Direction of Tornado Motions and Its Relationship with the Large-scale Wind Field

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Abstract

According to Niino et al. (1997), more than half of tornadoes in Japan from 1961 through 1993 moved toward the northeast quadrant. However, since this data was based on visual observations, the reported directions of tornado motions were biased toward 8 directions out of 16. Therefore, by collecting directional data of tornado motions in an objective way, this study investigates the relationship between directions of tornado motions and the large-scale wind field. First, the direction of tornado movement is calculated from the latitudes and longitudes of the locations of occurrence and extinction. These calculations show that approximately 70% of tornadoes moved toward the northeast quadrant regardless of the day of occurrences, regions, or weather conditions. The preference for the northeastward direction is presumably not a sampling bias because the qualitative results are the same for two independent time spans. This northeast quadrant preference is caused by the superposition of eastward and northward peaks. The eastward preference suggests that the cumulonimbus clouds are transported by the westerly wind at the middle troposphere. When classified by seasons, a similar eastward preference is observed in DJF and MAM. By contrast, the distribution of the direction of movement of JJA and SON tornadoes exhibit a northward predominance, due to tornadoes associated with typhoons. The high correlation between the direction of tornado motions and

the large-scale wind direction is also consistent with a notion that tornadoes are transported by winds along with cumulonimbus clouds.

Keywords tornado; direction of movement; circular statisttics

1. Introduction

A tornado is a violent updraft vortex that occurs in association with a cumulonimbus cloud. Tornadoes are generated when atmospheric conditions are extremely unstable, and can cause extensive damage over a narrow band-like area in a short period of time. The environmental fields preferable for tornado occurrence and their predictability (Sakurai and Ryuichi, 2008; Shibata, 2006), the climatological aspects (Galway, 1977) and the effect of their synoptic scale on tornado occurrence have long been discussed (Tippett et al., 2016; Tochimoto, 2022). Despite these efforts, tornado occurrence has been difficult to predict, and its theoretical background is largely unknown. Nevertheless, coastal areas, especially the Pacific coast, are prone to tornadoes (Hayashi et al., 1994). In areas with a large population, the possibility of severe damage is high, and if the weather becomes more unstable in the future, the anxiety of people living along the coast may increase.

Prediction of the occurrence and track of tornadoes is essential to minimize damage on people and infrastructures. In fact, tornadoes that caused over 100 casualties occurred in Japan (e.g., Nobeoka City, Miyazaki Prefecture in September 2006). According to Kobayashi and Keiko (2012), 1228 tornadoes occurred from 1961 through 2011, and 42% caused human or property damage. The total number of deaths was 39 and the number of injured was 2,022. However, the number of statistical studies on tornadoes is limited because of the reliance on visual observation reports. As the most comprehensive statistical study on tornadoes in Japan, Niino et al. (1997) (hereafter NFW97) conducted a large-scale statistical analysis of tornadoes and waterspouts for 33 years from 1961 through 1993, and estimated the risk of tornado encounters in each prefecture. Other previous studies on tornadoes in Japan include general statistical studies (Fujita, 1971; Hayashi et al., 1994) and observational research reports (e.g., Suzuki et al., 2000; Kobayashi et al., 2008). Although these previous studies discuss predictability of tornadoes before their occurrence, little research has been conducted on the subsequent movement of tornadoes.

This situation motivates us to discuss whether it is possible to predict the direction of tornado movements after its occurrence. According to NFW97, more than 50% of tornadoes from 1961 through 1993 moved toward the northeast quadrant and about 22% moved northeastward (Fig. 1a). However, these directions are not necessarily accurate, as visual observation reports tend to be stated in eight major directions (i.e, $45^\circ \times n$ (integer) from the east). Fig. 1

Therefore, in this study, we first calculate the direction of tornado movements, including those of newer periods than NFW97, based on the locations of occurrence and extinction. Then, we demonstrate that the northeastward propensity remains the same in a more recent time period. Next, we consider the characteristics of the distribution of the tornado moving directions by dividing tornado movements by seasons, regions of occurrence, and meteorological conditions at the time of occurrence. By doing so, we explore the cause of the propensity toward the northeast quadrant.

This article is organized as follows. The data used in this study are described in the next section. In the third section, after examining the statistics of the distribution of tornado movement directions, we calculate correlations to show that direction of tornado movement and tropospheric wind direction have a statistically significant correlation. Summary and Discussions including future challenges are given in section 4.

2. Data and Methods

2.1 Tornado movement

Tornado data used for statistical analyses are from the Japan Meteorological Agency (JMA). In this data, from January 1961 through December 2022, 1,611 tornadoes are recorded. From these samples, we use 1,068 tornado cases whose records of the time (on the second timescale) and location (latitude and longitude) are available. Observational errors are not taken into account. We use the time of occurrence, the place of occurrence and extinction, the major weather disturbance near the tornado (e.g., typhoons), and the direction from it. The direction of tornado movement provided by JMA is not used, because available data are limited for cases where the track has been determined or reported.

As shown in Fig. 1b, we calculate the direction of tornado movements using the locations of occurrence and extinction, without using visual observation reports or global wind direction. The angle of tornado movement θ_1 is calculated by the following equation 1.

$$\theta_1 \equiv \mathrm{arctan2}(\varphi_2 - \varphi_1, \lambda_2 - \lambda_1) \tag{1}$$

Here, the latitudes and longitudes of the occurrence (extinction) points are φ_1 (φ_2) and λ_1 (λ_2), respectively. When we present statistics in 16 directions, all directions are divided into 16 pieces with the 22.5° range. For example, when the movement angle θ_1 is 0°, the movement is eastward. The tornado case is extracted only if it moved for more than 1 second (approximately 40 meter) in either latitude or longitude from occurrence to extinction, and 650 cases are available in the statistical period (1961-2022) of this study. We will discuss later in section 4 whether it is appropriate to consider a tornado track as a straight line connecting the place of occurrence and extinction by ignoring the details of its complex movement.

2.2 Wind Direction

We use reanalysis data of horizontal wind at specified pressure levels (300 hPa, 400 hPa, 500 hPa and every 50 hPa from 600 hPa to 1000 hPa) provided by the European Medium-Range Weather Center (ECMWF) Reanalysis 5 (ERA5). The horizontal resolution is 0.25° in both zonal and meridional directions, and the time resolution is 1 hour. At the nearest time when the tornado is occurred, we take the average of winds at four nearest neighbors of the occurrence point for both zonal (u) and meridional (v) wind data. The angle of wind direction θ_2 is calculated by the following equation 2.

$$\theta_2 \equiv \text{arctan2}(v, u) \tag{2}$$

For example, the wind direction toward the east (i.e., westerly wind) is taken as $\theta_2 = 0°$, the north is represented by 90°, and the south is represented by $\theta_2 = -90°$.

2.3 Circular Statistics

Angular data poses a major problem when performing statistical analysis. The problem is that statistical analysis methods that target non-angular data cannot be used when analyzing angular data. This problem is caused by the fact that angles (or circumferences) have periodicity. For example, a mean will have unnatural definitions if applied naively to angular data.

The mean of 1° and 359° should not be (1°+359°)/2 = 180°, but should be 0°. The statistical analysis method for angular data is called the circular statistics (e.g., Fisher et al., 1993; Mardia et al., 2000).

In this study, we calculate the correlation between the two angular variables, the tornado movement direction and the wind direction at the time of tornado occurrence, using the circular correlation measure presented by Jammalamadaka et al. (2001). The circular correlation coefficient γ_c is defined as

$$\gamma_c \equiv \frac{\sum_{k=1}^{n} \sin(\theta_{1k} - \overline{\theta_1}) \sin(\theta_{2k} - \overline{\theta_2})}{\sqrt{\sum_{k=1}^{n} \sin^2(\theta_{1k} - \overline{\theta_1}) \sin^2(\theta_{2k} - \overline{\theta_2})}} \tag{3}$$

where the direction of movement of the tornado is θ_{1k}, and the direction of the wind is θ_{2k}. Here, the mean of θ_{1k} and θ_{2k} using circular statistics are represented by $\overline{\theta_1}$ and $\overline{\theta_2}$, respectively, and calculated as

$$\overline{\theta_i} \equiv \mathrm{arctan2}\left(\frac{1}{n}\sum_{k=1}^{n} \sin\theta_{ik}, \frac{1}{n}\sum_{k=1}^{n} \cos\theta_{ik}\right) \quad (i = 1, 2) \tag{4}$$

Based on Jammalamadaka and SenGupta (2001), the test statistic z_γ of two correlated variables is determined as

$$z_\gamma = \gamma_c \sqrt{\frac{n\gamma_{20}\gamma_{02}}{\gamma_{22}}} \tag{5}$$

where

$$\gamma_{ij} \equiv \frac{1}{n}\sum_{k=1}^{n} \sin^i(\theta_{1k} - \overline{\theta_1}) \sin^j(\theta_{2k} - \overline{\theta_2}) \tag{6}$$

and the statistical confidence interval is calculated assuming that z_γ follows a standard normal distribution.

3. Results

First, using the JMA data and the equation 1, new statistics and its geographical distribution of tornado movement directions are presented in subsection 3.1 and 3.2. After comparing with previous research, we further analyze the obtained data on the seasonality and their relationship with typhoons in 3.3 and 3.4. Next, in subsection 3.5 and 3.6, we show the relationship between the tornado movement and the large-scale wind at the time of tornado occurrence.

3.1 Comparison with the previous study NFW97

First, to establish the statistical confidence of the directional predominance shown in NFW97, we present statistics taken for the same period as in NFW97 and the subsequent period. During the same period, we have reproduced that the tornado movement directions are concentrated in the northeast quadrant (Fig. 1c). Here, the northeast quadrant denotes the 90-degree range counterclockwise from the east to the north. Of the 149 tornadoes that occurred between 1961 and 1993, 73% (109 cases) moved toward the northeast quadrant.

The protrusions in 8 directions in Fig. 1a become moderate in Fig. 1c. As NFW97 already pointed out, it is likely that these protrusions are caused by the fact that people tend to state in eight directions when giving visual observation reports. In NFW97, the northeast was the most frequent direction at about 22%, but in our result, east-northeast is the most frequent at 18%, followed by east and northeast during the same period.

501 tornadoes from 1994 through 2022, which is after the NFW97 time span, are also analyzed in the same manner. As a result, Fig. 1c shows that 64% (321 cases) moved to the northeast quadrant. During this period, the east direction has the highest number of occurrences at 20%, followed by east-northeast, north, and northeast. In both periods (i.e., 1961-1993 and 1994-2022), nearly a half of tornadoes are concentrated within the 45-degree range from the east to the northeast. The qualitative results are the same for two independent year periods, so the northeastward predominance is presumably not due to a sampling bias.

3.2 Geographical Distribution (1961-2022)

Tornadoes move to the northeast quadrant all over the Japanese mainland (Fig. 1d). In addition, the occurrence of tornadoes are concentrated on the coast and in the Kanto Plain. Of all 650 tornadoes between 1961 and 2022, 66% (430 cases) moved to the northeast quadrant which consists of east (19%), east-northeast (15%), northeast (11%), north (11%) and north-northeast (10%).

Based on the JMA data, many tornadoes move to the east along the Sea of Japan coast, and to the north along the Pacific coast of western Japan and inland areas such as the Kanto Plain. Figure 1d shows the distribution of the occurrence locations of tornadoes that moved to the northeast quadrant. The distribution of tornado occurrence is similar to previous statistical studies, with many tornadoes occurring along the coast, the Kanto Plain, and the plains of Miyazaki and Shizuoka. In Japan, which has many mountainous areas, this distribution is mostly due to the topography, but it also depends on the environment near the tornado occurrences (e.g., typhoons, fronts, low pressure systems).

3.3 Seasonal Distribution

More than 60% of the tornadoes that occur in Japan move toward the northeast in all seasons. Figure 2a shows the number of tornadoes observed in June-July-August (JJA) and September-October-November (SON), when the number of tornado occurrences is particularly high. SON experiences the highest number of cases of 321, followed by JJA (178 cases), December-January-February (DJF, 78 cases), and March-April-May (MAM, 73 cases). In these cases, 60% of tornadoes in SON, 66% in JJA, 83% in DJF, and

76% in MAM moved to the northeast quadrant. Fig. 2

In JJA and SON, the number of tornadoes exhibits peaks not only in the east but also in the north (Fig. 2a). Especially in SON, almost the same number of tornadoes move toward the east and the north (out of 321 SON tornadoes, 50 tornadoes move to the east and 48 to the north). This bimodal feature is particularly interesting, considering that, when we incorporate all seasons, the number of tornadoes exhibit moderate preference toward the northeast quadrant. Since these two peaks are seasonal, in the next subsection 3.4, we will discuss tornadoes associated with typhoons, which are common during this season. In DJF and MAM, when tornado occurrences are relatively rare, tornadoes often occur on the Sea of Japan side. 27% of tornadoes in DJF and 26% in MAM moved eastward.

The map in Fig. 2b shows the occurrence distribution of JJA and SON. This map reveals that tornadoes during these two seasons are particularly common in the Pacific coast and plains and there is not much difference in their geographical distribution. The peaks to the north are observed only in this season, suggesting that the timing of occurrence and its meteorological conditions are closely related.

3.4 Relationship with Typhoon

50 cases moved eastward and 48 moved northward out of 321 cases in SON. Presumably, these two peaks (north and east) are yielded due to different mechanisms. Therefore, in this subsection, we investigate the relationship with typhoons, because tornadoes that occur intensively from July through October are occasionally related to typhoons.

Typhoons are the second most common weather conditions for tornadoes after fronts. According to Hayashi et al. (1994), the number of typhoons has not decreased since the 1980s compared to the previous years, but the annual number of tornadoes caused by typhoons has decreased. According to the data used in this study, however, there were 31 cases in the first 20 years (1961-1980), 24 cases in the next 20 years (1981-2000), and 81 cases in the next 22 years (2001-2022), so the number is actually increasing. This increase is likely due to an increase in the number of reported cases since 2000, and may not be a real upward trend in the number of cases.

We extract 51 cases in JJA and 91 cases in SON tornadoes that occurred with typhoons. Here, a typhoon-related tornado is defined as a tornado that occurred when a typhoon is observed simultaneously near Japan, and is archived in the JMA database. Typhoon-related tornadoes have a protrusion to the north (Fig. 3a), and typhoon-unrelated tornadoes generally move eastward (Fig. 3b). These two peaks are consistent with the observational evidence that 66% of all tornadoes from 1961 through 2022 moved into the northeast quadrant (subsection 3.2), and about 70% (73% for JJA and 67% for SON) of typhoon-unrelated tornadoes moved into the northeast quadrant. By contrast, more than 70% of typhoon-related tornadoes (76% for JJA and 73% for SON) are concentrated in the northern quadrant (the northeast to the northwest), and few move eastward. Since the peak is clearly divided into the north and the east depending on whether the tornado was associated with a typhoon, the peak to the north is presumably caused by typhoon-related tornadoes. Fig. 3

The reason why tornadoes associated with typhoons move to the north is that most tornadoes occur at the northeast of the center relative to the typhoon, which has counterclockwise circulation. Based on the JMA data, more than 80% of typhoon-related tornadoes occurred in the northeast quadrant relative to the center of the typhoon, and nearly a half of these tornadoes occurred particularly in the 22.5° range of the northeast direction. A similar directional bias in the incidence of tornado events, rather than their movement after they occur, is also reported for hurricanes (e.g., Novlan and Gray (1974); Gentry (1983)).

3.5 Correlations with large-scale wind field at each pressure level

Except for typhoon-related tornadoes, the wind direction at the time of the tornado occurrence is mainly eastward, and most of them blow toward the northeast quadrant, regardless of altitude (Fig. 4a). As mentioned above, since eastward movements are the most common in all seasons, we hypothesize that the direction of tornadoes movement is determined by cumulonimbus clouds transported by the westerly wind at the middle troposphere. Therefore, in this subsection, we calculate angular correlations between the direction of tornadoes movement and the wind direction. Fig. 4

First, we focus on the 500 hPa level, which is about 5.5km in altitude at the middle troposphere. Figure 4b shows the scatter plot between the wind direction and the tornado movement direction. At the time of tornado occurrences, 75% of the winds were blowing toward the northeast quadrant. To investigate the relationship between wind and tornadoes moving toward the northeast quadrant, we hereafter consider only tornadoes whose wind direction and movement direction are within $-45^\circ < \theta < 135^\circ$ (523 cases, the black box shown in Fig. 4b). The correlation coefficient between the direction of tornadoes movement and the wind direction at 500 hPa is 0.59 (Fig. 4c), which is statistically significant at the 95% confidence level.

We similarly calculate correlations at each pressure level from 300 to

1000 hPa (Fig. 4c). The 500 hPa level exhibits the strongest correlation, and the correlation gradually decreases as the altitude decreases and approaches the Earth's surface. This decrease is because, as inferred from Fig. 4a, the northeastward predominance in wind direction becomes weaker as the altitude decreases.

For typhoon-related tornadoes, the correlation is not as strong as those for typhoon-unrelated tornadoes. For example, at the 500 hPa level, the correlation coefficients for typhoon-related and typhoon-unrelated tornadoes are 0.33 and 0.50, respectively. Although both results are statistically significant at the 95% significance level, the reason why the former value is small is presumably that the typhoon winds are more localized and difficult to reproduce in reanalysis data.

3.6 Geographical distribution of relationships with wind

Among tornadoes that occurred from 1961 through 2022, the direction of movement of the tornado and the wind direction are most often in the same direction, confirming the high correlation shown in subsection 3.5. Figure 4d shows the difference between the direction of tornado movement and the wind direction $\theta 1 - \theta 2$, i.e., the angle at which a tornado moves relative to the wind. In 252 out of 650 cases, the directions of the winds and tornado movements are within 30 degrees of each other. In 60% (388 cases) of all cases, the direction of tornado movement is within 90 degrees counterclockwise, as measured from the wind direction, and less than half (168 cases) are within 90 degrees clockwise.

In Fig. 4e, 144 tornadoes associated with typhoons are similarly illustrated. Although the number of tornadoes within 30 degrees is small (26 cases), 102 tornadoes travel within 90 degrees counterclockwise from the wind, accounting for 70% of the total. The number of clockwise cases is 11, which is an overwhelmingly smaller proportion than the case in Fig. 4d. As a future work, it will be necessary to physically understand the principle behind this observed evidence that most typhoon-related tornadoes move counterclockwise relative to winds.

4. Summary and Discussions

Approximately 70% of tornadoes that occurred in Japan from 1961 through 2022 moved into the northeast quadrant. We have confirmed the preference in the movement direction shown in the previous study NFW97 by calculating the direction in a more objective way. This preference has not changed between the NFW97 period (1961-1993) and the subsequent period (1994-2022), and the direction of movement of tornadoes is predominated from the east to the north all over Japan. This predominance is the same even when divided by season, but the tornadoes that occur in JJA and

SON have sharp peaks in the north and the east. By classifying tornadoes according to whether they occur simultaneously with typhoons, the peak to the north are largely explained by typhoons. By contrast, the peak to the east is not caused by a typhoon but is caused generally by middle tropospheric winds. Using the circular statistics, we have confirmed statistically significant correlations between the directions of the tornado movement and the wind directions throughout the entire tropospheric layer.

In this study, the direction of tornado movement is defined as a straight line connecting the point of occurrence and extinction. To justify this definition based on the cases with detailed reports since 2000, we select two tornadoes in Japan that yielded long damage areas and a large social impact. The first case is a tornado caused by the front that occurred in the Saitama prefecture at 14:00 on September 2, 2013 Japan Standard Time (JST) (available at `https://www.data.jma.go.jp/obd/stats/data/bosai/tornado/2013090201/ref01.pdf`). This tornado was long lasting (30 minutes), strong (Fujita(F)-scale was F2), and the length of the affected area was long (19 km). Comparing the synthetic radar images provided by the JMA and the areas affected by tornadoes, the flow of rain clouds and the movement of tornadoes match well. Although a slight meandering was observed, the line drawn through the center of the path aligns with the east-northeast direction of the movement. The wind direction at this time is the northeast, and the JMA's movement report is also the northeast.

Another typhoon-like tornado occurred in the Tochigi prefecture at 11:30 on August 10, 2014 JST (available at `https://www.data.jma.go.jp/obd/stats/data/bosai/tornado/2014081001/ref01.pdf`). This tornado was also strong, lasting 20 minutes, F-scale F1, the damaged area length of 15 km, and occurred to the east-northeast of the typhoon. The center of the typhoon was approximately 550 km away from the tornado occurrence, but strong rain clouds were forming in the area where the tornado occurred. Radar images show that it moved toward the north-northeast while slightly deviating from the southwesterly wind, which is consistent with the results of this study.

According to NFW97, the average length of the damage area of tornadoes in Japan is 3.2 km, so the majority of tornadoes are smaller and shorter than the two aforementioned examples. Therefore, even if the direction of movement is determined without considering the detailed meanderings of the movement track, it is useful at least as a first-order approximation. Nevertheless, the challenge is to analyze statistically while maintaining its accuracy. Although this study used the average wind direction as the environmental field, it could be more accurate to identify each cumulonimbus cloud to determine its direction of movement.

From a disaster prevention perspective, strong tornadoes that cause societal damage are especially important. When we perform the same analysis on tornadoes whose F-scale, which is an index for grasping the size of tornadoes, is F1 or higher, the results are consistent with our study (Fig. 5). The number of these strong cases is 305, which is half the number of all the cases (650 cases). The preference toward the northeast quadrant remains unchanged, but the distribution of movement directions is more evenly prominent to the east and the north (Fig. 5a). Compared to the all-case analysis, the reason for this different prominence is that many of the strong cases are tornadoes associated with typhoons. Specifically, 103 cases of strong tornadoes are associated with typhoons, and 202 cases of strong tornadoes are not associated with typhoons, which are in contrast to 144 cases and 506 cases, respectively, when considering all the cases. Fig. 5

Based on the results of this study, disaster prevention measures could be taken by issuing a warning to the northeastward area immediately after a tornado is observed. In particular, a simple system that issues warnings to the north if a typhoon is occurring near Japan, and to the east otherwise, could reduce substantial damage. Nevertheless, in this study, we have statistically processed the predominance in the direction of movement regardless of the size of the tornado or the region where it occurs. From the perspective of disaster prevention, it is further desirable to estimate the direction of tornado movement by considering details of regional characteristics for tornadoes (e.g., facing the sea or large mountain range) and by using data with a finer spatial resolution.

Data Availability Statement

Tornado data analyzed in this study are available at `https://www.data.jma.go.jp/stats/data/bosai/tornado/index.html`, and horizontal wind data analyzed in this study are available at `https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=form`.

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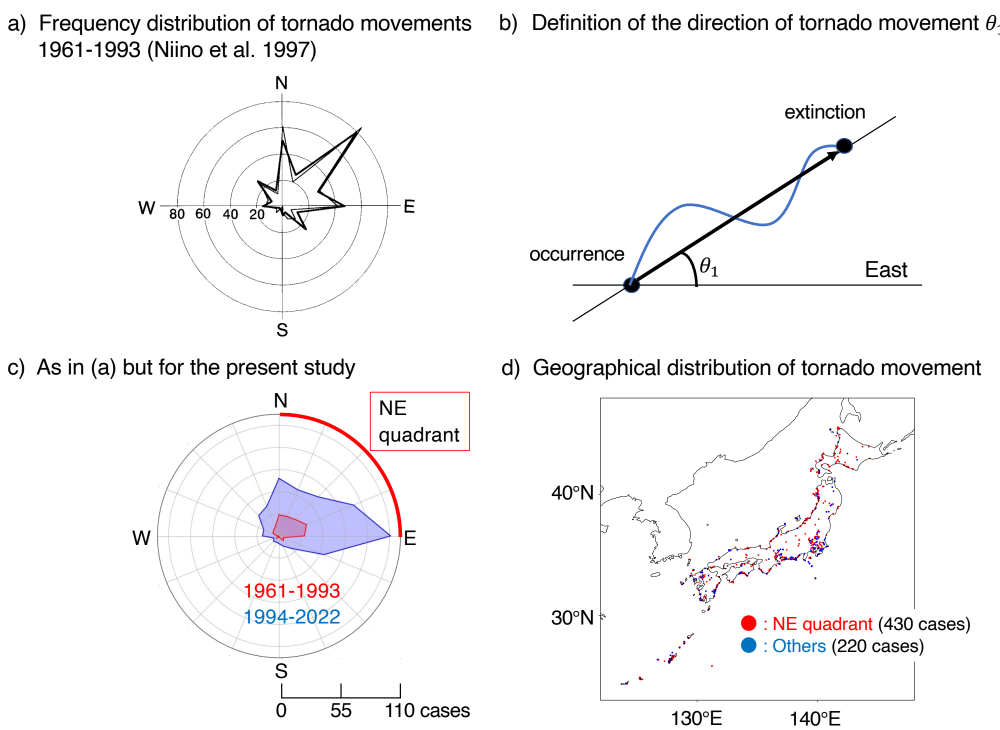

Fig. 1. a) Frequency distribution of the direction of tornado movements from 1961 through 1993 presented in Niino et al. (1997). b) Definition of the direction of tornado movement in this study. c) As in (a), but calculated using our definitions. d) Geographical distribution of tornado movement directions from 1961 through 2022.

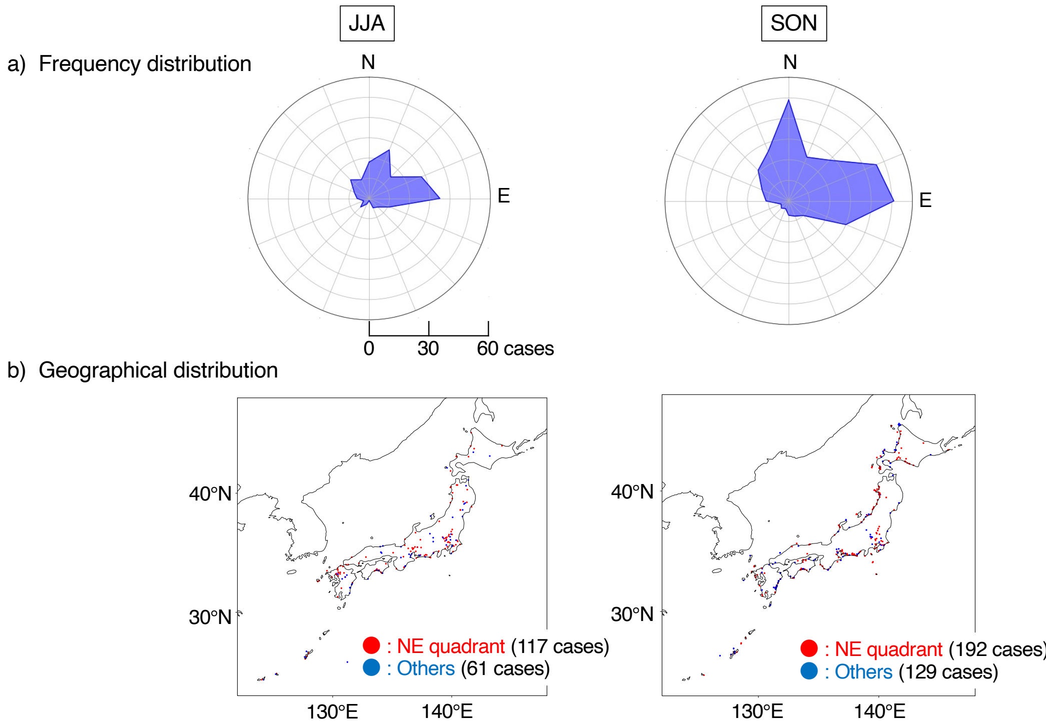

Fig. 2. a) Distribution of the direction of tornado movement that occurred in JJA (178 cases) and SON (321 cases). b) As in Fig. 1d, but for JJA (left) and SON (right).

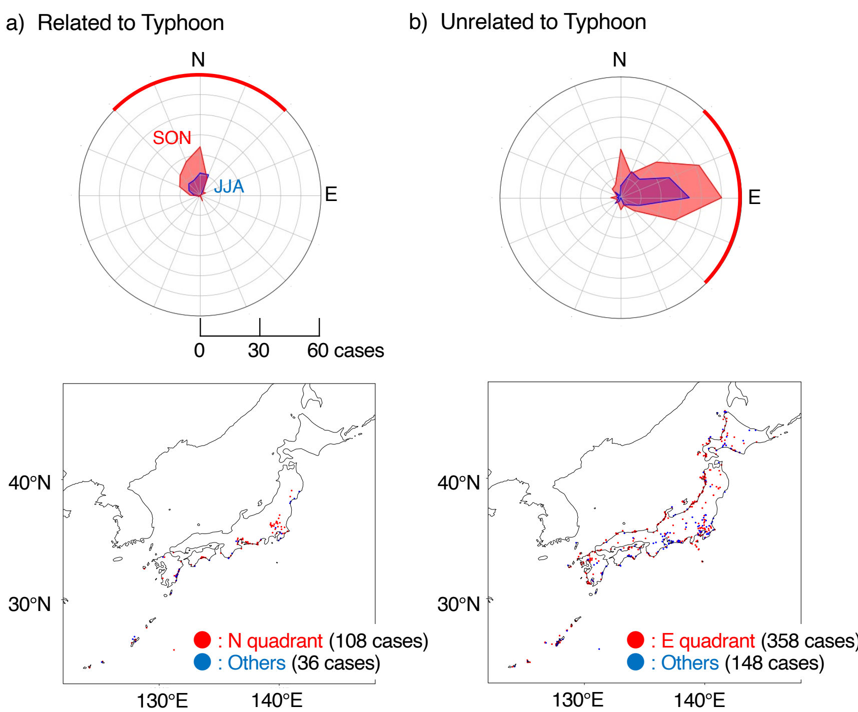

Fig. 3. Top: As in Fig. 2a, but for (a) typhoon-related and (b) typhoon-unrelated tornadoes. Bottom: As in Fig. 1d, but for (a) typhoon-related and (b) typhoon-unrelated tornadoes. Red markers denote the north and (b) the east quadrant.

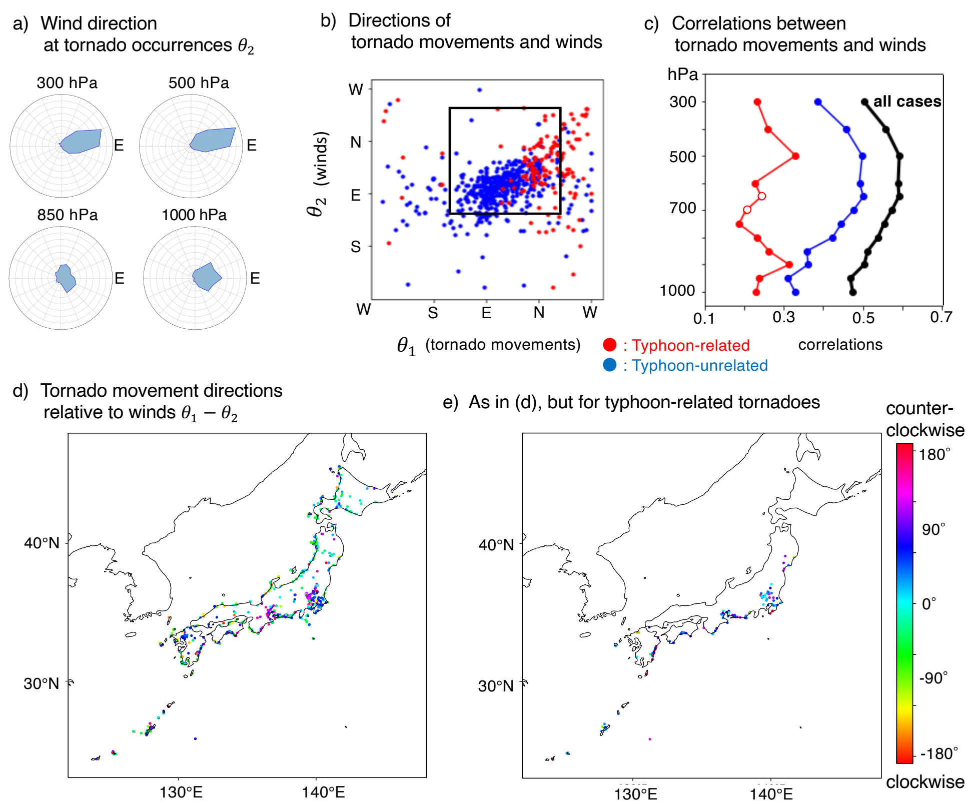

Fig. 4. a) Wind direction θ_2 at the time of tornado occurrence at 300, 500, 850 and 1000 hPa (650 cases each). b) Scatter plot of tornado movement direction θ_1 and wind direction θ_2. Typhoon-related (red) and typhoon-unrelated (blue) tornadoes are shown. c) Circular correlation coefficient between tornado movements and winds at each pressure level. Only data in the black box shown in (b) are used. d) Geographical distribution of tornado movements relative to winds $(\theta_1 - \theta_2)$. A positive value denotes the angle of the tornado movements counterclockwise relative to wind, and a negative value denotes the angle clockwise relative to wind. e) As in Fig. 4d, but for typhoon-related tornadoes.

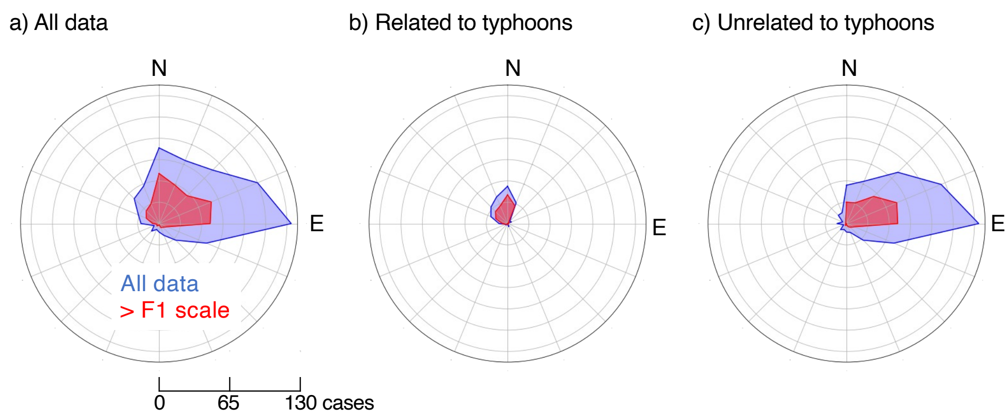

Fig. 5. a) Distribution of the direction of tornado movement for all tornadoes (blue) and those of F1 scale or higher (red) from 1961 through 2022. b) As in (a), but for typhoon-related tornadoes. c) As in (a), but for typhoon-unrelated tornadoes.