A Statistical Study of Tornadoes and Waterspouts in Japan from 1961 to 1993

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(Manuscript received 16 May 1996, in final form 5 November 1996)

ABSTRACT

A database on tornadoes and waterspouts in Japan from 1961 to 1993, which is believed to be most reliable at present, was compiled after an extensive survey of apparently almost all existing literature. Six hundred and seventy-seven tornadoes and 148 waterspouts were cataloged in the database, which is operated on a personal computer basis. Various statistical characteristics of tornadoes and waterspouts have been examined: 1) On average 20.5 tornadoes and 4.5 waterspouts occur per year in Japan. 2) Tornadoes occur most frequently in September and least frequently in March. Waterspouts occur most frequently in October. 3) Both tornadoes and waterspouts have high activities during daytime. The activity of tornadoes has two peaks between 1000 and 1100, and between 1500 and 1600 JST (Japan Standard Time). 4) About two-fifths of the tornadoes occur on multiple-tornado days. 5) The average lifetimes of tornadoes and waterspouts are 12 and 14 min, respectively. 6) About 15% of tornadoes are anticyclonic. 7) More than 50% of tornadoes move toward the northeast quadrant. Their average speed is 10 m s^{-1}. 8) The average damage path width and pathlength are 98 m and 3.2 km, respectively. 9) Fatality and injuries caused by tornadoes per year are 0.58 and 29.7, respectively. Completely destroyed, severely damaged, and partly damaged residential houses per year are 17.0, 39.0, and 329, respectively. 10) About 46% of tornadoes are associated with extratropical cyclones (16% in a warm sector and 15% associated with cold fronts) and 20% associated with typhoons. 11) A preliminary estimate of risk of a tornado encounter for each of 47 prefectures was made. The shortest recurrence interval is found for Tokyo Prefecture and is less than 7.7×10^3 yr. The recurrence interval for the whole country of Japan is less than 1.7×10^5 yr. A preliminary discussion on the stability of the tornado statistics was also made.

1. Introduction

Tatsumaki in Japanese is a general word denoting tornado, waterspout, and funnel-aloft in English. According to a statistical study by Omoto et al. (1983; hereafter referred to as OMM) on tatsumaki in Japan from 1961 to 1982, about 18 tornadoes yr^{-1} occurred in Japan on average. Tornado statistics from 1961 to 1990 (NOAA 1991) show that 804 tornadoes yr^{-1} occurred in the United States on average. This number is about 45 times as large as that in Japan. Since the United States is about 25 times as wide as Japan, however, the frequency of tornadoes per unit area in Japan amounts to about 55% of that in the United States. As far as the frequency per unit area is concerned, Japan is not a minor country for tornadoes.

Nevertheless, tornadoes seem to have been paid little attention by both the general public and scientists in Japan. Several reasons for this may be considered. First, the numbers of fatalities and damaged houses due to tornadoes have been much smaller than those due to heavy precipitation, typhoons, and lightning. Second, though closely related to the first point, there have been no extremely strong tornadoes ranked F4 or more in Japan [Fujita (1993) proposed that the Mobara tornado on 11 December 1990 was the first F4 tornado in Japan]. In fact, the largest number of fatalities caused by a single tornado between 1961 and 1993 was only two. If one looks back to records on tornado damage in the last 10 decades, however, much more serious damages are found: The tornado in Miyazaki city on 26 September 1881 demolished the Miyazaki Elementary School and caused 16 fatalities (Kasamura 1979). On 23 September 1903, an elementary school in Yodobashi Town, Toyotama County, Tokyo Prefecture, was hit by a tornado. Ten persons were killed and 14 persons were injured (Shimada 1977). The tornado in Toyohashi City, Aichi

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Prefecture, on 28 November 1941 killed 12 persons, injured 177 persons, and either completely destroyed or severely damaged 347 houses (Tokita 1970). Six persons were killed and 8 persons were injured by a tornado in Tomiye City, Nagasaki Prefecture, on 10 November 1957 (Takei 1963).

According to a reliable estimation, the maximum wind of a violent tornado may be between 110 and 135 m s^{-1} (Golden and Snow 1991). Bluestein et al. (1993), using a portable Doppler radar, observed wind speeds as high as 120–125 m s^{-1} in the Ceres, Oklahoma, tornado on 26 April 1991. In the United States, tornadoes are considered when one designs buildings and structures against extreme winds. However, such consideration is not taken in Japan. This is partly because there have been no tornadoes ranked F4 or more, as was mentioned above. Furthermore, the risk of a tornado encounter has been believed to be so small that one does not need to consider an extreme wind due to a tornado in Japan (e.g., Kanda 1991). According to a statistical study by OMM, the country-mean damage pathlength and pathwidth of tornadoes in Japan were 3.3 km and 110 m, respectively. Since those of the United States are 7.1 km and 117 m for 1950–82 (Schaefer et al. 1986) and the frequency per unit area is about two times larger in the United States, it is certainly true that the country-mean risk of a tornado encounter is smaller in Japan. However, the risk of a tornado encounter in the United States ranges from 5×10^{-4} yr^{-1} in Oklahoma to 5×10^{-7} yr^{-1} in Utah according to the data from 1954 to 1983 (Grazulis 1993). As will be revealed from the present study, the risk of a tornado encounter in Japan also varies quite largely from Prefecture to Prefecture. For some Prefectures, the risk is larger than 10^{-4} yr^{-1} and is comparable to that for Missouri. Increasingly, various important functions of modern cities are being supported by high technology products, which are not necessarily well prepared against localized wind hazard. In fact, there are an increasing number of facilities any damage to which would cause a serious damage to industries and human lives over a significantly wide region. Therefore, it seems important to have reliable statistics on tornadoes and especially on the risk of tornado encounter for Prefectures.

There have been a fair number of statistical studies on tatsumaki in Japan since the late 1940s. A detailed review of these studies is given in the appendix. Table 1 summarizes these previous statistical studies and may be used to see if there is any trend in the annual occurrence of tornadoes from the 1920s to 1990s. The average occurrence of tornadoes was 3.9 between 1926 and 1948, 4.8 between 1948 and 1959, 10.0 between 1955 and 1964, 18.0 between 1961 and 1982, and 15.8 between 1971 and 1990. Since the statistics between 1971 and 1990 by Watanabe (1993) are only for damage-producing tornadoes, these results suggest that the number of recorded tornadoes has increased with time until 1960. This does not mean that the number of tornadoes actually increased with time, but perhaps reflects that the number of reported tornadoes increased as the network of news media became denser (e.g., Fujita 1973). In fact, as will be described in this paper, the annual occurrence of tornadoes after 1961 does not show any noticeable trend. Therefore, it seems appropriate to deal with tornadoes after 1961 in order to make a reliable statistical study on tornadoes in Japan.

TABLE 1. Previous statistical studies on tornadoes and waterspouts in Japan. The numbers in the parentheses in the third and fourth columns are for waterspouts.

Authors	Statistical period	Number of tornadoes in the statistics	Number of tornadoes per year
Sekiya (1949, 1957)	1926–48	89	3.9
Ibaraki and Tanaka (1961)	1948–59	57	4.8
Shimada (1967)	1955–64	76 (24)	7.6 (2.4)
Shimada (1977)	1971–75	94	18.8
Miyazawa et al. (1980)	1971–78	163	20.4
Omoto et al. (1983)	1961–82	396 (55)	18.0 (2.5)
Watanabe (1993)	1971–90	317 (1)	15.9 (0.1)
Hayashi et al. (1994b)	1961–92	538 (63)	16.8 (2.0)
Present study	1961–93	677 (151)	20.5 (4.6)

As is described in the appendix in detail, the most reliable statistical study on tornadoes in Japan at present is the work by OMM, who dealt with 454 tornadoes for 22 yr between 1961 and 1982. However, year-to-year variations of tornado occurrence and tornado damage are fairly large, even in the United States where about 800 tornadoes occur per year. In fact, Schaefer et al. (1993) showed that to obtain stable statistics on geographical distribution of tornado probability in the United States, at least 35 yr of data are required. Therefore, it seems desirable to make a statistical study on tornadoes for a period as long as possible. In the present study, we have first completed a database on tornadoes and waterspouts for 33 yr from 1961 to 1993 and then made an extensive statistical analysis. Especially the risk of a tornado encounter for each Prefecture was estimated. It is also of interest to examine to what degree the results of the statistical analysis changes from that of OMM. This might give us some idea about the stability of the statistics on tornadoes. Considering that many tornadoes in Japan occur near the coast and a considerable fraction of them are of waterspout origin, we have made every effort to collect data on waterspouts and to catalog them in the database.

In the following section, the data source for the database and its design are described. The results of the statistical analysis are presented in section 3 and are discussed in section 4. In the last section, the results are summarized.

2. Data source and database

a. Data source

Records on both tornadoes and waterspouts between 1961 and 1993 have been extensively surveyed against almost all existing literature in Japan. These include *Geophysical Review* (*Kishou Youran* in Japanese) published by the Japan Meteorological Agency (JMA); Report on Unusual Weather and Meteorological Hazards (*Ijou-Kishou Kishou-Saigai Houkoku*) by the Meteorological Statistics Division of JMA; Annual Summary of Unusual Weather in Japan (*Zenkoku Ijou-Kishou Gaikyou*) by the Forecast Division of JMA; Report on Unusual Weather (*Ijou-Kishou Houkoku*) by District Meteorological Observatories (DMO) of JMA; *Bulletin of DMO* (*Jihou*); DMO News; Preliminary Report on Meteorological Hazard (*Saigai Sokuhou*) by Local Meteorological Observatories (LMO) of JMA; Monthly Report (*Geppou*) by LMO; several anniversary publications of LMO; summaries of natural hazards by a Prefecture and/or LMO; Annual Summary of Meteorological Phenomena (*Kishou-Nenkan*); individual research papers; technical reports; and newspapers.

The information on the tornadoes and waterspouts surveyed over this literature were used as inputs to the database, which can be operated on widely used personal computers. Commonly used database software such as LOTUS 1-2-3 and Filemaker II may be used to analyze the database. Every effort was made to exclude dust devils, whirlwinds, downbursts, and other strong winds by carefully examining descriptions in the literature. However, it was difficult to judge if several cases were definitely different from tornadoes. These cases are included in the database for the time being until some new reliable literature or record is found. The effect of these cases on the statistical results is believed to be small. Some tornadoes occur almost simultaneously in very close proximity, and many more waterspouts tend to do so. On such an occasion, tornadoes and waterspouts for which the location and time of the touchdown are precisely recorded were counted separately. On the other hand, those for which the location and time of the touchdown are not recorded separately were counted as one. In the latter case, a comment such that three waterspouts were observed at the same time was input to the database.

b. Structure of the database

The structure of our database is illustrated in Table 2. The data are input in Japanese, but an English version is shown in the table. The items recorded in the database basically follow those selected by OMM except that additional information such as the latitudes and longitudes of the tornado occurrence were added. The items described in the columns are explained from the left-hand side. First, the year, month, day, hour, and minute of the tornado occurrence is given; an empty cell means that no reliable datum is described in the literature. The location of the tornado occurrence is given in the order of latitude, longitude, and address. When the detailed address of the tornado occurrence is not known, the latitude and longitude of the city office are assigned to the corresponding cells. The damage pathlength L is given in kilometers. The direction of tornado movement is given in the 16 compass point direction and its speed in m s^{-1}. The duration of the tornado is given in minutes. The direction of the tornado rotation follows. The maximum width D of the damage path is given in meters, and the severity of the damage was classified according to the F-scale (Fujita 1971) when reliable damage data to specify the scale are available. The synoptic situation was determined somewhat subjectively by referring to surface weather maps published by JMA (see section 3g for details). Damage characteristics follow, such as fatalities; injuries; completely destroyed; severely damaged, and partly damaged residential houses; completely destroyed, severely damaged, and partly damaged nonresidential houses. For some tornadoes, only the total number of damaged houses, either residential or nonresidential, or both, is known and is recorded in the column of ''other features.''

In the column of ''other features,'' seven items of information are recorded:

1) Classification of the vortex according to the place of tornadogenesis (tornado, waterspout, tornado of waterspout origin);
2) Existence of a detailed map of the damage path;
3) Eyewitness evidence (funnel cloud, electrical phenomena associated with the funnel, existence of video or photographs);
4) Aural phenomena (roaring sound, feeling accompanied with the sudden pressure change);
5) Damage to special structures such as ships, power poles, trees, and cars, and damage to houses the detailed classification of which is unknown;
6) Existence of traces of meteorological elements such as pressure and wind; and
7) Reliability of the tornado event (inconsistency among literature if any).

The first item is used to obtain statistics according to the category of waterspouts, tornadoes of waterspout origin, and tornadoes. The second item will be used to obtain more accurate latitudinal and longitudinal position of the tornadogenesis as well as the position where it dissipated if desired. It may be also used to judge the reliability of the phenomena as a tornado. The third and fourth items also give some measure of reliability for the phenomena occuring on nights for which no eyewitness is available (see, e.g., Fujitani and Niino 1993). The fifth item provides a supplement to the house damage for which types of houses or degree of damage is known in detail.

Any literature that has a description of a tornado was recorded in the literature column. The literature was arranged in the order of regular publications of JMA, those of DMO, those of LMO, those of the Japan Weather Association, irregular publications of national or local governments, and individual papers. In the last column, the page number of a map is given [drawn to a scale

TABLE 2. Structure of the database.

Tornado number	Year	Month	Day	Time	Min	Lat	Long	Place of occurrence	Damage path-length	Direction of movement	Translational velocity	Dura tion	Direction of rotation	Damage path width	Fujita scale	Synoptic situation
6101	1961	1	24	13	45	3115	13023	Shioya, Chiran Town, Kawabe-Gun, Kagoshima Prefecture	0.3						1	Warm sector of extratropical cyclone
6102	1961	1	24	13	50	3354	13056	Oosato-Chou 4-chome~ Furou-Chou 3-chome, Moji City, Fukuoka Prefecture	0.1						0	Warm front
6103	1961	4	2	8	45	3620	13638	Shimo-Yoshitani~ Kami-Yoshino Region, Yoshinotani Village, Ishikawa-Gun, Ishikawa Prefecture	1.3	N			AC	100	1	Western side of trough
6104	1961	4	29	8	32	3237	13303	15 km south-southeast of Cape Ashizuri, Tosa-Shimizu City, Kouchi Prefecture		W		8				Western side of high pressure system

TABLE 2. Continued.

		Residential houses			Nonresidential houses					
Deaths	Injuries	Completely destroyed	Severely damaged	Partly damaged	Completely destroyed	Severely damaged	Partly damaged	Other features	References	Map page number
0	0	0	0	24	5	0	0	Waterspout-origin, Damage to trees	*Geophysical Review*, Unusual Weather Report of Fukuoka District Meteorological Observatory (Vol. 1), Record of Natural Disasters in Kagoshima Prefecture (1967), Fujita (1973), Torigoe and Tate (1974), Mitsuta (1983), Koreeda and Kohno (1991)	134
0	0	0	0	25	0	0	0	Signs	*Geophysical Review*, Unusual Weather Report of Fukuoka District Meteorological Observatory (Vol. 1), Fujita (1973), Torigoe and Tate (1974), Mitsuta (1983)	119
0	0	2	4	0	0	4	0	Damage map	Unusual Weather Report of Tokyo District Meteorological Observatory (Vol. 2-2), Record of Natural Disasters in Ishikawa Prefecture (1971), Shimada (1966), Fujita (1973)	87
0	0	0	0	0	0	0	0	Waterspout	*Geophysical Review*, Mitsuta (1983)	117

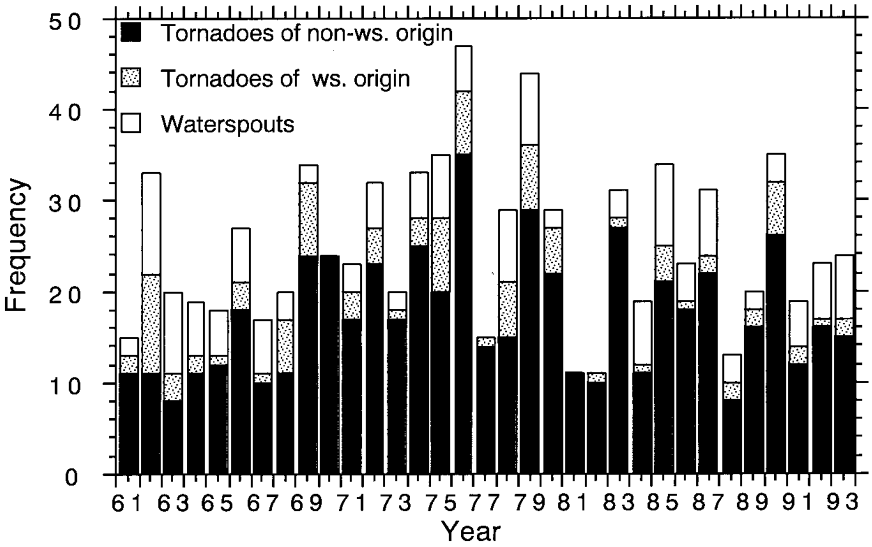

FIG. 1. Annual frequencies of tornadoes and waterspouts from 1961 to 1993. The black bar shows frequencies of tornadoes of nonwaterspout origin, the shaded bar those of tornadoes of waterspout origin, and the white bar those of waterspouts.

of 1:200 000, published and widely distributed by the Japan Map Center (1989)] on which the tornado path was plotted.

3. Results

a. Annual frequency

Figure 1 shows annual totals of tornadoes and waterspouts from 1961 to 1993. A total of 677 tornadoes, and eight funnel-alofts[1] are cataloged in our database for these 33 yr. This means that 20.5 tornadoes yr^{-1} occurred on average, a number being the largest among the previous statistical studies on tornadoes in Japan (see Table 1). This is because the amount of literature surveyed in the present study is larger than that of any previous statistical study. We have also made a very careful survey of the literature so that a number of tornadoes that were overlooked in past studies were compiled in our database.

As is easily expected, the number of tornadoes fluctuates largely from year to year: the maximum is 42 in 1976 and the minimum is 10 in 1988. However, one does not find any trend in the annual number of tornado occurrences during the 33 yr. This contrasts to the increase of the annually reported tornadoes before 1960 (see section 1).

Among the tornadoes, 104 tornadoes (about 15% of all tornadoes) are of waterspout origin. Shimada (1967) analyzed 76 tornadoes between 1955 and 1964, and found that 41 tornadoes (53%) were of waterspout origin. The present result differs considerably from Shimada (1967).

On the other hand, a total of 151 waterspouts (three of them are funnel-alofts) have been cataloged in our database. This means that about 4.5 waterspouts occurred per year on average. Shimada (1967) recorded 2.4 waterspouts yr^{-1} and OMM 2.5 waterspouts.[2] Thus, our extensive survey of the waterspouts is evident.

Figure 2 also shows annual totals of tornadoes associated with typhoons and those without typhoons, where typhoon-associated tornadoes have been defined as those that occur inside the outermost closed isobar of a typhoon on a surface weather chart. About 20% of the tornadoes are associated with typhoons. It is observed that the years with a relatively large number of tornadoes are not necessarily those having many typhoon-associated tornadoes.

b. Geographical distribution

Figure 3 shows the geographical distribution of tornadoes and waterspouts between 1961 and 1993. A majority of the tornadoes occur in coastal regions, except in the Kanto district, where a significant number of tornadoes do occur far from coastal regions (the Kanto district consists of Ibaraki, Tochigi, Gunma, Saitama,

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[1] It may look somewhat peculiar that only eight funnel-alofts have been recorded for 677 tornadoes. Since funnel-alofts do not produce damage, they are seldom reported. It is also noted that there are no tornado spotters in Japan.

[2] OMM counted only one waterspout when several waterspouts occurred at the same time in the same area. If the same rule to count waterspouts as ours is applied to OMM, the number of waterspouts would have increased by 14. Thus, they would have recorded 3.1 waterspouts yr^{-1}.

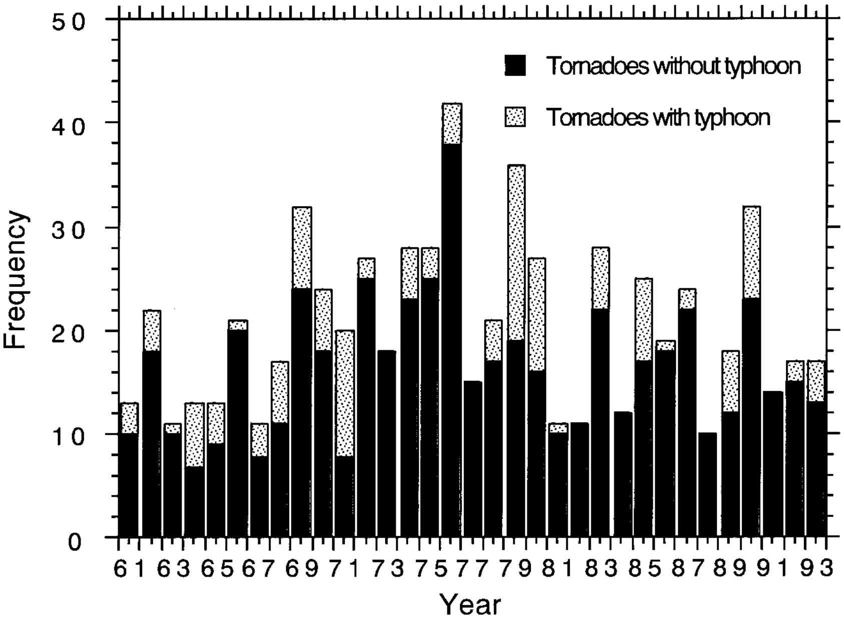

FIG. 2. Annual frequencies of tornadoes associated with a typhoon and those not associated with typhoons. The former are shown by shaded bars and the latter by black bars.

Tokyo, Kanagawa, and Chiba Prefectures; for their locations, see Fig. 7b). Most of the cataloged waterspouts are located near coastlines where a probability of observing waterspouts is much larger than that over open oceans. In the latter, however, ships do occasionally observe or even encounter waterspouts (e.g., a fishery ship was hit by a waterspout and became unable to cruise on 29 September 1978).

A probability, *P*, of a tornado occurence may be defined by the number of tornadoes per unit area of 10^4 $km^2\ yr^{-1}$. Figure 4 shows the values of *P* for each Prefecture. Here, *P* is the largest for Okinawa Prefecture and is 9.1. This number is larger than 2.9, the *P* value for Oklahoma in the United States for 1953–91 (Grazulis 1993; his Table 3.5). Generally, *P* is larger for Prefectures on the southern coasts of the Japan Islands: it is 4.3 for Tokyo Prefecture (*P* is 11.1 for the Izu and Ogasawara islands, and is 2.7 for the rest of the Prefecture). This is followed by Chiba (1.9), Miyazaki (1.7), Kagoshima (1.6), Ibaraki (1.5), Shizuoka (1.4), Nagasaki (1.4), Saitama (1.4), and Kouchi (1.3) Prefectures. On the Japan Sea side, *P* is generally small. However, it is noted that *P* values for Ishikawa (1.1) and Akita (0.9) Prefectures are larger than those for several Prefectures on the Pacific side. During the 33 yr, no tornadoes were reported in Kagawa, Nara, and Shiga Prefectures, which are surrounded by mountains.

As noted from Fig. 3, most of the tornadoes occur near the coastline and only a small number of tornadoes occur in mountainous areas. In fact, 391 tornadoes are found to occur in the region within 5 km from the coastlines (the region will be hereafter referred to as the coastal region). If the coastal region is assumed to occupy 20% of the whole area of Japan,[3] *P* for the coastal region is 1.4, a number between that of Alabama and Missouri (the 13th and the 14th largest) in the United States.

The *P* value for the coastal region is considerably large for several Prefectures. For examples, for the coastal region of Miyazaki Prefecture it is 9.2 and for Kouchi Prefecture 5.1. The probability of tornado occurrences has even smaller-scale spatial variability. In the Miyazaki plain of Miyazaki Prefecture, the coastal region experienced 23 tornadoes in the area of 5 km by 50 km, which leads to a *P* value of 27.9. The coastal region of the Kouchi plain in Kouchi Prefecture had 11 tornadoes in the area of 5 km by 13.5 km, which gives $P = 24.7$. In the Hamamatsu plain in Shizuoka Prefecture, the region within 10 km from the coastline of 40 km in length experienced 15 tornadoes, which leads to

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[3] The total length of the coastlines of Japan is estimated to be about 33 000 km and those for the main four islands 19 000 km (Kaizuka et al. 1985). Since the coastlines have complex indentations, however, a simple multiplication of 5 km to these lengths would give an erroneous overestimate of the coastal region. In this paper, a crude estimate of the coastal region was made in the following way: The Japan islands were divided into subregions with 10 s lat × 15 s long. Then, a fraction of the area within 5 km from the coastline in each subregion was estimated by eye to the accuracy of one-tenth of the area of the subregion. The sum of the fraction for each subregion turned out to be 195 times the area of the subregion. Since an average size of the subregion is 18.6 km × 22.5 km, the total area of the coastal region is estimated to be 8.2×10^4 km. A division of this number by the total area of Japan, 3.8×10^5 km, gives 0.22.

$P = 11.4$. These values are much larger than the P value, 2.9, for Oklahoma. Such small-scale variabilities of probability of tornado occurrences described above probably reflect some kind of topographic effect on mesoscale meteorological conditions.[4] However, their study is outside the scope of the present study.

c. Monthly and hourly frequencies

1) MONTHLY FREQUENCY

Figure 5 shows monthly totals of tornadoes and waterspouts during 1961–93. About 56% of tornadoes occur between July and October. They occur most frequently in September and least frequently in March. These results are similar to OMM. In the United States, tornadoes are most frequent in May, followed by June (e.g., Grazulis 1993). Note that, however, monthly tornado distribution changes largely from the east coast to the midwest in the United States (e.g., Mississippi has two peaks in the monthly frequency: one in April and the other in November).

On the other hand, about 50% of waterspouts occur in September and October: they occur most frequently in October and slightly less frequently in September. These features do not change even if tornadoes of waterspout origin are included in the statistics of waterspouts. Only three waterspouts in September and October were associated with typhoons. Therefore, the reason why waterspouts are frequent in September and October is not explained in terms of typhoons. One possible speculation may be that the air temperature decreases rapidly but the sea surface temperature remains relatively warm in these months, so that activities of cumulus or cumulonimbus clouds remain reasonably high. However, climatic data on monthly-mean sea surface temperature T_S around the Japan islands (Marine Department of Japan Meteorological Agency 1989) and monthly-mean sea level air temperature T_a near the coastlines of Japan (Japan Meteorological Agency 1971) show that T_S is about 4 to 5 K higher than T_a both in March and in October. Furthermore, though it is true that T_S is lower than T_a in June, July, and August, $T_S - T_a$ in December, January, and February is about two times as large as that in October. Therefore, the temperature difference between T_S and T_a does not explain the frequent occurrence of waterspouts in October and September. Unfortunately, no data exist on the activities of cumulus clouds over oceans. It may be also possible to speculate that waterspouts would be more frequently eyewitnessed in a season with better visibility. However, more study is required to substantiate these hypotheses.

Golden (1973) studied waterspouts around the Florida Keys and found that the months of high frequency of waterspouts were August, June, and July, which is different from the present result. He also found that the monthly frequencies of waterspout days are larger when the sea surface temperatures are higher and that convective rainfall had a good correlation with waterspout occurrence.

Figure 6 shows seasonal variations of tornadoes and waterspout occurrences for each 10 days. The frequency of tornadoes suddenly increases from the last 10 days of August and remains high until the end of September. A fairly large portion of the tornadoes that occur from the end of August to that of September are associated with typhoons. During the last 10 days of August, for example, more than half of the tornadoes were associated with typhoons (cf. OMM). If tornadoes associated with typhoons were excluded from the statistics, the frequency of tornadoes is the largest in the first 10 days of September. They are followed by the middle 10 days of July, the last 10 days of September, and the middle 10 days of January. Only one tornado has been reported in the middle 10 days of February during the 33 yr.

On the other hand, the frequency of waterspouts becomes large from the first 10 days of September and remains high until the end of October. This contrasts with the less frequent occurrence of waterspouts in spring.

Figure 7a shows seasonal variations of tornado occurrence in the Pacific Ocean side and the Japan Sea side of Japan, where the way to divide the two sides is shown on the map in Fig. 7b. In winter, a cold dry air mass, flowing southeastward from the Asian continent, is heated and moistened from below by the relatively warm Japan Sea and reaches the Japan Islands, which have a chain of mountains along the center line between the coasts of the Pacific Ocean and the Japan Sea. Accordingly, high activities of cumulonimbus clouds associated with a considerable precipitation mostly in the form of snow occur in the Japan Sea side, while dry weather continues on the Pacific side. As is expected from Fig. 3, more than 75% of tornadoes occur on the Pacific side, where the highest frequency is found in September and the lowest in March. The variation of the monthly frequency is monotonic between March and September. On the Japan Sea side, however, there are two maxima in the frequency: one in September and the other in January. The latter maximum is associated with the enhanced convective activities caused by cold air outbreaks. Overall, the seasonal variations of tornado occurrence in the Pacific Ocean side and the Japan Sea side of Japan are similar to those found by OMM.

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[4] In the United States, effects of population bias on tornado statistics have been extensively examined (e.g., Schaefer and Galway 1982). Schaefer and Galway (1982) found that the number of reported tornadoes has surprisingly small population bias. Since the country-mean population density of Japan is 318 people km^{-2}, which is much larger than 25 people km^{-2} in the United States, and since most of population in Japan is concentrated in the coastal area, there seems to be little chance that a tornado in the coastal area is not reported. Therefore, we believe that the small-scale variability in the coastal region is not caused by population bias.

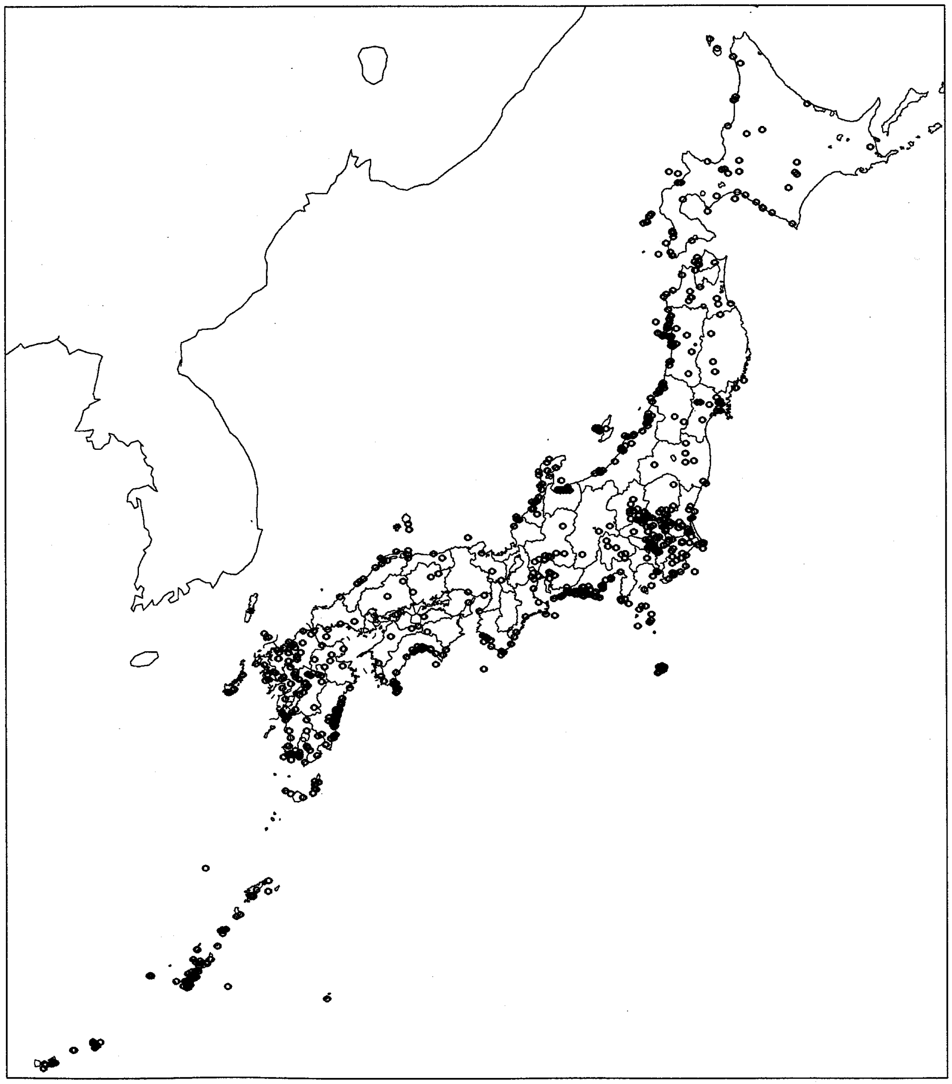

FIG. 3. Geographical distribution of tornadoes and waterspouts in Japan from 1961 to 1993. The points where tornadoes or waterspouts were eyewitnessed or their damage started are indicate by open circles.

2) HOURLY FREQUENCY

Figure 8 shows diurnal variations of tornado and waterspout occurrences. High frequency of tornadoes is found between 0900 and 1700 JST with two peaks at 1000–1100 and 1500–1600 JST. On the other hand, few tornadoes occur between 2100 and 2400 JST. The higher frequency of tornadoes during the daytime probably reflects the higher activities of cumulonimbus clouds caused by solar heating in a general sense. The diurnal variation of tornado frequency in the United States shows that the frequency increases after 1100 and decreases after 1800 until 2100 LST (Grazulis 1993). The most frequent time interval is between 1600 and 1700 LST. Therefore, the peak frequency of tornado occurrence seems to come slightly earlier in Japan than it does in the United States.

Figure 8 also shows that tornadoes associated with typhoons do not show any systematic diurnal variation. Most of the typhoon-associated tornadoes may be produced by cumulonimbus clouds in a rainband in a typhoon. The effect of surface heating may be less important for maintaining such cumulonimbus clouds. Fujita et al. (1972) analyzed 68 typhoon-associated tornadoes during 1951–70 and found a significant oscillation of tornado frequency with a period of 6 h. No such significant oscillation was found in the present results.

Waterspouts also have high frequencies during daytime, especially from 0900 to 1200 JST and from 1300 to 1700 JST. The less frequent occurrence of waterspouts during nighttime may be partly caused by the fact that they have less chance of being eyewitnessed.

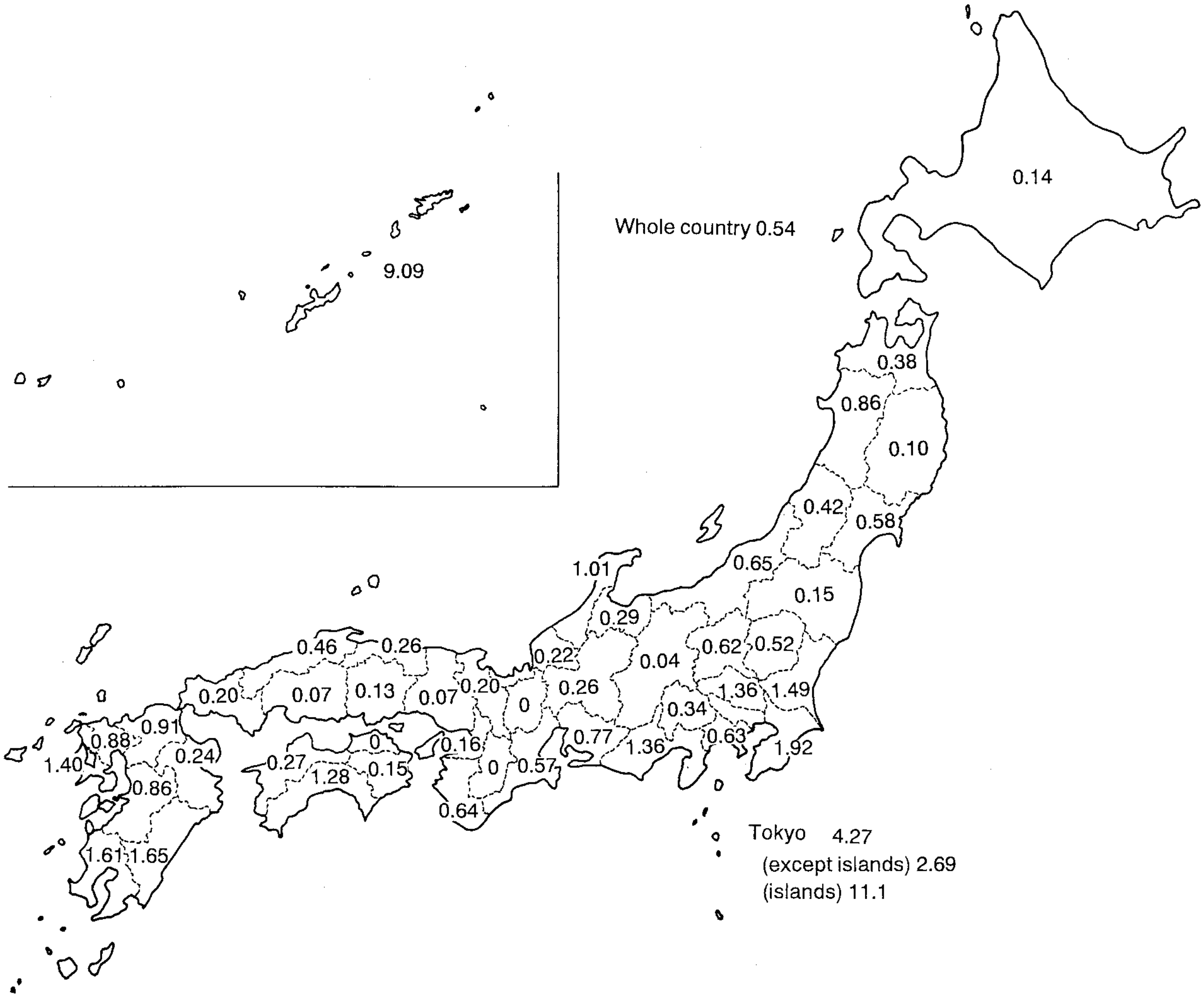

FIG. 4. Annual number of tornadoes per unit area (10^4 km^2) during 1961–93.

d. Number of tornadoes and waterspouts in a day

Several tornadoes and/or waterspouts tend to occur on a single day, probably because the mesoscale environment favorable for their formation persists for a day or so. Table 3 summarizes frequency distributions of numbers of tornadoes and/or waterspouts that occurred on the same day. A day with more than two tornadoes will be hereafter termed a multiple-tornado day and that with *n* tornadoes a *n*-tornado day.[5]

There were 92 multiple-tornado days between 1961 and 1993. The number of tornadoes on the multiple-tornado days is 259, which amounts to about 38% of all tornadoes during the period. Among the 92 multiple-tornado days, there were 61 two-tornado days. However, it should be noted that there were 4 six-tornado days and 4 seven-tornado days. These facts seem to demonstrate that a mesoscale environment favorable for generating tornadoes definitely exists: for example, Typhoon 7912 (the 12th typhoon in 1979) spawned 11 tornadoes from 3 September to 4 September 1979; Typhoon 8019 produced 8 tornadoes from 13 October to 14 October 1980.

There were 25 multiple-waterspout days: 19 were two-waterspout days and 6 were three-waterspout days. The number of waterspouts on the multiple-waterpout days is 56, which amounts to about 37% of all waterspouts. There were 12 cases in which at least one tornado and one waterspout occurred on the same day.

e. Tornado damage characteristics

1) DAMAGE PATHLENGTH

Figure 9 shows frequencies of tornadoes according to their damage pathlength *L*. Following OMM, *L* is

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[5] In the United States, if a particular mesoscale environment produces more than seven tornadoes, it may be called a tornado outbreak (Grazulis 1993). Fujita (1987) suggested that a day with 20 or more occurrences may be called an outbreak day.

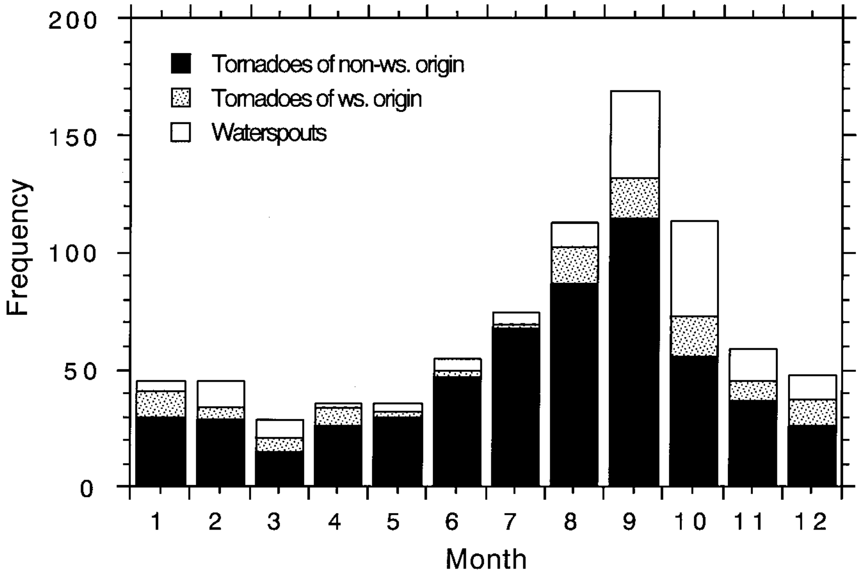

FIG. 5. Same as Fig. 1 except for monthly frequencies.

divided into five categories according to Pearson's length scale (Fujita and Pearson 1973), in which the boundary values of *L* between two adjacent categories increase by a factor of $10^{1/2}$.

OMM analyzed data for 171 tornadoes, while we have analyzed 351 data. About one-half of the tornadoes have *L* less than 1.6 km. The frequency of tornadoes decreases rapidly with increasing *L*. There have been only six tornadoes having *L* larger than 16.1 km. The maximum value of *L*, 41.2 km, was recorded by the Tokyo tornado on 28 February 1978 (e.g., Mitsuta et al. 1979; Muramatsu 1979). The average damage pathlength for 351 tornadoes for which data of *L* exist is 3.2 km, which is very close to 3.3 km, the result of OMM. Since it is likely that characteristics of tornadoes with long damage pathlength are well documented in the literature (e.g., Schaefer et al. 1986), the average damage pathlength may be even smaller than 3.2 km. An average pathlength of tornadoes in the United States between 1950 and 1982[6] is 7.1 km (Schaefer et al. 1986). Thus, the average pathlength of tornadoes in Japan is about one-half of that in the United States.

2) DAMAGE PATH WIDTH

Figure 10 shows frequencies of tornadoes according to the damage path width *W*. Following OMM, *W* is divided into five categories according to Pearson's width scale (Fujita and Pearson 1973) again. OMM analyzed data for 134 tornadoes, while we have analyzed data for 295. About half of the tornadoes have *W* between 16 and 51 m. The frequency of tornadoes decreases rapidly with increasing *W*. There have been only six tornadoes having *W* larger than 509 m. The maximum value of *W*, 1500 m, was recorded by the Mobara tornado on 11 December 1990 (e.g., Niino et al. 1991; Niino et al. 1993a; Niino et al. 1993b; Fujita 1993). The average damage path width for 295 tornadoes for which data of *W* exist is 98 m, which is again very close to 101 m, the result of OMM. For the same reason for *L*, the actual average damage path width is probably smaller than 98 m. An average path width of the tornadoes in the United States between 1950 and 1982 is 117 m (Schaefer et al. 1986) and is fairly close to that in Japan.

3) FATALITIES AND INJURIES

Among 591 tornadoes for which data for fatalities and injuries exist, only 16 tornadoes caused fatalities during the 33-yr period. Thirteen tornadoes produced one fatality and three killed two persons (Fig. 11). The latter are the Azuma village, Chiba Prefecture, tornado on 2 July 1962 (this tornado was not included in the list of tornadoes by OMM); the Ooami-Shirasato town, Chiba Prefecture, tornado on 28 October 1967; and the Sashima town, Ibaraki Prefecture, tornado on 23 August 1969. Fatality per tornado is less than 0.032 persons and that per year is 0.58, a number comparable to 0.5, the result of OMM, who analyzed data for 82 tornadoes.

Figure 12 shows frequencies of tornadoes according to the number of injuries. Five hundred tornadoes out of 591 did not cause injuries. Only four tornadoes caused injuries to more than 51 persons. The maximum number of injuries, 107, was caused by the Sashima town, Ibaraki Prefecture, tornado on 23 August 1969.

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[6] Strictly speaking, the period of their statistics is between 1 January 1950 and 1 January 1983.

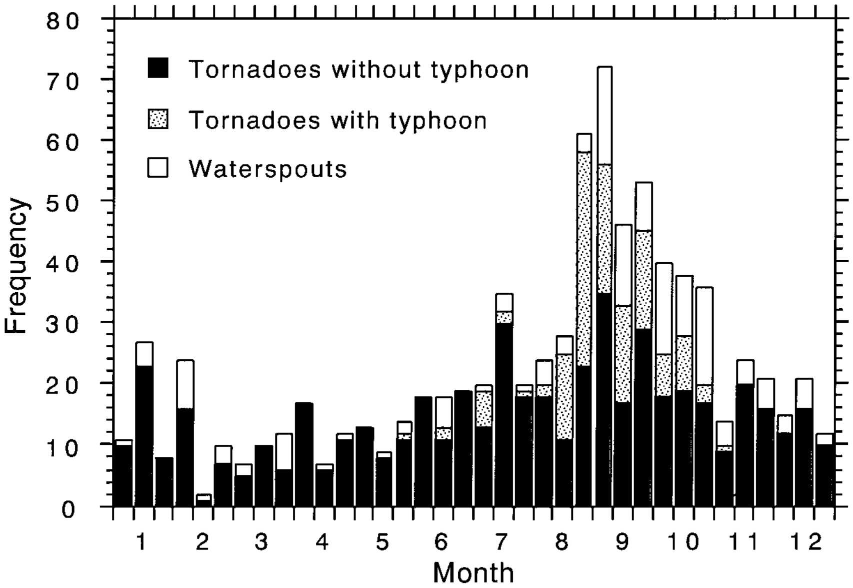

FIG. 6. Seasonal variations of tornadoes and waterspouts for each 10 days. The number of tornadoes associated with a typhoon is indicated by the black bar, that not associated with a typhoon by the shaded bar, and the number of waterspouts by the white bar.

Injuries per year is 29.7 persons, which is fairly larger than 20.6, the result of OMM. Injuries per tornado are 1.67 persons, much smaller than 5.7 for the 82 tornadoes (OMM). The difference was caused because many tornadoes that produced a small number of injuries or did not produce injuries were not used for their statistical calculation. However, the fact that injuries per year is larger than those in OMM demonstrates that we have used more tornadoes in the statistics than they did.

4) DAMAGE TO RESIDENTIAL HOUSES

Figure 13 shows the frequencies of tornadoes according to the number of completely destroyed (Fig. 13a), severely damaged (Fig. 13b), and partly damaged residential houses (Fig. 13c). Here, a completely destroyed house (CDH) is defined as one for which the damage amounts more than 70% of the total floor area or more than one-half of the estimated price of its main structure; a severely damaged house (SDH), one that can be lived in after repair work (i.e., the damage to which is between 20% and 70% of the total floor area or between 20% and 50% percent of the estimated price of its main structure); and a partly damaged house (PDH), the damage to which is less than 20% of the total floor area or less than 20% of the estimated price of its main structure.

Among 561 tornadoes for which data for CDHs exist, 508 tornadoes did not produce CDH (Fig. 13a): that is, only 53 tornadoes produced CDHs. Among the latter, only five tornadoes produced CDHs more than 16. The maximum CDHs of 82 were produced by the Mobara tornado, Chiba Prefecture, on 11 December 1990 (e.g., Niino et al. 1991; Niino et al. 1993a; Niino et al. 1993b). CDHs per year is 17.0 and CDHs per tornado is 0.78. The latter is close to 0.7, the result of OMM for 274 tornadoes.

The data of SDHs exist for 549 tornadoes (Fig. 13b). Four hundred and sixty-three tornadoes did not produce SDH. Only four tornadoes caused SDH larger than 51. The maximum SDHs of 168 were produced by the Hamamatsu, Shizuoka Prefecture, tornado on 26 August 1962. SDHs per year is 39.0, and SDH per tornado is 2.34.

Five hundred and twenty-four tornadoes have data for PDHs (Fig. 13c). About 43% of tornadoes did not damage houses at all, but about 50% of tornadoes produced 1–50 PDHs. Only two tornadoes produced PDHs more than 508. The maximum number of PDHs was caused by the Mobara tornado on 11 December 1990. PDHs per tornado is 18.3, and PDHs per year is about 290. OMM gave a number of 364 for the total of SDHs and PDHs per year. This number is slightly larger than our result of 329. This occurred because we did not include the houses, the degree of damage to which is not known, to obtain the statistics, but they did by regarding that all such houses belong to the category of PDH.

f. Characteristics of tornadoes

1) LIFETIME

Figure 14 shows the frequencies of tornadoes according to their lifetime. About 45% of 118 tornadoes, for which data for the lifetime exist, have a lifetime

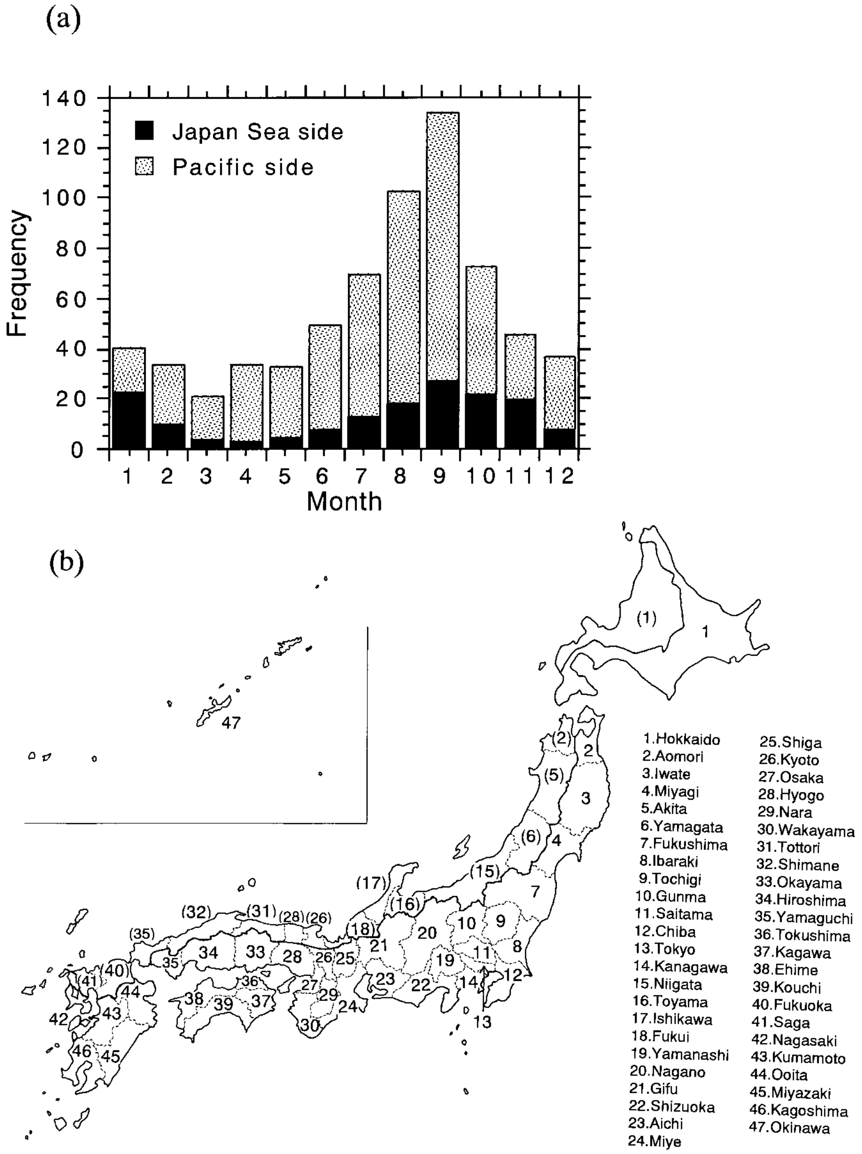

FIG. 7. (a) Monthly frequencies of tornadoes in the Pacific Ocean side and in the Japan Sea side of the Japan islands. The former is shown by the shaded bar and the latter by the black bar. (b) Geographical locations of 47 prefectures and their classification into the Japan Sea side and the Pacific Ocean side. The dashed lines denote prefectural boundaries and the solid lines the dividing lines between the Japan Sea side and the Pacific Ocean side. The locations of the prefectures are indicated by the prefectural numbers listed in the lower-right corner of the figure. The prefectural numbers in the Japan Sea side are parenthesized. Note that several prefectures have both Japan Sea side and Pacific Ocean side parts.

between 5.1 and 16.1 min. Only a few tornadoes have a lifetime shorter than 1.6 min. This may be an underestimate, since a tornado having a very short lifetime is likely to be weak and may not be observed or reported. There may be a possibility, however, that, once organized as a tornado, the vortex tends to last longer than 1.6 min. The average lifetime is 12 min, and the longest lifetime was 41 min for the Hachirohgata village, Akita Prefecture, tornado on 11 January 1987.

Ninety-five waterspouts have records on their lifetime. The average lifetime for the waterspouts is 14 min. This number is close to 14.6 min, an average duration calculated by Golden (1973) for funnel clouds and waterspouts over the lower Florida Keys in the United States between 1958 and 1967.

2) DIRECTION OF ROTATION

Ninety-five tornadoes have records on the direction of their rotation. Eighty-one tornadoes (85%) were cy-

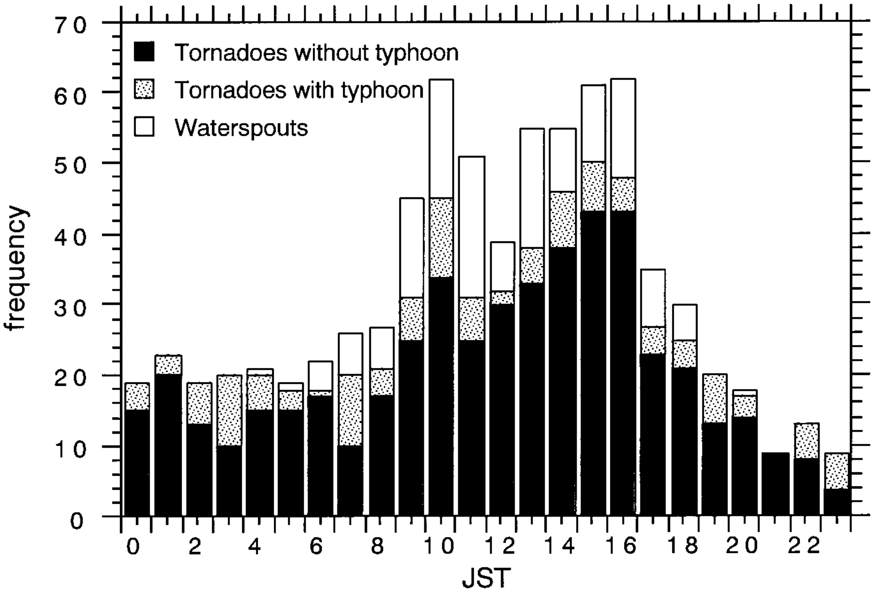

FIG. 8. Same as Fig. 6 except for hourly frequencies.

clonic and 14 (15%) anticyclonic. These records are mainly based on damage surveys made by officers at local meteorological observatories. Since they are not professional tornado researchers, the possibility that they estimated the direction of rotation erroneously from the damage survey cannot be ruled out completely. However, their report on the damage survey shows that their damage surveys were fairly extensive even for the present standard. Furthermore, at least one clockwise tornado was videotaped and four were eyewitnessed.

OMM found 31 tornadoes with records on the direction of the rotation. Eighty-one percent were cyclonic and the rest anticyclonic. Thus, the percentages of anticyclonic and cyclonic tornadoes in the present study are nearly similar to those of OMM.

In the United States, the frequency of anticyclonic tornadoes has not been estimated reliably (Davies-Jones 1981). Fujita (1973) estimated that the percentage of anticyclonic tornadoes is about 1% of all tornadoes. Fujita (1977) listed 29 anticyclonic tornadoes between 1950 and 1976. Wakimoto (1983) estimates that 1 in 700 may be anticyclonic. These estimates, although they may not be very reliable, show that the percentage of anticyclonic tornadoes in Japan is much larger than that in the United States. On the other hand, the percentage of anticyclonic waterspouts in the United States is estimated to be roughly 15% (Davies-Jones 1981). This number is close to the percentage of anticyclonic tornadoes in Japan.

TABLE 3. Number of multiple-tornado days.

Number of tornadoes on the same day	Number of multiple-tornado days	Total number of tornadoes
2	61	122
3	9	27
4	12	48
5	2	10
6	4	24
7	4	28
Total	82	259

3) DIRECTION OF TORNADO MOVEMENT

Records on the direction of tornado movement exist for 353 tornadoes. The frequencies according to 16 compass point directions are shown in Fig. 15. More than 50% of tornadoes move toward the northeast quadrant. Especially about 22% of tornadoes move northeast. One

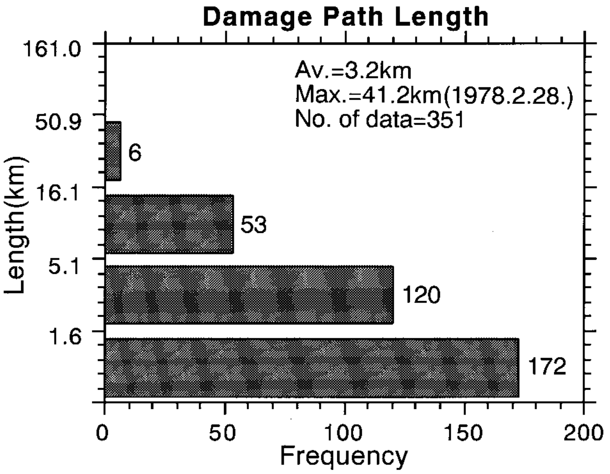

FIG. 9. Frequencies of tornadoes categorized by damage pathlength.

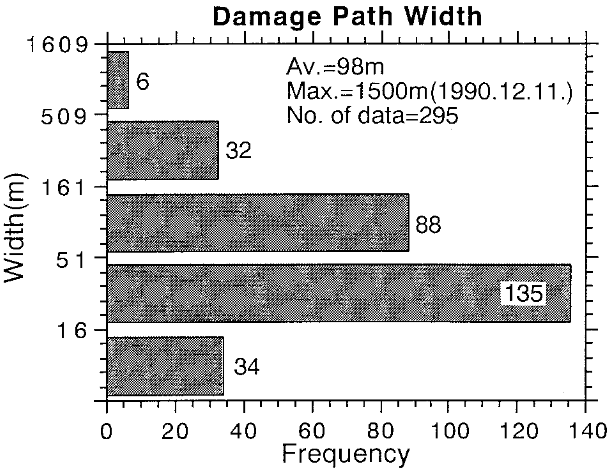

FIG. 10. Same as Fig. 9 except for damage path width.

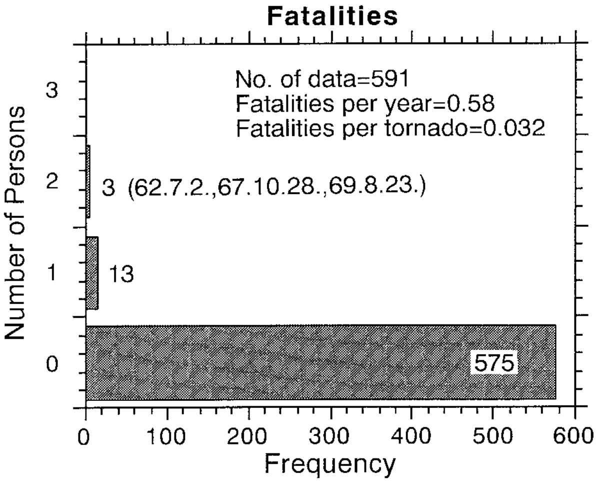

FIG. 11. Same as Fig. 9 except for fatalities.

notices that the frequencies in the direction of 22.5 + 45*n* degree (e.g., NNE, ENE, ESE, etc.) are smaller than those in the direction of 45*n* degree (e.g., N, NE, SE, etc.), where *n* is an integer between 0 and 7. This is because eyewitness evidence during a damage survey tends to be stated in terms of eight compass point directions. The results of OMM, who examined 183 tornadoes, are almost similar to the present one (see Fig. 15).

In the United States, Fujita (1987) examined 17 081 tornadoes, for which directions of the movement are known, during 70 yr between 1916 and 1985. In terms of eight compass point directions, about 59% of tornadoes moved northeastward, about 6% northward, and about 19% eastward. These facts indicate that many more tornadoes move toward the northeast quadrant in the United States than they do in Japan.

4) TRANSLATION SPEED OF TORNADO

Figure 16 shows the frequency distribution of the translation speed of tornadoes. Seventy-three tornadoes have records on the translational speed. More than 60% of tornadoes have a translational speed less than 10 m s^{-1}, and a few have a speed larger than 25 m s^{-1}. The average translational speed turns out to be 9.7 m s^{-1}. OMM examined 19 tornadoes that had records on translational speed and found that the average speed was 10 m s^{-1}, which is very close to the present result.

g. Synoptic situations

In this subsection, the frequency distribution of tornadoes according to synoptic situations is examined. For some tornadoes, a synoptic or mesoscale weather chart near the times of their touchdowns are shown in literature. For the rest, however, a synoptic situation that led to each tornadogenesis was determined rather subjectively by referring to synoptic charts published by JMA around the time of its touchdown. In this case, there are only two charts in a day at 0900 and 2100 JST. Therefore, it was sometimes difficult to pinpoint exactly the location of the touchdown with respect to a particular synoptic system such as a cold front, a warm front, or a center of an extratropical cyclone. When the location of the touchdown is pinpointed with confidence in a warm sector of an extratropical cyclone, it is classified to a category of cyclone (warm sector). When they are certainly associated with a cold front or a warm front but it is difficult to locate which side of the front, they are simply classified to a category of cold front or warm front, respectively. When they are certainly associated with an extratropical cyclone but their location relative to the cyclone system is not determined precisely, they are simply classified to a category of cyclone (other locations).

Figure 17 shows the frequency distribution of tornadoes according to categories of synoptic situations

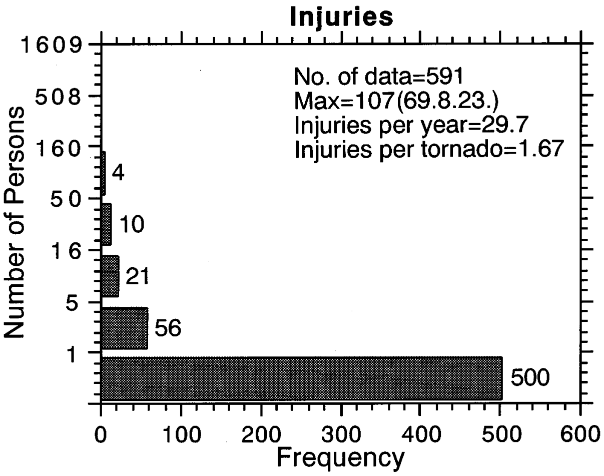

FIG. 12. Same as Fig. 9 except for injuries.

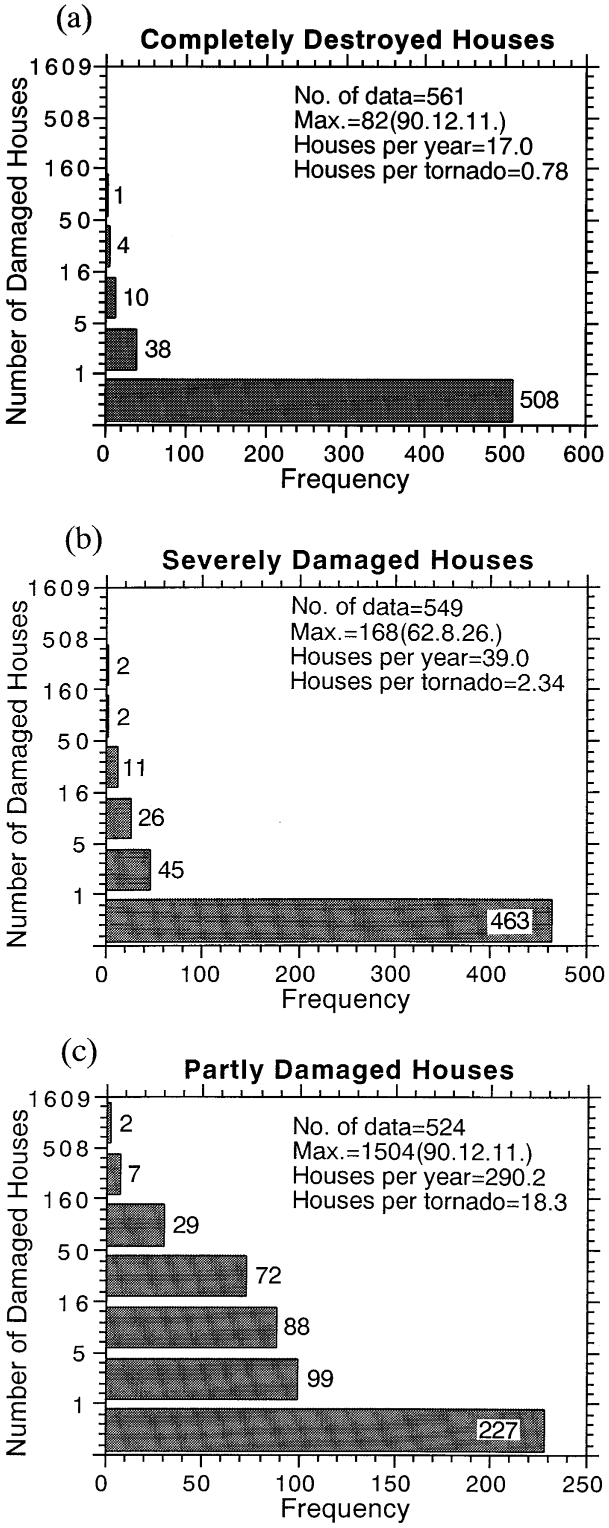

FIG. 13. Same as Fig. 9 except for (a) CDHs, (b) SDHs, and (c) PDHs.

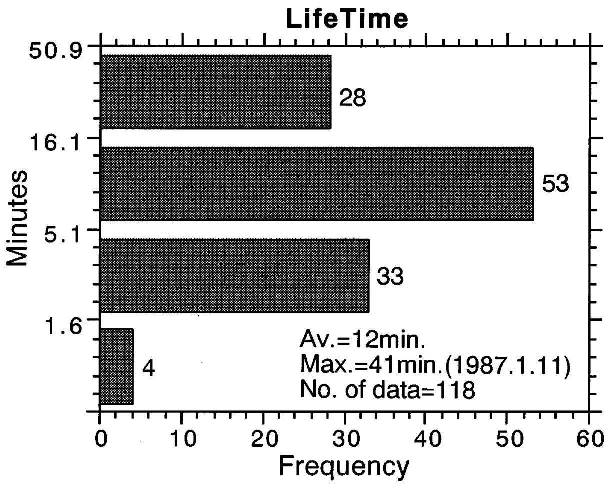

FIG. 14. Same as Fig. 9 except for lifetime.

thus determined. About 46% of tornadoes are associated with extratropical cyclones: about 16% occur in the warm sector and about 15% in association with a cold front; tornadoes associated with a warm front amount to only 2.1%; the remaining 13% occur in an extratropical cyclone but their exact positions relative to the cyclone center, the cold front, or warm front are not known. Typhoon-associated tornadoes are about 20% of all tornadoes. In winter, some tornadoes occur near the coastline of the Japan Sea because of high cumulus cloud activities during cold air outbreak over the warm

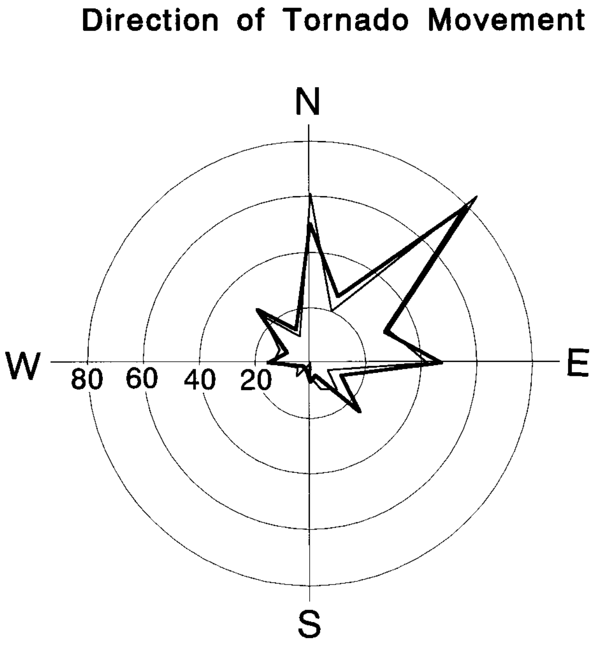

FIG. 15. Frequency distribution of the direction of tornado movement. The thick sold line shows the present result and the thin one the result of OMM, where the total number of tornadoes in the latter is adjusted to that in the former for the sake of comparison.

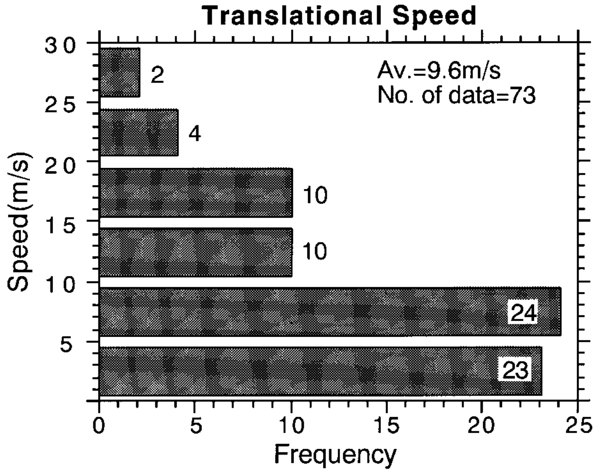

FIG. 16. Same as Fig. 9 except for translational speed.

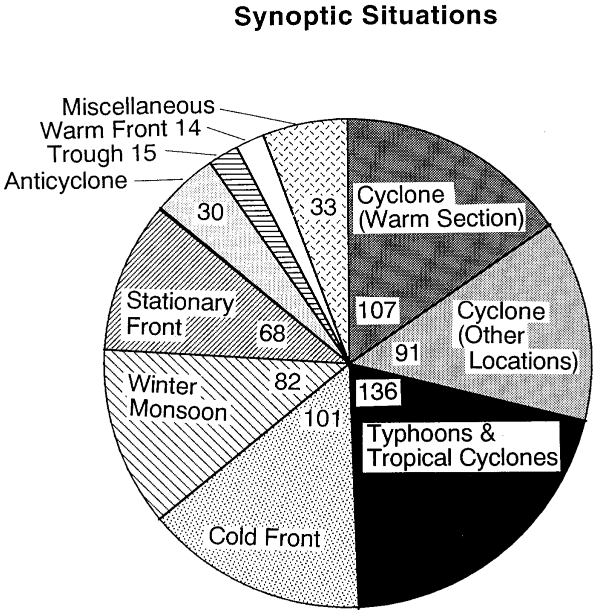

FIG. 17. Frequency distribution of the synoptic situations when tornadoes occurred.

sea surface (see section 3c.1). Such winter-monsoon tornadoes share 12% of all tornadoes. About 10% of tornadoes are associated with a stationary front. Some tornadoes (4%) may develop in a high pressure system when there is a cold advection at the mid- to upper troposphere.

OMM made a similar study on tornadoes between 1971 and 1982 and found that about 57% of tornadoes occur in association with extratropical cyclones and fronts and about 28% in association with typhoons. The present result is nearly similar to theirs with respect to the fact that about 56% of tornadoes are associated with extratropical cyclones or stationary fronts. According to OMM, however, about 26% are associated with cold fronts, 15% with other kinds of fronts, and 15% with other part of extratropical cyclones. The percentage of tornadoes associated with a cold front is somewhat smaller in the present study. This is partly because some fraction of tornadoes classified into those associated with cold fronts in OMM are classified into those in a warm sector after careful examinations of literature and weather charts. The percentage of typhoon-associated tornadoes is also somewhat smaller in the present study.

h. Risk of a tornado encounter

Risk of a tornado encounter is one of the basic and important parameters for designing structures. There have been no data on such a probability in Japan. As a preliminary attempt to calculate the probability for each Prefecture, the following three simple approaches were adopted.

In the first method, an average damage pathlength $\bar{L}$ and an average damage path width $\bar{W}$ were calculated for tornadoes that have records on damage pathlength and damage path width, respectively, for each Prefecture. The numbers of tornadoes for which damage pathlength and path width are known are 351 and 295, respectively, for the whole country of Japan. The tornado damage path was assumed to be a lozenge whose long and short axes are given by $\bar{L}$ and $\bar{W}$, respectively. Therefore, the area of the damage path is given by $\bar{L}\bar{W}/2$. If this is multiplied by the probability of tornado occurrence P for each Prefecture (described in section 3b), one obtains a probability, Pe_1, of encountering tornadoes, where Pe_1 has a unit of yr^{-1} and is defined as the probability that a certain point in a particular Prefecture enters a tornado damage path.

In this method, a problem arises when a tornado of a long damage length crosses prefectural boundaries: for example, one calculates the average length of the damage path by including in the long pathlength some portion of that which belongs to different Prefectures. This tends to overestimate the pathlength and possibly the path width as well, resulting in an overestimation of the probability. To obtain some idea about to what degree the probability calculated by the first method is reliable, another method was considered.

In the second method, only the tornadoes for which both the damage pathlength and path width are known were used for the calculation. There are 267 of such tornadoes for the whole country. For these tornadoes, one can easily calculate the area of damage path in each Prefecture even if the damage path crosses prefectural boundaries, though the number of tornadoes that can be used to calculate the probability for a particular Prefecture is reduced. In this method, one simply needs to sum up, for each Prefecture, the area of the damage paths of all the tornadoes for which the damage pathlength and width are known, divide the area S by the number of the tornadoes and multiply it by P. The tornado encounter probability calculated in this way is de-

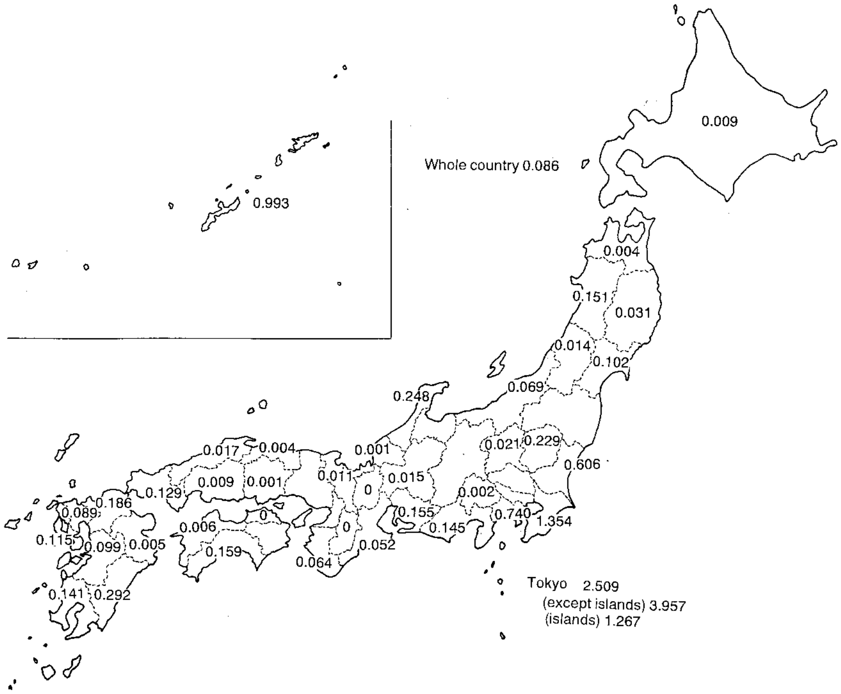

FIG. 18. Risk of a tornado encounter, Pe_1, for each prefecture. The unit is 10^{-4} yr^{-1}.

noted by Pe_2. Since stronger tornadoes tend to have records both on the damage path and width, however, this method also may give an overestimate of the probability.

In the third method, the calculation is similar to that for Pe_2 except that only the sum of the areas covered by the tornado path during the 33 yr were divided by the area of the Prefecture and divided by 33 yrs. A similar definition of a tornado encounter probability was used by Thom (1963) and Schaefer et al. (1986) for the tornadoes in the United States. The tornado encounter probability Pe_3 calculated in this way gives the minimum estimate of the risk of a tornado encounter; that is, one is sure that the risk is at least larger than Pe_3.

Figure 18 shows the distribution of Pe_1 for each Prefecture. Here, Pe_1 for the whole country of Japan is 0.086×10^{-4} yr^{-1}, which means that a particular point in Japan comes into a tornado damage path once in 1.2×10^5 yr. The largest probability is calculated for Tokyo Prefecture and is 2.5×10^{-4} yr^{-1} (this corresponds to a recurrence interval R of 4000 yr). For the Izu and Ogasawara islands of Tokyo Prefecture, Pe_1 is 1.3×10^{-4} yr^{-1} ($R = 7700$ yr) and that for the rest of the Prefecture is 4.0×10^{-4} yr^{-1} ($R = 2500$ yr). Comparison with Fig. 4 shows that, although tornadoes are more frequent in the islands than they are on the mainland, their damage paths are generally smaller in the islands. Chiba Prefecture has Pe_1 of 1.4×10^{-4} yr^{-1} ($R = 7000$ yr), Okinawa 1.0×10^{-4} yr^{-1} ($R = 10\,000$ yr), Kanagawa 0.74×10^{-4} yr^{-1} ($R = 14\,000$ yr), and Ibaraki 0.61×10^{-4} yr^{-1} ($R = 16\,000$ yr). These are followed by Miyazaki, Ishikawa, Tochigi, Saitama, Fukuoka, Kouchi, Aichi, Akita, Shizuoka, and Kagoshima Prefectures.

The high probabilities in Tokyo and Kanagawa result from the contribution of the Tokyo tornado on 28 February 1978, which recorded the maximum pathlength of 41.2 km over Kanagawa, Tokyo, and Chiba Prefectures. Since the number of the tornadoes for which the damage pathlength and path width are known is small for Tokyo and Kanagawa, the probabilities calculated for these Prefectures may be somewhat unreliable. However, it is evident that the Prefectures in Kanto district except Gunma Prefecture clearly have higher probabilities than other Prefectures (except Okinawa) do. Several Prefectures on the Pacific coast have large probabilities. It is worth noting that Ishikawa, Fukuoka, and Akita Prefectures on the Japan Sea coast have considerably large probabilities. The probabilities for Shiga, Nara, and Kagawa are calculated to be zero, since no tornado occurred in these Prefectures during the 33 years. In Fukushima, Nagano, Toyama, Osaka, Hyogo, and Tokushima Prefectures, no tornado had a record on damage pathlength and path width, therefore, the probability was not calculated.

Table 4 lists the probability Pe_2 calculated by the second method. For the whole country of Japan, Pe_2 was calculated to be 0.15×10^{-4} yr^{-1} and is larger than Pe_1. This occurs because tornadoes for which both the damage pathlength and path width are recorded tend to be stronger than those for which they are not recorded. The largest probability is again found for Tokyo Pre-

TABLE 4. Risk of a tornado encounter estimated by the three method. The geographical locations of the prefectures are shown in Fig. 7b according to the prefectural number in the first column from the left. The rest of the columns from the left show 2) name of the prefecture; 3) number of tornadoes that occurred in the prefecture during the statistical period, N; 4) area of the prefecture, A; 5) sum of the tornado damage path area, S; 6) average damage pathlength, $\overline{L}$; 7) average of maximum damage path width, $\overline{W}$; 8) number of tornadoes that have data on damage path area, M; 9) risk of a tornado encounter $Pe_1 \equiv [(\overline{LW})/(2A)]N/33$; 10) $Pe_2 \equiv S/A(N/33M)$; 11) $Pe_3 \equiv S/(33A$; 12) recurrence calculated from $Pe_3(Pe_3^{-1})$.

								Risk of a tornado encounter			Recurrence
n	Prefecture	N	A ($\times 10^4$ km^2)	S (km^2)	$\overline{L}$ (km)	$\overline{W}$ (m)	M	Pe_1 ($\times 10^{-4}$)	Pe_2 ($\times 10^{-4}$)	Pe_3 ($\times 10^{-4}$)	Pe_3^{-1} ($\times 10^4$ yr)
1	Hokkaido	39	8.34	0.60	1.91	69	13	0.009	0.007	0.0022	4.5×10^6
2	Aomior	12	0.96	0.12	1.01	23	9	0.004	0.005	0.0038	2.6×10^6
3	Iwate	5	1.53	0.79	2.10	300	3	0.031	0.026	0.016	6.3×10^5
4	Miyagi	14	0.73	0.15	1.17	300	3	0.102	0.029	0.0062	1.6×10^6
5	Akita	33	1.16	3.1	5.94	59	18	0.151	0.15	0.081	1.2×10^5
6	Yamagata	13	0.93	0.16	2.20	30	7	0.014	0.010	0.0052	1.9×10^6
7	Fukushima	7	1.38	—	—	—	—	—	0.550	—	—
8	Ibaraki	30	0.61	9.1	5.72	142	26	0.606	0.089	0.45	2.2×10^4
9	Tochigi	11	0.64	1.2	7.23	122	7	0.229	0.017	0.057	1.7×10^5
10	Gunma	13	0.64	0.11	0.93	75	4	0.021		0.0052	1.9×10^6
11	Saitama	17	0.38	2.6	1.75	172	10	0.203	0.35	0.21	4.8×10^4
12	Chiba	33	0.52	15.6	6.24	225	24	1.354	1.3	0.91	1.1×10^4
13	Tokyo	31	0.22	91	6.40	184	7	2.509	5.6	1.3	7.7×10^3
14	Kanagawa	5	0.24	0.29	11.7	200	4	0.740	0.046	0.037	2.7×10^5
15	Niigata	27	1.26	0.55	3.46	62	5	0.069	0.071	0.013	7.6×10^5
16	Toyama	4	0.42	—	—	—	—	—	—	—	—
17	Ishikawa	14	0.42	3.5	2.93	168	8	0.248	0.44	0.26	3.9×10^4
18	Fukui	3	0.42	0.0025	0.50	10	1	0.001	0.001	0.00018	5.6×10^7
19	Yamanashi	5	0.45	0.011	0.60	23	2	0.002	0.002	0.00074	1.4×10^7
20	Nagano	2	1.36	—	0.40	—	—	—	—	—	—
21	Gifu	9	1.06	0.47	2.21	52	7	0.015	0.017	0.014	7.4×10^5
22	Shizuoka	35	0.78	3.3	3.37	63	22	0.145	0.20	0.13	7.8×10^4
23	Aichi	13	0.51	2.5	4.38	92	9	0.155	0.21	0.15	6.7×10^5
24	Miye	11	0.58	1.2	2.28	80	8	0.052	0.086	0.061	1.6×10^5
25	Shiga	0	0.40	0	—	—	0	0	0	0	∞
26	Kyoto	3	0.46	0.098	2.25	50	2	0.011	0.010	0.0064	1.6×10^6
27	Osaka	1	0.19	—	—	—	—	—	—	—	—
28	Hyogo	2	0.84	—	—	—	—	—	—	—	—
29	Nara	0	0.37	0	—	—	0	0	0	0	∞
30	Wakayama	10	0.47	0.74	2.83	70	6	0.064	0.080	0.048	2.1×10^5
31	Tottori	3	0.35	0.020	0.60	50	2	0.004	0.003	0.0017	5.9×10^6
32	Shimane	10	0.66	0.013	3.15	23	5	0.017	0.001	0.00060	1.7×10^7
33	Okayama	3	0.71	0.010	0.65	20	2	0.001	0.001	0.00042	2.4×10^7
34	Hiroshima	2	0.85	0.23	5.00	50	2	0.009	0.008	0.0082	1.2×10^6
35	Yamaguchi	4	0.61	0.65	6.50	200	1	0.129	0.13	0.032	3.1×10^5
36	Tokushima	2	0.41	—	—	—	—	—	—	—	—
37	Kagawa	0	0.19	0	—	—	0	0	0	0	∞
38	Ehime	5	0.57	—	2.25	19	—	0.006	—	—	—
39	Kouchi	30	0.71	1.9	2.97	83	17	0.159	0.14	0.081	1.2×10^5
40	Fukuoka	15	0.50	1.8	2.75	149	11	0.186	0.15	0.11	9.1×10^4
41	Saga	7	0.24	0.31	3.67	55	3	0.089	0.091	0.039	2.6×10^5
42	Nagasaki	19	0.41	1.7	1.89	87	12	0.115	0.20	0.13	7.7×10^4
43	Kumamoto	21	0.74	0.59	3.14	73	9	0.099	0.056	0.024	4.2×10^5
44	Ooita	5	0.63	0.11	0.80	55	5	0.005	0.005	0.0053	1.9×10^6
45	Miyazaki	42	0.77	6.8	3.91	90	34	0.292	0.33	0.27	3.7×10^4
46	Kagoshima	49	0.92	4.1	1.95	90	33	0.141	0.20	0.14	7.1×10^4
47	Okinawa	69	0.23	3.3	3.48	63	36	0.993	0.83	0.43	2.3×10^4
	Japan	677	37.77	73	3.24	98	267	0.086	0.15	0.058	1.7×10^5

fecture for which $Pe_2 = 5.6 \times 10^{-4}$ yr^{-1}. This corresponds to a recurrence interval of 1800 yr. Chiba, Okinawa, Ibaraki, Ishikawa, Saitama, Miyazaki, Aichi, and Kagoshima Prefectures follow. In most of these Prefectures except Okinawa, Pe_2 is larger than Pe_1 for the reason described above. The high probability in Tokyo again results from the Tokyo tornado on 28 February 1978. The probability for Kanagawa, calculated by this method, is much smaller, since only a small part of the damage path of the Tokyo tornado fell in Kanagawa Prefecture.

Listed also in Table 4 are the probability Pe_3. For the whole country Pe_3 is 0.058×10^{-4}. The largest Pe_3 is for Tokyo Prefecture (1.3×10^{-4} yr^{-1}). The high probability in Tokyo again is caused by the Tokyo tornado and it would take many years to lower Pe_3. The probabilities of 0.91 × 10^{-4} yr^{-1} for Chiba Prefecture, 0.46 × 10^{-4} yr^{-1} for Ibaraki and Okinawa, 0.27 × 10^{-4} yr^{-1} for Miyazaki, 0.26 × 10^{-4} yr^{-1} for Ishikawa, and 0.21 × 10^{-4} yr^{-1} for Saitama are fairly significant. Aichi, Kagoshima, Shizuoka, and Nagasaki Prefectures have probabilities larger than 10^{-5} yr^{-1}. As was mentioned above, the way to calculate Pe_3 gives the lowest estimate for the risk of a tornado encounter. Nevertheless, the fact that the recurrence intervals are shorter than 7700 yr for Tokyo Prefecture, 11 000 yr for Chiba, and 22 000 yr for Ibaraki and Okinawa, respectively, is noteworthy. It is also noted that Pe_3s for these Prefectures with high risk of a tornado encounter are generally as large as halves of Pe_1s: that is, the risk of a tornado encounter is estimated within a factor of 2 even if the way to calculate the risk is changed.

4. Discussion

a. Stability of the statistics

One of our interests before we started the present statistical study was to examine how the results of OMM based on the data between 1961 and 1982 changes by adding new data between 1983 and 1993, and by revising some of their data after examining the original references carefully. It turned out that, though the number of tornadoes analyzed in the present paper was about 1.7 times as large as that in OMM and it was about four times as many for some data such as translational speed, most of the statistical properties in the present paper were similar to those in their study. Thus, it may appear that the statistical period of 22 yr adopted by OMM was sufficient to have stable statistics on tornadoes in Japan. Figure 19 shows variations of 1-yr averages of tornado damage pathlength. The number of tornadoes that have data on damage pathlength vary largely from year to year. Therefore, one has to be careful when interpreting the meaning of the variations from the figure. The annual mean of tornado damage pathlength varies from 1 km to 6 km. Eleven-year averages for tornadoes between 1961 and 1971, between 1972 and 1982 and between 1983 and 1993 are 3.9, 2.8, and 3.4 km, respectively. The average for 243 tornadoes between 1961 and 1982 is 3.3 km, which coincides with the result of OMM for 171 tornadoes during the same period.

As was shown in Fig. 9, the frequency distribution of the damage pathlength L is far from a Gaussian. However, the central limit theorem tells that, if the number of data, N, is large, the probability distribution of the averages $\overline{L_j} = (L_1 + L_2 + \cdots + L_N)/N$ tends to approach a Gaussian the standard deviation σ of which is given by $\sigma_0/\sqrt{N}$, where σ_0 is the standard deviation of the original frequency distribution. Using the data of L for 350 tornadoes out of 351 for which the data for L exist, we have calculated the standard deviations for various values of N: for $N = 5$, 10, 20, 40, and 80, the standard deviations are 1.93, 1.38, 0.92, 0.55, and 0.17 km, respectively [the average of $\overline{L_j}$, defined by $\Sigma_{j=1}^{M}(\overline{L_j}/M)$ is nearly the same for all Ns and was 3.3 km, where $M = (350/N)$]. Note that the number of averages, M, decreases with increasing N: it is 70, 35, 17, 8, and 4 for $N = 5$, 10, 20, 40, and 80. This shows that, as N increases, the number of samples decreases. When N is not large, the central limit theory is not applicable. When the number of the samples is small, on the other hand, to calculate a standard deviation σ becomes less meaningful. If one calculates $\sigma\sqrt{N}$, which would be equal to σ_0 when the central limit theorem holds, it becomes 4.31, 4.36, 4.11, 3.48, and 1.52 km for $N =$ 5, 10, 20, 40, and 80, respectively. Considering the small number of the samples for $N = 40$ and 80, we may crudely estimate that σ_0 is around 4 km. If this were the case, a standard deviation σ for $N = 171$ (for the case of OMM) would be 0.3 and that for $N = 351$ (for the present case) would be 0.2. Therefore, with 95% confidence level, the result of OMM suggests that the mean damage pathlength is 3.3 ± 0.6 km. Our result tells, on the other hand, that, with the same confidence level, the mean pathlength is 3.2 ± 0.4 km.

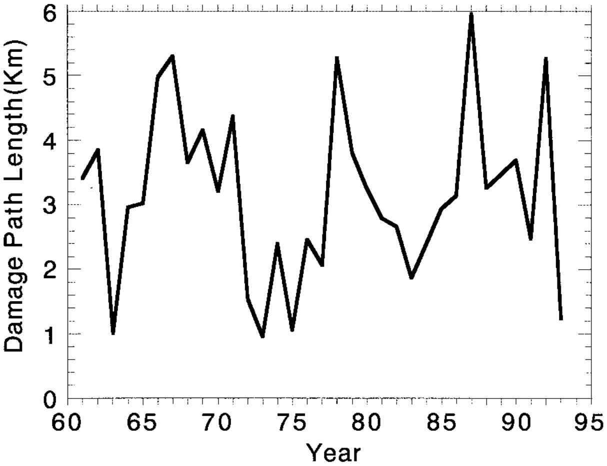

FIG. 19. Variation of annual average of tornado damage pathlength.

A similar analysis was done for the damage path width and the lifetime. For the damage path width, σ_0 is estimated to be 180 m. Therefore, the result of OMM with 134 tornadoes would have a standard deviation of 16 m and the mean damage path width would be 101 ± 32 m with 95% confidence level. Our results with 295 tornadoes would have a standard deviation of 10 m and the mean damage path width would be 98 ± 20 m with the same confidence level. For the lifetime, σ_0 is estimated to be 10 min. Therefore, the present result with 118 data concerning the lifetime suggests that the standard deviation is 0.9 min and the mean lifetime is 12 ± 1.8 min.

The above results show that in order to reduce the standard deviations for the mean damage pathlength, mean damage path width, and mean lifetime to less than ±5% of the mean values, about 6, 16, and 9 times as many as the present data for damage pathlength, damage path width, and lifetime, respectively, need to be collected. Though this would take several hundred years, such effort to collect reliable data on tornadoes and waterspouts should be continued in a governmental organization. The results that our mean damage pathlength, 3.2 km, and mean damage path width, 98 m, were very close to 3.3 km and 101 m of OMM, respectively, seem to be only coincidental from the statistical point of view. The above consideration shows that the mean pathlength for the original ensemble could be 3.6 km, for example, and the damage pathlength for 1983–93 could have been 4.0 km. If this were the case, the damage pathlength for 1961–93 could have been 3.6 km. Similarly, it could have been 3.0 km. Since about half of the data included in the present analysis are the same as those of OMM, the mean values for the present study showed less deviation from those in OMM than that expected from a statistical consideration.

b. Risk of a tornado encounter

The risk of a tornado encounter in the United States has been estimated from the average length and width of tornado damage path by Schaefer et al. (1986) for 1950–82 and by Grazulis (1993) for 1954–83. According to Grazulis (1993), 20 states have a recurrence interval less than 10^4 yr, 17 states between 10^4 and 10^5 yr, 10 states between 10^5 and 10^6 yr, and 1 state longer than 10^6 yr. Oklahoma has the shortest recurrence interval of 1980 yr. Tokyo has a recurrence interval less than 7700 yr. This recurrence interval is between that of Tennessee and Missouri, which are the 14th and 15th shortest in the United States (Grazulis 1993). The country mean recurrence interval in Japan is less than 1.7×10^5 yr.

As is evident from Fig. 3, a significant fraction of tornadoes occur near the coastlines. In fact, the number of tornadoes that occurred within 5 km of the coastlines is 391, which amounts to 58% of all tornadoes. If the coastal region (the area within 5 km of the coastlines) is assumed to be about 20% of Japan (see section 3c), the risk of a tornado encounter for the region would be roughly three times larger than that for the country mean. This means that the recurrence interval for the coastal region is less than 6×10^4 yr, which corresponds to the recurrence interval between Vermont and Colorado (the 34th and 35th shortest in the United States). As was discussed in section 3b, coastal regions of several Prefectures have high probabilities of tornado occurrences. Accordingly, the recurrence intervals for these coastal regions are considerably short. For example, the coastal region of Miyazaki Prefecture has a recurrence interval of 1.0×10^4 yr and that of Kouchi Prefecture 3.2×10^4 yr. The plains that have extremely high probability of tornado occurrences (see section 3b) have even shorter recurrence intervals: the Miyazaki plain has a recurrence interval of 2.8×10^3 yr, a value comparable to Iowa, the seventh shortest in the United States (Grazulis 1993). The Kouchi and Hamamatsu plains have recurrence intervals of 6.3×10^3 yr and 1.9×10^4 yr, respectively. Since most of the population, important structures, and mass transportation systems are concentrated in plains in Japan, these shorter recurrence intervals need to be considered seriously.

The risk of a tornado encounter discussed in the present paper was defined for an area in which some kind of damage was observed. As far as wind engineering is concerned, the probabilities of F2, F3 wind or more would be much more important. Fujita (1978) suggested using a concept of a ‘‘design tornado.’’ If one uses the concept, one can determine the percentage of the area with Fn damage in the total damage path width of an Fm tornado, where m and n are integers and $n \leq m \leq 5$. To this end, an extensive project to determine the F-scale of the tornadoes in the database by referring to literature needs to be conducted. It would also be necessary to compare the statistics of the damage characteristics in Japan with those of the design tornadoes in the United States. The present results show, however, that the risk of a tornado encounter in Japan has a small-scale variability (typically meso-β-scale and, in some region, meso-γ-scale). This means that, to obtain a reliable estimation for the risk of a tornado encounter for such a small-scale region, a much longer statistical period is required. Considering the small number of tornadoes in each small region and the small number of detailed studies on damage characteristics for the previous tornadoes, we have to leave the important work of estimating the probabilities of F2 and F3 wind due to tornadoes for a future study.

5. Summary and conclusions

A tornado and waterspout database, which is believed to be most reliable at present in Japan, was compiled for the period of 1961–93. Six hundred and seventy-seven tornadoes and 148 waterspouts were cataloged in the database. Various statistical characteristics of tornadoes and waterspouts, including their physical properties and damage characteristics, have been examined. The results may be summarized as follows. 1) On average 20.5 tornadoes occur in Japan per year and 4.5 waterspouts are observed per year. 2) Tornadoes occur most frequently in September and least frequently in March. Waterspouts occur most frequently in October. 3) Both tornadoes and waterspouts have high activity during daytime. The activity of tornadoes has two peaks at 1000–1100 and 1500–1600 JST. 4) About 38% of tornadoes occur on multiple-tornado days. 5) The average lifetimes of tornadoes and waterspouts are 12 min and 14 min, respectively. 6) About 15% of tornadoes are anticyclonic. 7) More than 50% of tornadoes move toward the northeast quadrant and their average speed is 10 m s^{-1}. 8) The average damage path width and pathlength are 98 m and 3.2 km. 9) Fatality and injuries caused by tornadoes per year are 0.58 and 29.7, respectively. Completely destroyed, severely damaged, and partly damaged residential houses are 17.0, 39.0, and 329 per year, respectively. 10) About 46% of tornadoes are associated with extratropical cyclones (16% in a warm sector and 15% associated with cold fronts) and 20% associated with typhoons.

In addition to the above statistical study, a preliminary estimate of risk of a tornado encounter for each Prefecture was made. The shortest recurrence interval is found for Tokyo Prefecture and is less than 7.7×10^3 yr. The recurrence interval for the whole country of Japan is less than 1.7×10^5 yr. For the coastal regions, however, it was shown that the recurrence interval can be shorter than 2×10^4 yr. Especially for Miyazaki plain, the recurrence interval is as short as 3×10^3 yr, and for Kouchi plain it is about 6×10^3 yr. Coastal regions, in general, are where most of the important facilities, mass transportation systems, and population are concentrated. Therefore, the short recurrence intervals for coastal regions need to be considered seriously. To obtain more reliable data on the risk of a tornado encounter, however, an effort to compile the data for tornadoes needs to be continued for a much longer time.

A preliminary discussion on the stability of the tornado statistics was also made. In view of the central limit theorem, an increase in the number N of data reduces the standard deviation of the average by a factor of $\sqrt{N}$. Thus, for the statistical quantities examined in the present study, the deviation of the average from the ensemble average may be said to be reduced only by a factor of $1/\sqrt{2}$ from those in OMM. If one would like to reduce the deviation by a factor of 10, it would take a thousand years (which is not realistic). Therefore, if the statistics on averages are concerned, one might not be able to obtain significant additional information even if the statistical period would be further increased by a factor of 10. Considering that violent tornadoes of F4 or F5 category occur very rarely but could affect significantly the frequency distribution of various quantities and risk of a tornado encounter, however, one needs to continue efforts to accumulate records of good quality on tornadoes and compile them into a database like the one reported in the present paper.

Acknowledgments. The authors are grateful to the reviewers for helpful comments. The database in the present study was compiled as a part of the project entitled ‘‘A Study on Tornadoes and Downbursts,’’ which started as the first cooperative project among research departments in the Meteorological Research Institute (MRI). The first two authors are grateful to Dr. Y. Okamura, the former Director General of MRI, and the staff of the Planning Office, for their invaluable support for the initiation and fulfillment of the project. Data input into the database was carefully done by Mrs. K. Yoshiye. The database described in this paper may be provided to research scientists on a floppy basis upon request. Those who would be interested in the database, please write to the corresponding author.

The content of this paper was presented at the spring meeting of the Japan Meteorological Society (Niino et al. 1994), where the content of Hayashi et al. (1994b) was presented in the same session (Hayashi et al. 1994a).

APPENDIX

Review of Statistical Studies on Tornadoes and Waterspouts in Japan

Statistical studies on tatsumaki in Japan since the late 1940s are reviewed here. Though there are many more studies on tatsumaki in a Prefecture or a district consisting of several Prefectures, only those dealing with tatsumaki all over Japan will be considered.

Sekiya (1949, 1957) picked up 89 tornadoes between 1926 and 1948 from *Geophysical Review* (*Kishou Youran* in Japanese), Meteorological Notes (*Kishou Zassan*), Weather and Climate (*Tenki-to-Kikou*), Bulletin of Division of Meteorological Section of the Japanese Navy (*Kaigun Kishou Ihou*), Geophysical Notes of District Meteorological Observatories (*Kanku Kishoudai Kenkyu Kaishi*), and newspapers. He examined frequencies according to synoptic situation, region, month, and hour. He mentioned that the largest frequency was associated with cold fronts in September and between 1200 and 1400 JST (Japan Standard Time; all reference to time in this paper is made in JST; 0900 JST is 0000 UTC). Ibaraki and Tanaka (1961) analyzed 57 tornadoes between 1948 and 1959 (extracted from 94 tornadoes between 1927 and 1959 in *Geophysical Review*) and reported that the largest frequency was found on the warmer side of a cold front, in September, and in daytime. Shimada (1967) examined 100 tatsumaki recorded in *Geophysical Review*, Bulletin of the Meteorological Society of Japan (*Tenki*), Weather (*Kishou*), and Space Science (*Tenmon-to-Kishou*) between 1955 and 1964. He classified the tatsumaki into three categories: a waterspout, which remained over sea throughout its lifetime (hereafter this is simply referred to as waterspout); a waterspout, which moved over land (hereafter this is referred to as a tornado of waterspout origin); and a tornado, which remained over land throughout its life. The percentages of waterspouts, tornadoes of waterspout origin, and tornadoes were 24, 41, and 35, respectively. Fujita (1973) described 242 tornadoes between 1950 and 1971, and made a brief statistical study. He noticed a trend that the number of tornadoes increased with year and mentioned that it was not showing a real increase but was merely reflecting an increase of tornado reports. Shimada (1977) examined 94 tornadoes between 1971 and 1975. Because of the short statistical period he used, however, the month of the highest frequency was August, which disagreed with the previous studies. He also examined the frequencies of tornadoes according to the F-scale (Fujita 1971). Miyazawa et al. (1980) made a statistical study on 163 tornadoes between 1971 and 1978. The largest frequencies were found in September and between 1000 and 1600 JST. Omoto (1982) examined 267 tornadoes between 1965 and 1980, again finding that the month of the highest frequency was September. He showed that about half of the tornadoes in September were associated with typhoons. OMM analyzed 454 tornadoes between 1961 and 1982. They picked up tornadoes from *Geophysical Review*, Annual Summary of Meteorological Phenomena (*Kishou Nenkan*) published by the Japan Weather Association, and Report of Unusual Weather of District Meteorological Observatories (*Kanku-Kishoudai Ijou-Kishou Houkoku*). Their analysis seems to be the most reliable and most comprehensive at present. They examined various characteristics of tornadoes: the frequency per unit area for each Prefecture; the monthly and hourly variations of the frequency; frequencies according to synoptic situation; direction and speed of tornado movement; fatalities; injuries; numbers of completely destroyed, severely damaged, and partly damaged houses; length and width of damage swath; and so on. Watanabe (1993) picked up 317 tornadoes, which are described in Report on Unusual Weather and Meteorological Hazards (*Ijou-Kishou Kishou-Saigai Houkoku*) from 1971 to 1990 and made a similar analysis to OMM. The statistical study by Watanabe (1993) considered only the tornadoes that caused some damage. Recently, Hayashi et al. (1994a,b) surveyed *Geophysical Review*, Annual Summary of Meteorological Phenomena, and the Asahi newspaper for 1983–92. By adding the tornadoes picked up from the survey to the list of tornadoes by OMM, they studied statistical characteristics of 538 tornadoes between 1961 and 1992. The number of tornadoes considered in their study, however, is much smaller than that in our study.

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