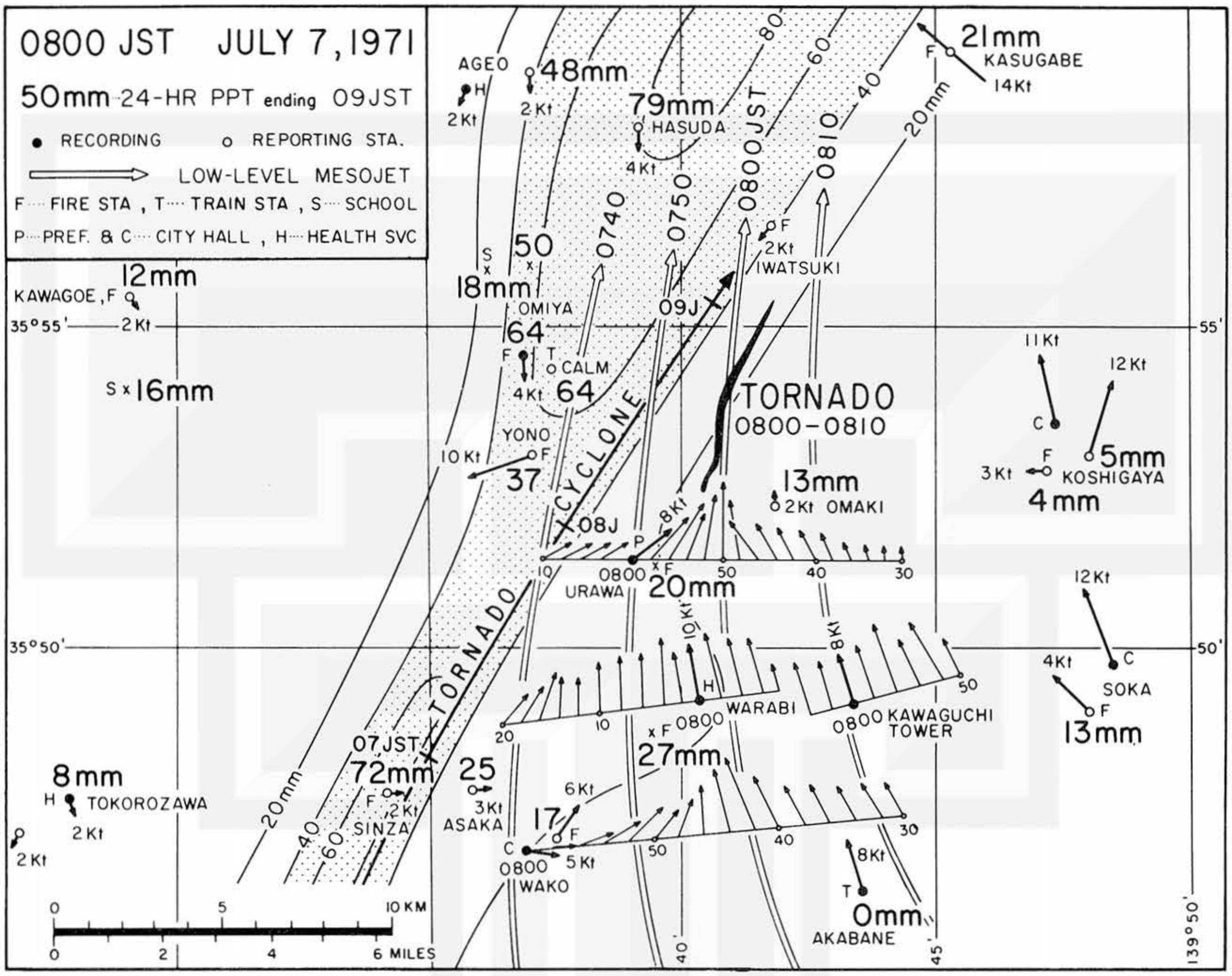

Figure 12. Distribution of recording and non-recording stations in the vicinity of the Omiya tornado. Time-space conversions of recorded wind data reveal the existence of a mesoscale low-level jet. Note that the tornado cyclone traveled parallel to the southeast edge of the heavy rain area.

As in most hook-echo cases in the United States, the heavy rain area of this storm was located to the left of the circulation center. The location of the tornado relative to the tornado cyclone was also quite similar to that of U. S. cases in which tornadoes form beneath radar hook echo to the right of the cyclone center. The Illinois tornado of April 9, 1963 studied by Stout and Huff (1953) and Fujita (1958) was the first evidence of the hook-echo and tornado relationship. Since then a number of cases confirming a similar relationship were studied by various researchers. So far, no explanation of this preferable location of tornado formation has been given.

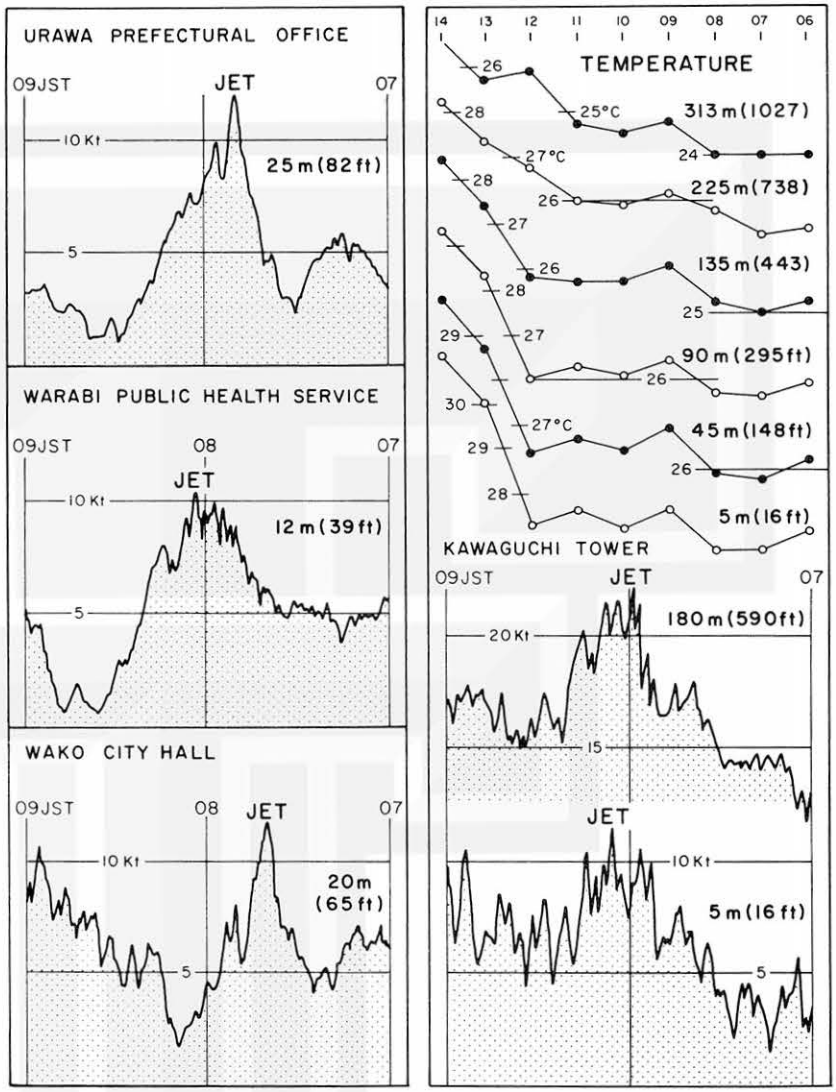

Figure 13. Wind speeds of the tornado mesojet as recorded by four stations in the upwind side of the tornado. Multi-level temperature changes measured at Kawaguchi Tower reveal a slight warming at 9 AM, extending from the ground to 313 m (1027 ft), the highest level.

Wind data obtained from the dense station network around the Omiya tornado permitted us to establish a proposed mechanism of tornado formation to the right of the tornado-cyclone center. As shown in Fig. 13, four stations located to the east of the tornado-cyclone track recorded a distinct peak of the surface wind. Isochrone analysis of the times of the peak in Fig. 12 clearly shows that a mesoscale low-level jet with its north-south axis moved eastward. The space variation of the flow vectors of this jet implies that a very narrow jet of southerly air was being fed into the spawning region of the tornado. We may, thus, call this low-level jet a "tornado mesojet".

Fortunately, the two-level winds of this tornado mesojet were recorded at Kawaguchi Tower, located 6 km (4 mi) SSE of the tornado. The peak wind speeds recorded at 180 m (590 ft) and 5 m (16 ft) were 11.2 m/sec and 5.9 m/sec, respectively. Three stations in Fig. 13 recorded the maximum speeds, 5.1 m/sec, 5.8 m/sec, and 6.1 m/sec at the anemometer heights of 12m, 20m, and 25 m, respectively. These data support a linear increase of the mesojet speed along the vertical. Thus we may write

$$V_j = 5.1 + 0.033\,H \quad \text{in m/sec} \tag{4}$$

where V_j is the maximum mesojet speed at the height, H meters above the ground. This equation is useful in estimating the speed of the mesojet up to a few hundred meters above the ground.

A detailed mesoanalysis of the tornado cyclone at 0800 JST, when the Omiya tornado had just formed, is presented in Fig. 14. Isohyets are drawn for the 1-hr precipitation ending at the map time. If a P P I radar picture were available at this time, a hook echo extending from the major precipitation area to the north of the cyclone is likely to be identified. The area of 5 m/sec (10 kt) or faster mesojet speed is hatched.

The location of the Omiya-tornado formation is seen slightly to the left of the axis of the tornado mesojet where significant cyclonic vorticity is expected. The magnitude of the vorticity mostly contributed by the horizontal wind shear can be computed from

$$\zeta_j \cong \frac{\Delta V_j}{\Delta x} \cong \frac{3\ \text{m/s}}{1\ \text{km}} = 300 \times 10^{-5}\,\text{sec}^{-1} \tag{5}$$

where ζ_j denotes the cyclonic vorticity to the left of the jet axis, Δx, the distance perpendicular to the jet axis.

The mean vorticity of the tornado-cyclone core with approximate radius, R = 3 km and average tangential speed V = 3 m/sec can be computed as

$$\zeta_m \cong \frac{2V}{R} \cong \frac{2 \times 3\ \text{m/s}}{3\ \text{km}} = 200 \times 10^{-5}\,\text{sec}^{-1} \tag{6}$$

where ζ_m is the relative vorticity of the tornado cyclone. It should be noted, however, that these vorticity values must be multiplied by a factor of 2 or even 3 in order to estimate the vorticity at the levels a few hundred meters above the ground. For this purpose, Eq. (4) can readily be used.

Although the cyclonic vorticity just to the west of the mesojet axis is only 50% larger than the tornado-cyclone vorticity, the former could be much larger if the width of the jet becomes narrower. Furthermore, a significant lateral convergence is expected on both sides of the jet axis (see Fig. 12). As a result, the location just to the left of the mesojet turns out to be the most favorable spot of vorticity concentration favorable for tornado formation. It is also very likely that a hook echo encircling the tornado-cyclone core is found in the vicinity of this spot.

The tornado mesojet in Fig. 14 extends farther to the north serving as a feeder flow of moisture into the most active portion of the rain area to the north of the tornado cyclone. If a tornado cyclone further intensifies, the north end of the mesojet will curve cyclonically, following the front edge of the tornado-cyclone core. The high energy mesojet air will then spiral up into the upper portion of the storm cloud which may be identified as a rotating thunderstorm or a hook-echo thunderstorm. Tornadoes spawned from such a fast rotating thunderstorm will be drifting toward the front side of the parent storm before their dissipation. This process will explain the parallel-mode tornado tracks reported by Fujita (1963) and commonly observed in family tornadoes in the United States.

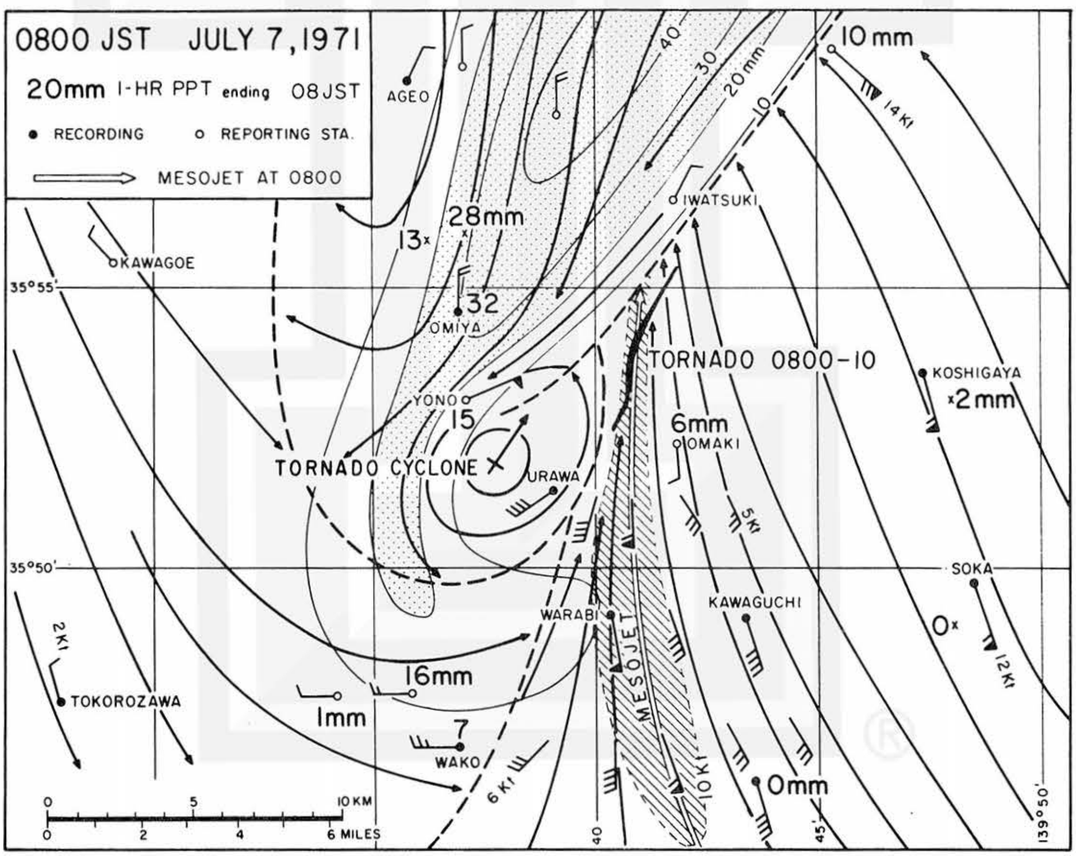

Figure 14. Mesosynoptic map of the tornado cyclone at 0800 JST when the Omiya tornadoes formed to the east-northeast of the cyclone center, just to the left of the tornado-jet axis.

6. CHARACTERISTICS OF OMIYA TORNADO

Eyewitness accounts and a ground survey revealed that the first indication of the Omiya tornado appeared at Saido, Urawa City (see Fig. 15). After disturbing young peach and bamboo trees, the tornado quickly gained its intensity until a portion of a building housing a beauty salon was blown off by an estimated F2 wind. Over 10 white radishes pulled out of the neighboring field were scattered on the ground. After causing this damage, the tornado apparently lifted or weakened until a tomato field and small trees in Mimuro were damaged. The tornado intensity there reached up to F2 when an open porch was demolished. After snapping a few tree tops and disturbing bushes, the tornado moved over Minuma rice field where it crossed the Omiya-Urawa City border.

The width of the tornado damage at the north end of Minuma rice field was as wide as 250m (800 ft). The owner of a cardboard box factory had just arrived from Tokyo in his 2-ton truck. It was suddenly lifted 2 meters (6 ft) and dropped broadside on the ground. His factory was demolished by an estimated F3 wind. About 50 cedar trees, one-foot in average diameter, were either snapped or leveled in a forest south of the factory. A wide-spread damage area was seen in aerial color photographs taken by Fujita from a helicopter, courtesy of Asahi Newspaper. Examination of these areal photographs revealed that the storm occasionally caused F3 damage as it moved north-northeast over a newly developed residential area.

Six suction-vortex swaths, to be discussed later, were spotted from the air, leading to a detailed ground survey of their characteristics. Several tombstones were blown down from their foundations most of which were left intact. The tornado weakened gradually as it moved over Sometani causing a few F1 damages to roofs and trees. An old tree of 1.5m (5 ft) diameter in Yakumo Shrine collapsed to the ground. Large debris such as pieces of roof, wall, door, etc. were found scattered in the rice field north of Sometani, suggesting that they were thrown into the left front quadrant of the tornado.

Several houses in Hizako were damaged slightly. Only F1 damage confirmed there is a vinyl greenhouse with arch-shaped structure. The last tornado damage was found through ground survey in Uegumi, Iwatsuki City where several houses lost a number of roof tiles.

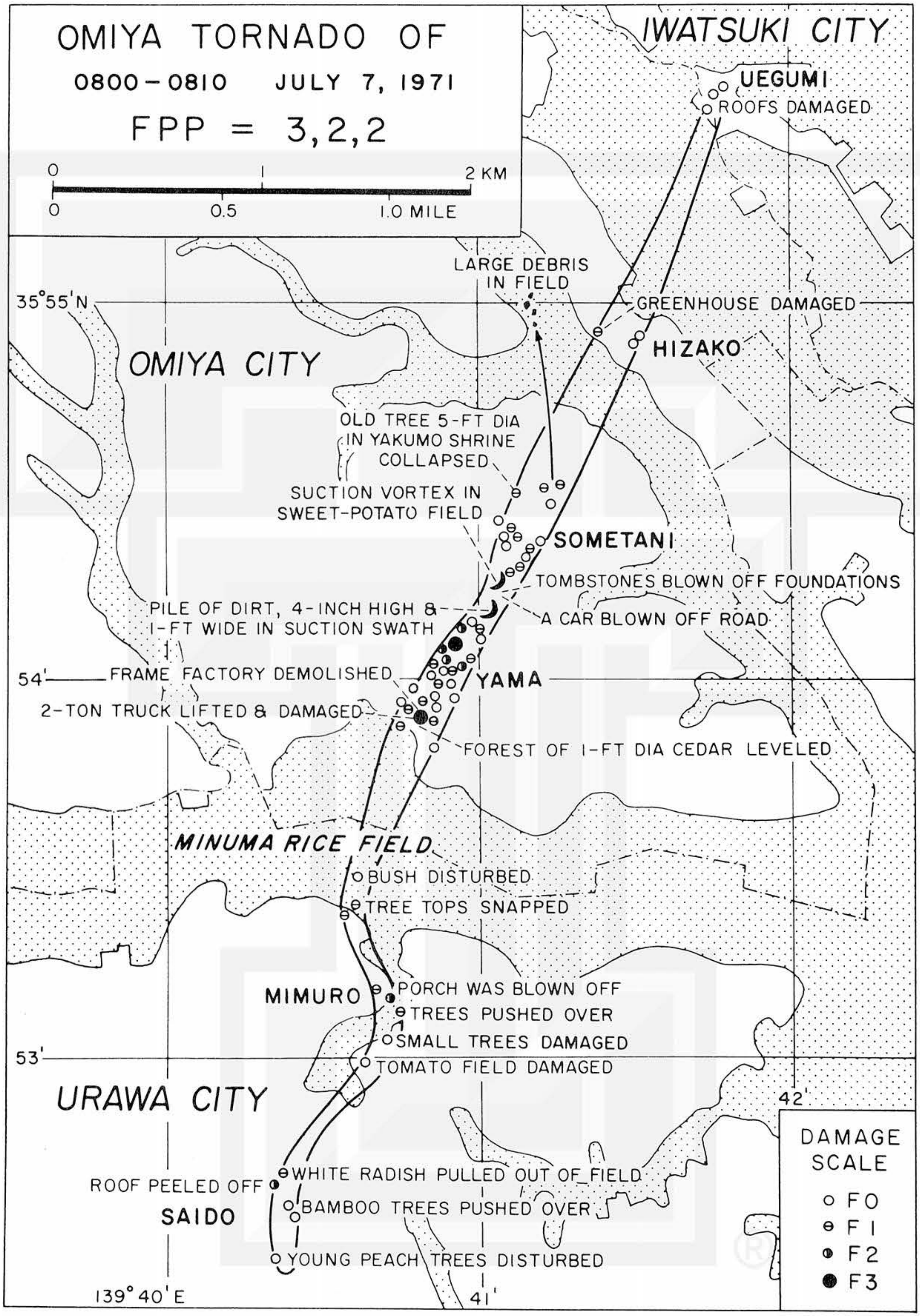

Figure 15. Overall damage map of the Omiya tornado of July 7, 1971. F-scale assessment of the damage was made based on both aerial and ground surveys.

Nobody saw a well-defined funnel cloud attached to the cloud base, however, a farmer looking toward Minuma rice field from Yama noticed that a black, chimney-like cloud was approaching him from the dark field. There are several reports of "freight train" and/or "bulldozer" noise followed almost immediately by a damaging wind.

The duration of the tornado which moved along a 6.2-km (3.9 mile) track in three cities, Urawa, Omiya, and Iwatsuki was about 10 minutes. Although the storm is called the Omiya tornado because of the heaviest damage in Omiya, it was in fact a tri-city tornado. Various reports and eyewitness accounts narrow down the tornado time between 0800-0810 JST. After all, the tornado killed one person while 12 were injured. A total of 145 houses and structures were damaged.

7. NEW EVIDENCE OF SUCTION VORTICES

Since the mechanism of multi-suction vortices within a tornado was proposed by Fujita (1971b) based on research by Van Tassel (1955), Prosser (1964), Waite and Lamoureux (1969), Fujita, Bradbury, and Van Thullenar (1970), and Fujita (1970), the collection of new evidence and subsequent research was thought to be highly desirable. We did not expect, however, that two important features of suction vortices were hidden inside the storm-stricken fields located between Yama and Sometani in Omiya City.

Most tornadoes with small vortex cores may be regarded as axially symmetric, each acting as a rotating suction head. Such a tornado may be identified as a "single-suction tornado". When the core diameter of a tornado increases, the suction field around the large core can no longer maintain the stability, thus splitting into several spots where suction intensity concentrates locally. A wide damage swath of a large-core tornado is often characterized by a number of elliptic or cycloidal ground marks which were first found by Van Tassel (1955) in a series of aerial photographs. Strange enough, these ground marks are identifiable only from the air. A ground survey without prior knowledge of the precise locations of the marks often fails.

When suction effects concentrate around several spots distributed around a large tornado core, each spot must be in a state of secondary rotation in order to maintain the suction intensity during its travel around the core. The divergence term

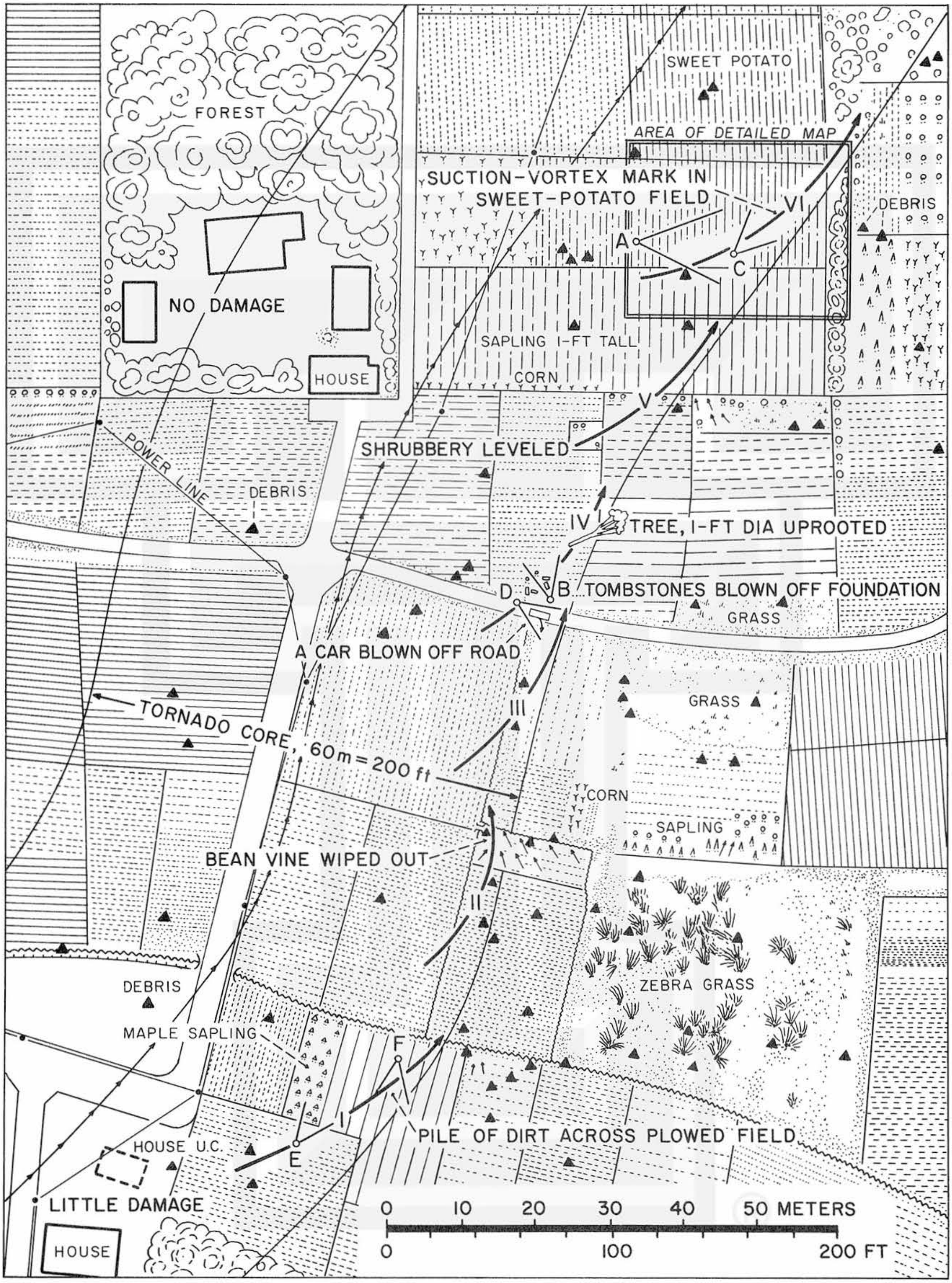

Figure 16. An area between Yama and Sometani in Omiya City, where six suction-vortex swaths were found. Mapping was done by Watanabe with the help of local government and by Fujita using aerial photogrammetric facilities at the University of Chicago.

in the vorticity equation also implies the concentration of vorticity in and around each suction spot. So far nobody has seen or photographed such suction spots in action to prove or disprove their rotational identity. Nonetheless, there are evidences of secondary vortices around giant dustdevil cores as reported by Hallet and Hoffer (1971) and Fujita (1971b).

Two of the six ground marks presented in Fig. 16 became the most important ones, including evidence for the solution of suction-vortex mechanism within a large core tornado. Fujita has flown over tornado damage areas in the United States, attempting to find evidence of secondary vortices, fruitlessly so far. He failed to confirm definite evidence of the rotational characteristics of suction spots because the distinction of straight suction and rotational suction is extremely difficult when the dimensions of suction areas are small. It was, therefore, to his great astonishment to find in Japan particular ground features that he had long been hoping to find in the United States.

A suction-vortex mark in a sweet potato field near the upper right corner of Fig. 16 was mapped in detail (see Fig. 17). This suction vortex affected four fields with land numbers 1483, 1490, 1491, and 1492, originating near the boundary between a pine sapling nursery and a sweet potato field. Rotational characteristics of this secondary vortex became definite by mapping the direction of sweet potato vines extended in the direction of the strongest wind. Aerial and ground views of these vines are shown in pictures A and C in Fig. 18. The diameter of the suction- (secondary-) vortex core was estimated to be 1 to 2 meters (3 to 6 ft). The core was surrounded by an outer vortex similar to the v-r vortex, extending to about 10 m (30 ft) in diameter.

There was no evidence of suction-vortex damage to the west of the F0 boundary in Fig. 17, leading to the conclusion that the suction vortex gained intensity all of a sudden, so to speak. This conclusion agrees very well with an abrupt (two seconds) development of secondary vortices in giant dustdevils as reported by Hallet and Hoffer (1971) and Fujita (1971b).

Suction vortex No. 1 near the bottom of Fig. 16 showed another very important evidence. The vortex left a pile of dirt across a plowed field. The dirt was 30 cm (1 ft) in width piled up to 10 cm (4 inches) with an appearance of a narrow dirt road

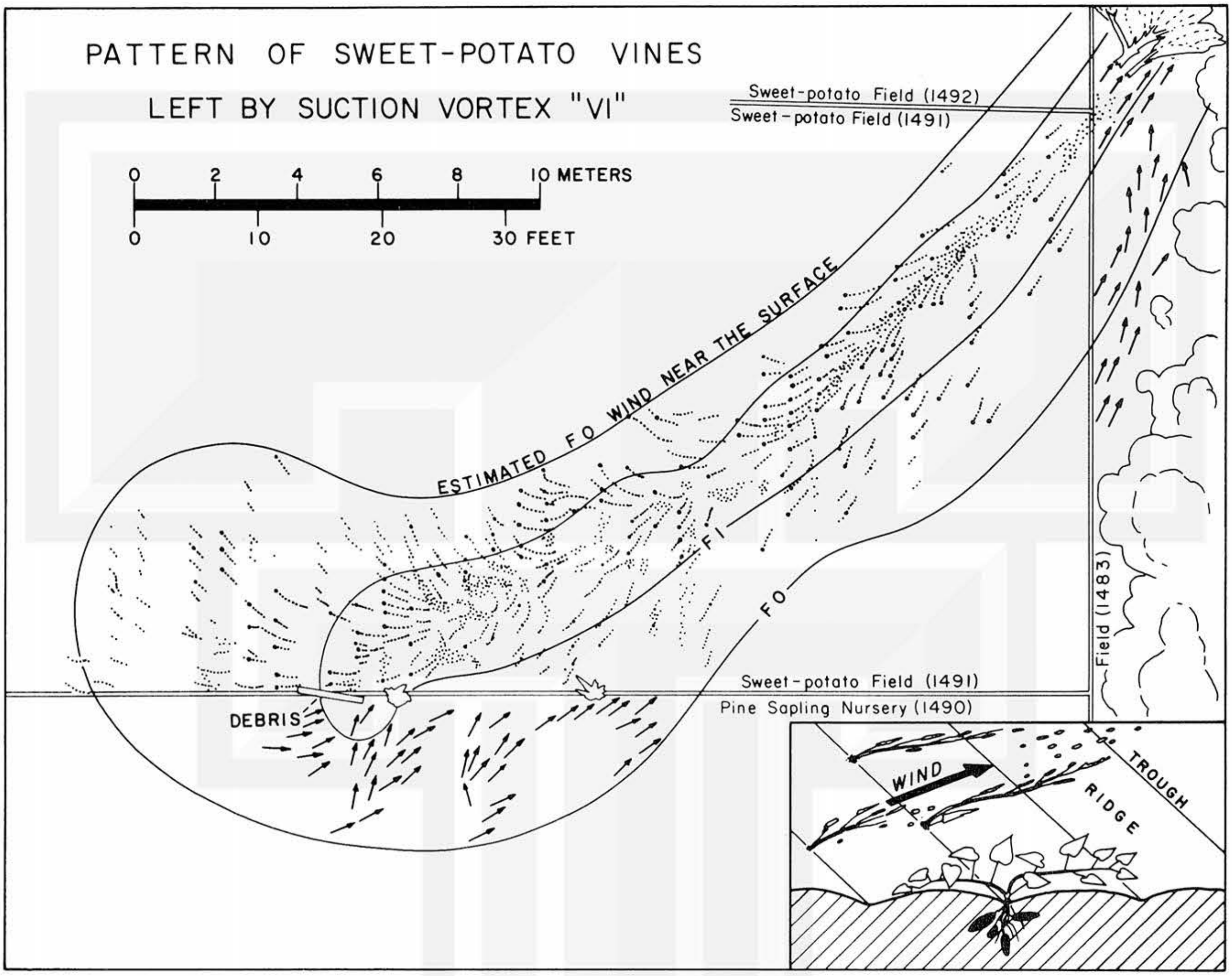

Figure 17. Detailed map of a suction-vortex swath left in a sweet potato field. The final directions of stretched sweet potato vines gives the first known evidence of a tornado suction vortex in a state of fast rotation.

constructed by the suction vortex (see photo F in Fig. 18). Although the parallel troughs in the field were filled in part with rain water, the top of this natural dirt road was dry in pitch dark color. It is assumed that the dirt was brought into the vortex core along with the boundary layer inflow and was deposited near the core center where the rotational wind is weak. A detailed ground survey revealed that the small vegetation on both sides of the dirt pile was swept clean, leaving exposed dark-colored soil. The width of the exposed soil was about 2 to 3 meters (6 to 10 ft).

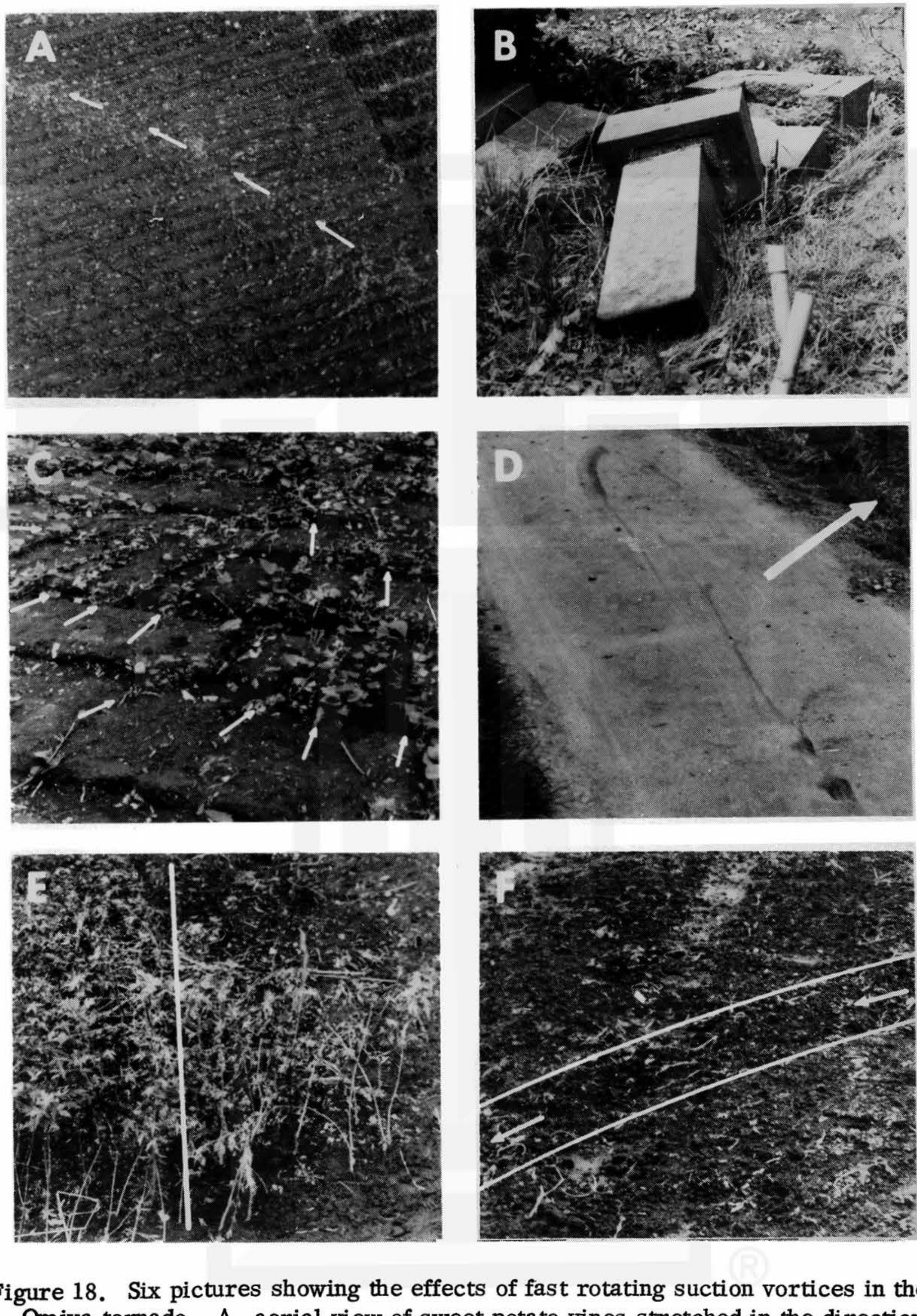

Figure 18. Six pictures showing the effects of fast rotating suction vortices in the Omiya tornado. A, aerial view of sweet potato vines stretched in the direction of the translation-rotation combined wind. B, tombstones blown off the foundations toward suction vortex IV. C, a ground view of stretched vines. D, skid marks of a car swept into suction vortex III. E, undamaged and mud-coated maple saplings standing side by side, and F, a natural dirt road produced by suction vortex I along the path of the center.

As shown in Fig. 16, southeast corner of a maple-sapling field extended into the area of this exposed soil, offering an excellent opportunity to determine the vertical structure of the suction vortex. Picture E in Fig. 18 was taken facing northeast to show the conditions of maple saplings. Saplings to the right of a white vertical line in the picture, which happened to be inside the exposed soil boundary, were all dead and spattered with mud, somewhat like grey batter. When viewed in the original color picture, saplings to the left of the line were practically unharmed, still maintaining a beautiful light green color.

This evidence leads to a conclusion that the central region of this suction vortex was filled with wet dirt suspended within the fast-rotating column of air. Small and weak vegetation was swept clean by the dirt-filled air by which maple saplings were spattered. The dirt concentration inside this suction vortex must have dropped down abruptly outward in order to produce a distinct boundary of the sapling damage. If this vortex were observed from a safe distance it would appear to be a column of wet dirt mixed with small vegetation. The diameter of the fast-rotating core would be between 1 and 2 meters.

Both suction vortices II and V produced typical damage, wiping out bean vine and leveling shrubbery, etc. Vortex No. III moving north and a car traveling east happened to be in collision course, ending up with short skid marks engraved on the pavement a split second before the car was swept into the suction vortex (see picture D, Fig. 18).

Suction vortex No. IV moved through a small cemetery with several tombstones. All of the tall ones were blown off the foundations (see picture B, Fig. 18). The vortex continued to travel northeastward uprooting a large tree standing in the field.

Numerous debris was spotted in aerial photographs and entered in Fig. 16 with triangular symbols. The outermost width of scattered debris extended way beyond the area of Fig. 16, suggesting that the overall circulation of the tornado extended some 100 m (300 ft) on both sides of the swath of the tornado core. A 60-m (200 ft) core diameter was estimated from curvatures of the six suction-vortex marks.

It is obvious that the most severe damage within the area of Fig. 16 was caused not by the overall circulation of the tornado but by six suction vortices induced by the parent tornado.

8. FOUR SCALES OF MOTION ASSOCIATED WITH OMIYA TORNADO

The foregoing evidence of tornado-associated phenomena will now permit us to relate four scales of motion, the smallest one of which being 10-meter size suction vortices which are spawned out of tropical storm Ivy, 120,000 times larger in horizontal dimensions.

A sequence of events leading to a cause and effect relationship can be stated: "Suction vortices were produced by the Omiya tornado which spawned inside a mesocyclone induced by tropical cyclone Ivy." If we simplify this statement into "suction vortices were produced by Ivy", a long chain of events might be as implicit as the Japanese story, "Whenever spring storms develop coopers get rich". This is because intense spring storms stir up a lot of fine dust which will get into human eyes, thus increasing the number of blind people who would make their living by playing stringed instruments made of cat skins. When more cats are caught, mice will play by chewing wooden tubs, resulting in more of a demand for the work of coopers.

The suction vortex-Ivy relationship is no more than the cooper-spring storm relationship because this is the first time that a remote cause and effect relationship involving a typhoon and suction vortices has been interrelated in Japan as well as in the United States. This paper should, therefore, simply offer the best possible explanation of the Omiya tornado and its related disturbances.

The chain of events may be enumerated as follows:

(1) A weak tropical depression that originated at 23°N and 136°E on July 4, 1971 developed into typhoon Ivy the next day.

(2) The warm, moist maritime air in the right front quadrant of Ivy moved northward toward Japan.

(3) Early in the morning of July 7 a cold advection at 530 mb coupled with the warm advection at lower levels triggered the formation of a large cumulonimbus convection to the west of Tokyo.

(4) A mesocyclone similar to that observed frequently as hook-echo storm formed to the right of this major thunderstorm which spread quickly north-northeast.

(5) A narrow mesoscale low-level jet formed inside the southerly maritime air while there was no high-level outflow jet from the tropical storm.

(6) The Omiya tornado spawned at the edge of the mesocyclone core just to the west of the mesojet axis.

(7) The core diameter of the tornado increased to 60 m, resulting in the formation of multiple suction vortices along the right rear edge of the tornado core.

(8) Wind speeds inside these suction vortices reached to those of F 2 or F 3 causing severe damage.

Now the question arises if Ivy was absolutely necessary for the formation of this F 3 tornado or not. The answer could be yes or no as long as the coopers' business may pick up under circumstances other than spring storms. Further research on Japanese tornadoes will be necessary for better understanding of tornadic severe storms which have long been recognized but not fully understood.

Finally, four scales of motion associated with Ivy and the Omiya tornado are summarized in Table 5.

The rotational speeds tabulated are approximate values obtained from the shape of cycloidal swaths, by means of the method proposed by Fujita, Bradbury, and Black (1967).

Table 5. Statistics of 4-scales of motion. Direction of motion of Ivy is measured at the time of the tornado; all others, average direction.

Wind System	Tropical Storm Ivy	Tornado Cyclone	Tornado	Suction Vortex
Outermost diameter	1200 km (750 mi)	15 km (10 mi)	250 m (820 ft)	10 m (30 ft)
Core diameter	Unknown	6 km (4 mi)	60 m (200 ft)	1 to 2 m (3 to 6 ft)
Direction of motion	049°	032°	020°	060°
Traveling speed	35 k/h (22 mph)	8 k/h (5 mph)	40 k/h (25 mph)	120 k/h (75 mph)
Rotational speed	25 m/s (56 mph)	3 m/s (7 mph)	80 k/h (50 mph)	120 k/h (75 mph)
Duration of storm	5 days	4 hours	10 minutes	1 to 2 seconds

9. CONCLUSIONS

Results of a study of the Omiya Tornado of July 7, 1971 and statistical investigation of typhoon-associated tornadoes clarified various aspects of Japanese tatsumaki in relation to U. S. tornadoes.

It was concluded that there are no basic differences between Japanese tatsumaki and U. S. tornadoes except that most tatsumaki do not exceed 3, 3, 3 according to the F P P scale while several U. S. tornadoes each year may be rated as 5, 5, 5. Literally, tatsumaki include both tornadoes and waterspouts, necessitating their distinction in order to obtain storm statistics comparable to that of the United States.

Preferable locations relative to the parent storms of typhoon-associated and hurricane-associated tornadoes are practically identical suggesting that research results in both the U. S. and Japan are likely to compliment each other.

Although most Japanese tornadoes are small in horizontal dimensions, some are large enough to be characterized by multi-suction vortices occasionally found in severe U. S. tornadoes. Waterspout-originated tornadoes in Japan seem to be much stronger on the average than the counterpart storms in the Gulf Coast states.

A significant 6-hour variation in tornado occurrences was found through Fourier analysis of typhoon- and hurricane-associated tornadoes. These amplitudes, respectively, are 0.65 and 0.41 of the average hourly frequency. There should be definite reasons for such variations since these amplitudes are too large to be accidental.

As a final conclusion, it is recommended that future tatsumaki be investigated in detail both from the air and ground immediately after each storm. For comparison of U. S. and Japanese storms, analytically and theoretically, establishment of a standard method applicable to both countries is highly desirable.

Acknowledgement:-

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