Structure and Environment of Tornado-Spawning Extratropical Cyclones around Japan

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Abstract

This study used the JRA-55 reanalysis dataset for analyzing the structure and environment of extratropical cyclones (ECs) that spawned tornadoes (tornadic ECs: TECs) between 1961 and 2011 in Japan. Composite analysis findings indicated that the differences between the structure and environment of TECs, and those of ECs that did not spawn tornadoes (non-tornadic ECs: NTECs), vary with the seasons. In spring (March–May), TECs are associated with stronger upper-level potential vorticity and colder mid-level temperature than NTECs. The colder air at the mid level contributes to the increase in convective available potential energy (CAPE) of TECs. TECs in winter (December–February: DJF) and those northward of 40°N in autumn (September–November: SON) are accompanied with larger CAPE than are NTECs. The larger CAPE for TECs in DJF is caused by larger moisture and warmer temperature at low levels and that for TECs northward of 40°N in SON (NSON) is caused by the colder mid-level temperature associated with an upper-level trough. The distribution of the energy helicity index also shows significant differences between TECs and NTECs for DJF and NSON. On the contrary, the distribution of the 0–1 km storm-relative environmental helicity (SREH) showed no significant differences between TECs and NTECs in most seasons except DJF. A comparison of TECs between Japan and the United States (US) shows that SREH and CAPE are noticeably larger in the US. These differences possibly occur because TECs in the US (Japan) develop over land (ocean), which exerts more (less) surface friction and diurnal heating.

Keywords  storm environments; tornadoes; extratropical cyclones

1. Introduction

Extratropical cyclones (ECs) are principal synoptic-scale disturbances that provide environments favorable for tornadogenesis. In particular, numerous tornadoes are occasionally generated in the warm sector of an EC (e.g., Newton 1967; Johns and Doswell 1992; Hamil et al. 2005). These events, which are referred to as tornado outbreaks, are often accompanied with supercell storms that have mesocyclones associated with strong updrafts. Environments favorable to supercell storm genesis are known to frequently occur in warm sectors containing westerly jets in the upper troposphere and strong southwesterly jets in the lower troposphere. The strong vertical shear and veering wind contribute to the generation of the mesocyclones through the tilting of the horizontal vorticity. In addition, the low-level advection of warm and moist air by the strong low-level jets creates an unstable atmosphere that is favorable for deep moist convection.

Extensive studies regarding the environmental parameters associated with severe storms, on the basis of moisture, instability, and shear, have been performed for distinguishing tornadic from non-tornadic storms, or tornado outbreaks from non-outbreaks (e.g., Rasmussen and Blanchard 1998; Rasmussen 2003; Shafer 2009; Thompson et al. 2003; Thompson et al. 2012; Tochimoto and Niino 2016). In the United
States (US), storm-relative environmental helicity (SREH; Davies-Johns et al. 1990) near the ground (0–1 km) has been noted to be a useful parameter for those attempting to distinguish tornadic from non-tornadic environments (e.g., Rasmussen 2003; Shafer 2009; Thompson et al. 2003). Moreover, Rasmussen (2003) suggested that an energy helicity index (EHI; Hart and Korotky 1991) on the basis of the 0–1 km SREH and convective available potential energy (CAPE) is most effective for discriminating between tornadic and non-tornadic environments. Sakurai and Kawamura (2008) demonstrated that K-helicity index (KHI), defined for the first time by them, has larger values for tornadic environments in Japan even when the EHI is small owing to small CAPE. KHI is defined as follows:

\[
KHI = \frac{K^2 \times \sqrt{SREH}}{8.1 \times 10^7},
\]

where KI is K-index (George 1960). However, they did not compare the structures and environments of the tornadic ECs with those of the non-tornadic ECs.

The relationships between synoptic processes and tornadogenesis in the US have been extensively studied (e.g., Miller 1972; Uccellini and Johnson 1979; Johns and Doswell 1992; Stensrud et al. 1997; Thompson and Edwards 2000; Mercer et al. 2009, 2012; Shafer et al. 2009; Corfidi et al. 2010; Boustead et al. 2013; Tochimoto and Niino 2016). Corfidi et al. (2010), for example, studied the synoptic features of the “Super Outbreak” over the central and eastern United States on 3–4 April 1974, and found that the outbreak was accompanied with an EC associated with a strong jet streak in the upper troposphere. A statistical modeling study conducted by Shafer et al. (2009) also showed that SREH is valuable for discriminating between tornadic and non-tornadic outbreaks. Tochimoto and Niino (2016) focused on the relationships between the structure of ECs and their associated environmental parameters in tornado outbreaks in the US. They revealed that the SREH and CAPE of ECs that cause tornado outbreaks (outbreak cyclones) are significantly larger than the values found in those that do not (non-outbreak cyclones). Outbreak cyclones have a structure with a meridionally elongated low-level, low-pressure distribution that causes a stronger zonal pressure gradient in the warm sector, which results in stronger low-level southerly winds and increased SREH (Tochimoto and Niino 2017).

In Japan, about 56% of tornadoes are accompanied with ECs or stationary fronts (Niino et al. 1997). However, few studies exist on the relationship between the structure and environment of ECs and tornadogenesis in Japan. Omoto et al. (1983) examined tornadoes associated with ECs in Japan and showed that numerous tornadoes occurred in the warm sector. Niino et al. (1993) examined the characteristics of the tornadoes, and their parent supercells, that affected the cities of Kamogawa and Mobara in Chiba Prefecture on 11 December 1990. However, they did not study the synoptic environment, such as the structure of the EC. Seko et al. (2009) examined the mesoscale environment of the tornado that hit Saroma, in Hokkaido Prefecture, on 7 November 2006. They performed ensemble experiments and showed that the region in which the EHI was large for a considerable fraction of the ensemble members was located near Saroma. However, they did not examine the structure of the EC either. A majority of the previous studies were confined to individual events and did not analyze the structure and environment of the ECs, which necessitates the need to develop an understanding of the statistical characteristics of the structure and environment of ECs that cause tornadoes in Japan.

In the present study, we aimed to clarify the structure of ECs that cause tornadoes (hereafter referred to as tornadic ECs: TECs; a definition will be given in Section 2b) and their associated environmental parameters using a reanalysis dataset. For accentuating the characteristics of TECs, we compared them with those of ECs that did not cause tornadoes (i.e., non-tornadic ECs: NTECs). Since the characteristics of ECs change significantly with the seasons, we will also examine their seasonal variations. Furthermore, the structure and associated environmental parameters of TECs that developed in Japan will be compared with those from the US.

The remainder of this paper is organized as follows. The methods used in the present analysis are described in Section 2. The results are presented in Section 3 and discussed in Section 4. Lastly, we present the summary in Section 5.

2. Methodology

2.1 Dataset and detection of extratropical cyclones

We used the following two tornado datasets in this study: one covering the period 1961–1993 (obtained from Niino et al. 1997), and the other for the period 1994–2011 (the “Database of Tornadoes and Severe Winds”, which was compiled by the Japan Meteorological Society (JMA) and is available at http://www.data.jma.go.jp/obd/stats/data/bosai/tornado/index.html. For the former dataset, the tornado data were
collected from the existing literature published between 1961 and 1993 in Japan and were deliberately recorded in the database after careful examinations. The JMA dataset (1994–2011) was on the basis of comprehensive damage surveys and the determination of the type of phenomenon with reference to radar analysis and eyewitness reports. For examining the climatology of TECs, we used the Japanese 55-year Reanalysis data (JRA-55; Kobayashi et al. 2015) that provides 6-hourly data with a horizontal resolution of 1.25° × 1.25° at 37 vertical levels. The vertical grid spacing is 25 hPa from 1000 to 750 hPa, 50 hPa from 750 to 250 hPa, and 25 hPa from 250 to 100 hPa. For the calculation of SREH, the interpolation of zonal wind components to 250 m vertical levels regarding sea level is made. Our analysis period was between 1961 and 2011.

ECs were detected by applying the tracking algorithm of Hodges (1994, 1995, and 1999) to the 6-hourly relative vorticity at 900 hPa. The vorticity at this level is useful for reasonably detecting ECs (e.g., Yanase et al. 2014). The vorticity was truncated to the T42 horizontal resolution for picking up synoptic-scale cyclones (e.g., Hoskins and Hodges 2002; Bengtsson et al. 2006; Hodges et al. 2011). This algorithm has also been used to detect outbreak cyclones and non-outbreak cyclones in the US (Tochimoto and Niino 2016). The method is applied to the region 10–80°N, 80–180°E in the present study. As the typical tracks of ECs over East Asia are known to vary with the seasons (e.g., Chen et al. 1991), the ECs were classified into those that occurred in spring (March, April, and May: MAM); summer (June, July, and August: JJA); autumn (September, October, and November: SON); and winter (December, January, and February: DJF). As no TECs were detected in JJA, we excluded the ECs that occurred in JJA from our analysis (see the definition of a TEC in the following sections).

2.2 Definition of tornadic extratropical cyclones and non-tornadic extratropical cyclones

We defined a TEC as an EC that developed within the region 120–145°E, 25–50°N and was accompanied with at least one tornado in an area covering 5° × 5° from its center within 3 hours of the 6-hourly analysis time of JRA-55. The number of TECs recorded in MAM, SON, and DJF was 47, 59, and 39, respectively. An NTEC was defined as an EC that satisfied the following conditions: an EC that passed through the region within 0.5° × 0.5° of the center of TECs in each season but for which no tornado activity was observed within 5° × 5° of its center through its lifetime. The number of NTECs recorded in MAM, SON, and DJF was 1198, 1240, and 912, respectively.

2.3 Composite analysis

We used composite analysis to examine the cyclone structures and associated environmental parameters. For this composite analysis, the physical variables were superposed with respect to the cyclone center, which was defined by the vorticity maximum at 900 hPa, at the key time (KT), where KT was defined as the time at which a TEC was accompanied with the largest number of tornadoes within 3 hours of analysis time in JRA-55. Notably, if the same number of tornadoes were accompanied at different analysis times, the earlier time was adopted as KT.

To focus on the differences in the structures between TECs and NTECs, we excluded very weak and very strong NTECs from our analysis and compared TECs and NTECs of similar intensity. Figure 1 shows a scatter diagram of the minimum sea level pressure (SLP) and maximum vorticity for TECs and NTECs. We used a Student’s t-test to examine whether the average vorticity and SLP differed between TECs and NTECs. The t-test showed that both the SLP and vorticity of the TECs were significantly lower and stronger, respectively, than those associated with the NTECs in DJF (t = 3.91 and 5.60 for SLP and vorticity, respectively) and MAM (t = 2.85 and 3.06 for SLP and vorticity, respectively), whereas they showed no significant difference in SON (t = 0.13 and 1.40 for SLP and vorticity, respectively). As ECs with weak vorticity are rarely accompanied with tornadoes (Figs. 1a–c), those NTECs with weak vorticity (less than 3.5 × 10⁻⁵ s⁻¹ in MAM and DJF, or less than 3.0 × 10⁻⁵ s⁻¹ in SON) were excluded from the analysis. In addition, NTECs with a central SLP greater than 1010 hPa were also excluded from the analysis for MAM and DJF. Furthermore, since there is only one TEC with SLP lower than 985 hPa in DJF and MAM, and no TECs with SLP lower than 985 hPa, NTECs with a central SLP less than 985 hPa were excluded for all seasons. The frequency of NTECs with SLP lower than 985 hPa is less than 5 % among all NTECs in each season. The number of NTECs selected for composite analysis in MAM, SON, and DJF was 816, 1034, 524, respectively. Around Japan, there are two major EC tracks. The first runs from the Sea of Japan to the northwestern Pacific, and the second from the south of Japan to the northwestern Pacific (Chen et al. 1991). During SON, the latitudinal difference between these two major tracks are much greater than in other seasons, and a larger number of TECs occur.
Thus, TECs and NTECs that developed during SON were categorized into those located to the north of 40°N (NSON) and those located in the south of 40°N (SSON) at KT. On the other hand, as the differences in the latitudinal distributions during MAM and DJF are relatively small, we did not categorize the ECs in these seasons. The number of TECs (NTECs) in NSON and SSON was 29 (259) and 30 (775), respectively. In the present study, permutation testing (Efron and Tibshirani 1993) was used to determine whether the means of the distributions were statistically different, with p values of 0.1, 0.05, and 0.01 corresponding to the 90%, 95%, and 99% confidence levels, respectively. To examine the impact of the difference in sample size between TECs and NTECs, we also performed the composite analysis and the permutation test using 50 NTECs that were randomly selected from all NTECs in each season. This process was repeated 10 times, resulting in 10 composite fields. The results were consistent with those based on all NTECs (not shown).

2.4 Mesoscale environmental parameters

We used SREH, CAPE, and EHI to examine the environment of the tornadoes. SREH gives a measure of the streamwise vorticity within the inflow environment of a convective storm (American Meteorological Society Glossary of Meteorology), and is defined as follows:

$$SREH = \int_0^h k \times \frac{\partial V}{\partial z} \cdot (V - c)dz,$$

(2.1)

where $V$ is the environmental wind vector, $c$ is the storm motion vector, $h$ is assumed inflow depth, and $k$ is a unit vertical vector. In the present study, we used $h = 1$ km, and estimated $c$ using the method by Bunkers et al. (2000).

CAPE is defined as the positive buoyant energy available to a parcel that rises from its initial height level to the level of neutral buoyancy (LNB):

$$CAPE = - \int_{LFC}^{LNB} R_d (T_v(z) - T_e(z))d\ln p,$$

(2.2)

where $p$ is the pressure, $T_v$ is the virtual temperature of the parcel, $T_e$ is the virtual temperature of the environment, $R_d$ is gas constant of dry air, and LFC is the level of free convection. In the present study, the initial height level of the lifted parcel was set to the closest pressure level of JRA-55 above the ground.

EHI is defined by:

$$EHI = \frac{SREH \times CAPE}{1.6 \times 10^5}.$$

(2.3)

Note that CAPE in this study was calculated for a parcel lifted from the near-surface, which differs from Rasmussen (2003) who used a parcel having a mean property over the lowest 1 km.
3. Results

3.1 Seasonal variability in the distribution of tornadoes and tracks of tornadic extratropical cyclones

The distribution of tornadoes associated with ECs shows seasonal variability (Figs. 2a–c). During MAM (Fig. 2a), tornadoes occurred around Okinawa (ca. 125–130°E, 25–30°N), along the southern coastal regions of Kyushu Island (ca. 130–132°E, 30–32°N), Shikoku Island (ca. 132–135°E, 33°N), and the Pacific side of Honshu Island (ca. 135–140°E, 33–35°N). No tornadoes were observed on Hokkaido Island. During SON (Fig. 2b), on the other hand, tornadoes occurred along nearly all of the coastal regions of the Japanese islands, including Hokkaido Island. During DJF (Fig. 2c), many tornadoes were observed in the coastal region of the Sea of Japan and around the Kanto Plain (ca. 140°E, 36°N).

This seasonal variability in the distribution of tornadoes may be associated with the difference in the TEC tracks between the seasons (Figs. 2d–f). The tracks that the TECs follow during MAM pass from the mainland of China to around the Japanese islands through the East China Sea or the Yellow Sea (Fig. 2d). During SON, the TECs follow two main tracks (Fig. 2e): from Eurasia continent to the Sea of Japan, and from the East China Sea to the south of Japan. During DJF (Fig. 2f), majority of the TECs move from the mainland of China to the East China Sea and the Yellow Sea, but some originate in the East China Sea and move along the southern coast of Japan.

3.2 Composite analysis

a. Spring

In this subsection, we examine the distribution of the mesoscale environmental parameters of TECs during MAM and compare this with that of NTECs (Fig. 3). For TECs, the area in which SREH exceeds 100 m² s⁻² extends over the region to the east and...
Fig. 3. Horizontal distributions of mesoscale environmental parameters in MAM: (a) SREH (color shading; m² s⁻²), (d) CAPE (color shading; J kg⁻¹), and (g) EHI (color shading) for TECs. (b), (e), and (h): As in (a), (d), and (g), but for NTECs. (c), (f), and (i): The $p$ values for the differences between TECs and NTECs. Contour lines in left and middle panels indicate geopotential height at 900 hPa with an interval of 30 m, and those in right panels show differences in SREH, CAPE, and EHI between TECs and NTECs, respectively. Note that the contour interval in (c), (f), and (i) are 10 m² s⁻², 10 J kg⁻¹, and 0.005, respectively. Blue dots indicate the locations of tornadoes with respect to the cyclone center. The unit of numerals on the axes is degree.
southeast of the cyclone center, which corresponds to the warm sector (Fig. 3a). Although a considerable proportion of tornadoes develop in the region in which SREH is large, no significant difference is noted in the distribution of SREH between TECs and NTECs (Fig. 3c). Thus, it is suggested that SREH is not an appropriate discriminator for TECs and NTECs during MAM.

Although the values of CAPE are small, there is a region in which the differences between TECs and NTECs are statistically significant (exceeding the 99% confidence level). In Fig. 3d, a CAPE value of more than 50 J kg\(^{-1}\) for TECs extends from the south to the southeast region of the cyclone center, but this is not evident for NTECs (Fig. 3e). Although the difference in CAPE between TECs and NTECs is at most 30 J kg\(^{-1}\) in that region (Fig. 3f), the environment associated with the TECs is thermodynamically more unstable than that of the NTECs. Since the values in JRA-55 are underestimated compared with sounding data (Appendix), the difference in CAPE between TECs and NTECs may be larger when other datasets such as real-time sounding data or outputs of mesoscale models are used. A region in which the difference in EHI between TECs and NTECs is statistically significant (exceeding the 95% confidence level) is located around the warm sector, but it is relatively narrow (Fig. 3i).

The difference in CAPE between the TECs and NTECs is strongly associated with the mid- to upper-level temperature. Although near-surface temperature for TECs is slightly colder than that for NTECs, the mid-level temperature around the cyclone center for TECs is notably colder than that for NTECs (Fig. 4), and the difference exceeds 3 K. In the warm sector, the mid-level temperature for TECs is also 1.5–3 K colder than that for NTECs and contributes to the larger CAPE. On the other hand, specific humidity at low levels for TECs is smaller than that for NTECs, which negatively contributes to larger CAPE for TECs.

The features of the upper-level disturbances between TECs and NTECs may also influence large-scale ascent. The large-scale low- to mid-level upward motion in the southeast region of the cyclone center of the TECs is stronger than that seen in the NTECs, and the region in which the differences between TECs and NTECs is statistically significant is close to the locations of the tornadoes (Figs. 5g–i). The large-scale upward motion may contribute to the destabilization of the low- to mid-level atmosphere as discussed in previous studies (e.g., Markowski and Richardson 2010; Tochimoto and Niino 2016). The present results suggest that the upper-level trough associated with the TECs is stronger than that of the NTECs and it thus induces stronger upward motion around the warm sector.

The box and whisker plots in Fig. 6 show the maxima of CAPE, the upper-level PV at 250 hPa, and the temperature difference ΔT between the surface and 500 hPa in the 5° × 5° area around the centers of the TECs and NTECs. The 75th percentile value of CAPE exceeds 400 J kg\(^{-1}\) for the TECs, while it is about 200 J kg\(^{-1}\) for the NTECs. More than half of TECs have maximum value of CAPE larger than 150 J kg\(^{-1}\). Most TECs have a maximum PV greater than 2.8 PVU (10th percentile). More than half of the TECs were accompanied with an upper-level maximum PV exceeding 6 PVU, but only about 25% of NTECs exceeded this value. Differences in the maximum ΔT value between the TECs and NTECs were also evident. Although
75% of NTECs were accompanied with $\Delta T$ values of less than 35 K, more than half of the TECs showed $\Delta T$ exceeding 36 K. Furthermore, 25% of the TECs had $\Delta T$ exceeding 39 K, but only 10% of the NTECs did. Thus, cooler temperature aloft and steeper temperature lapse rates contributed to the larger CAPE for TECs. The statistical t-test showed that the mean of CAPE, that of the upper-level PV maximum, and that of the maximum temperature statistically significantly differed (95% confidence level) between the TECs and NTECs.

Fig. 5. (a) and (d): PV (PVU; color shading) at 250 hPa and vertical pressure velocity (Pa s$^{-1}$) at 600 hPa, respectively, for TECs. (b) and (e): As in (a) and (d) but for NTECs. (c) and (f): $p$ values for the difference in PV and vertical pressure velocity between TECs and NTECs, respectively. Contour lines in (a), (b), (d), and (e) indicate geopotential height at 900 hPa with an interval of 30 m, and those in (c) and (f) indicate the difference in the PV and vertical pressure velocity with an interval of 1 PVU and 0.1 Pa s$^{-1}$, respectively.

b. South of 40°N in autumn

For ECs south of 40°N during SON (SSON), the SREH of the TECs in the northeast region of the cyclone center was greater than 125 m$^2$ s$^{-2}$ (Fig. 7a) but was less than 75 m$^2$ s$^{-2}$ for the NTECs (Fig. 7b). The difference in SREH between the TECs and NTECs was statistically significant (exceeding the 95% confidence level) in that region (Fig. 7c). However, the location of many tornadoes, which were to the southeast and southwest of the cyclone center, was not consistent with the region of large SREH.

Values of CAPE in SSON were the largest among the seasons (Figs. 7d–f). For TECs, the region of CAPE between 50 and 100 J kg$^{-1}$ extends throughout warm sector. Differences between the TECs and NTECs exceeded 50 J kg$^{-1}$ in much of the warm
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sector; however, the area of statistical significance that exceeded the 95% confidence level is somewhat narrow.

The EHI for the TECs is greater than that for the NTECs in the southeast region of the cyclone center, which corresponds to the warm sector, although the EHI is relatively small (Figs. 7g–i). Moreover, the region in which EHI exceeds 0.03 for the TECs is wider than that for the NTECs. However, more than half of the tornadoes were located outside the region where the statistical significance of the difference between TECs and NTECs exceeded the 95% confidence level.

In the southeast region of the cyclone center, the low-level southerly winds associated with the TECs were stronger than those associated with the NTECs (Fig. 8). These southerly winds are likely to have contributed to the larger CAPE values of the TECs through warm and moist air advection (not shown) and to the larger SREH through stronger low-level vertical wind shear (Figs. 7a–c). The stronger southerly winds seem to be associated with the TECs structures that are meridionally more elongated than those of NTECs (Fig. 8), as have been described for outbreak cyclones in the US (Tochimoto and Niino 2016).

Differences in the maximum CAPE and EHI values between TECs and NTECs are less evident, although the maximum tends to be larger for the TECs (Fig. 9). The 75th percentile value of the TECs (800 J kg$^{-1}$ for CAPE; 0.15 for EHI) is slightly larger than that of the NTECs (600 J kg$^{-1}$; 0.1 for EHI). The median value of EHI for the TECs is lower than the 75th percentile value for the NTECs. The mean of the maximum of EHI shows a statistically significant difference between the TECs and NTECs, while that of CAPE shows no significant difference between TECs and NTECs. The values of EHI and CAPE are smaller than those (about 2000 J kg$^{-1}$ for CAPE, and 1.40 for EHI) for significant tornadic supercell environments in the US (e.g., Rasmussen 2003).

c. North of 40°N in autumn

For ECs north of 40°N during SON (NSON), the difference in SREH between TECs and NTECs was less significant (Figs. 10a–c). The regions of large SREH exceeding 100 m$^2$ s$^{-2}$ extend over the northeast of the cyclone center for both TECs and NTECs. The values of SREH for the NTECs were larger than those for the TECs, and most of the tornadoes occurred in the south or southeast region of the cyclone center,
Fig. 7. Same as Fig. 3 except for SSON.
which does not correspond with the region of large SREH values.

In contrast to SREH, there were significant differences in CAPE and EHI between the TECs and NTECs although the values were relatively small (Figs. 10d–f). The region of CAPE greater than 70 J kg$^{-1}$ for the TECs extends over the southwest, south, and southeast of the cyclone center and nearly coincides with the tornado locations. In this region, the difference in CAPE between the TECs and NTECs exceeds 40 J kg$^{-1}$ and statistical significance exceeds the 99 % confidence level. This result indicates that thermodynamic instability is an important element of tornadogenesis in NSON.

EHI is found to be a useful parameter for distinguishing TECs from NTECs during NSON (Figs. 10g–i). The region in which differences in EHI between TECs and NTECs are statistically significant (at the 95 % or 99 % confidence level) is to the southeast and southwest of the cyclone center, and a considerable proportion of the tornadoes occurred in that region (Figs. 10g–i). The region of larger EHI associated with the TECs was primarily caused by the larger CAPE.

Figure 11 shows longitude–height cross sections of temperature and specific humidity along the line A–A’ in Fig. 10d. The distribution of low-level specific humidity is comparable for both the TECs and

Fig. 8. (a) Meridional winds at 900 hPa (color shading; m s$^{-1}$) for TECs in SSON, (b) same as (a) but for NTECs, and (c) $p$ values for the difference in meridional winds between TECs and NTECs. Contour lines in (a) and (b) indicate geopotential height with an interval of 20 m, and those in (c) indicate the differences in meridional winds between TECs and NTECs with an interval of 1 m s$^{-1}$.

Fig. 9. Same as Fig. 6 except for (a) CAPE and (b) EHI in SSON.
Fig. 10. Same as Fig. 3 except for NSON.
NTECs. On the other hand, the low-level temperature is warmer and mid-level temperature colder for the TECs, resulting in more unstable stratification. Thus, the difference in CAPE between the TECs and NTECs is associated with a difference in the temperature fields, rather than a difference in the water vapor fields.

The colder temperature at mid-levels for TECs is considered to be due to the differences in the position of upper-level PV between TECs and NTECs. The upper-level PV exceeds 5 PVU for the TECs and is located right above the cyclone center (Fig. 12a). It is suggested that tornadoes in NSON are associated with mature cyclones. On the other hand, the PV maximum for the NTECs is about 500 km west of the cyclone center (Fig. 12b). The difference in the upper-level PV between the TECs and NTECs is statistically significant above the cyclone center (Fig. 12c). Thus, the cold air mass associated with the upper-level trough seems to contribute to the larger CAPE of the TECs. The tornadoes associated with upper-level cold lows are also observed in the US (e.g., Davies 2006).

The box and whisker plot of the maximum CAPE values shows noticeable differences between the TECs and NTECs (Fig. 13a). The 75th percentile value of CAPE is about 400 J kg$^{-1}$ for the TECs but is about 170 J kg$^{-1}$ for the NTECs, which is nearly equal to the median value for the TECs. About half of the NTECs have CAPE values of less than 100 J kg$^{-1}$. Marked differences in the maximum EHI between the TECs and NTECs are also evident, although the magnitude is small (Fig. 13b). The 75th percentile value of EHI for the TECs is about 0.08, which is considerably larger than the value of about 0.04 for the NTECs. The means of the maximum CAPE and EHI values for the TECs are larger than those associated with the NTECs (significant at the 95% confidence level). The difference in CAPE and EHI is likely to be associated with

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**Fig. 11.** Zonal-vertical cross section of differences in temperature (color shading; K) and specific humidity (contour lines; g kg$^{-1}$) between TECs and NTECs along line A–A’ in Fig. 10 for NSON.

**Fig. 12.** (a) PV at 250 hPa (color shading; m s$^{-1}$) for TECs, (b) that for NTECs, and (c) p values for the difference in PV between TECs and NTECs for NSON. Contour lines in (a) and (b) indicate geopotential height with an interval of 20 m, and those in (c) indicate the differences in PV between TECs and NTECs with an interval of 0.5 PVU.

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that in vertical lapse rate of temperature (Fig. 13c). The maximum values of the lapse rate for TECs tend to be larger than that for NTECs. The difference in the mean of the maximum lapse rate between TECs and NTECs is statistically significant (95% confidence level).

d. Winter

During DJF, the SREH in the northeast to southeast regions of the cyclone center of the TECs is significantly larger than that of the NTECs (Figs. 14a–c). The region with SREH exceeding 100 m$^2$s$^{-2}$ extends over the southeast of the cyclone center for the TECs. In contrast, there is no region where SREH exceeds 100 m$^2$s$^{-2}$ for the NTECs. The difference in SREH between the TECs and NTECs exceeds 30 m$^2$s$^{-2}$, and the statistical significance passes the 95% or 99% confidence level in that region. Some of the tornadoes developed in the southeast region where SREH was large.

Although the values of CAPE during DJF were relatively small compared with other seasons, the distribution of CAPE displays significant differences between the TECs and NTECs (Figs. 14d–f). Major-
and the statistical significance exceeds the 99% confidence level (Fig. 15c). In addition, the low-level temperature of the TECs is more than 4 K warmer than that of the NTECs (Figs. 15d–f). The vertical profiles of temperature and specific humidity fields along line A–A’ in Fig. 15d also shows warmer temperatures and increased water vapor at low levels for the TECs (Fig. 15g).

Fig. 14. Same as Fig. 3 except for DJF.
Fig. 15. (a) and (d): Specific humidity (color shading; kg kg$^{-1}$) and temperature (color shading; K), respectively, at 950 hPa (color shading; K) for TECs. (b) and (e): As in (a) and (d) but for NTECs. (c) and (f): $p$ values for the difference in specific humidity and temperature between TECs and NTECs, respectively. Contour lines in (a), (b), (d), and (e) indicate geopotential height at 900 hPa with and interval of 30 m, and those in (c) and (f) indicate the difference in the specific humidity and temperature with an interval of 0.2 g kg$^{-1}$ and 1 K, respectively. (g) The zonal-vertical cross section of the difference in temperature (color shading; K) and specific humidity (contour lines; kg kg$^{-1}$) between TECs and NTECs along line A–A’ in (d).
Southerly winds exceeding 14 m s\(^{-1}\) are evident in the southeast region of the cyclone center for the TECs (Fig. 16a), whereas the wind speeds associated with the NTECs are less than 12 m s\(^{-1}\) (Fig. 16b). The maximum difference between the TECs and NTECs exceeds 4 m s\(^{-1}\) (Fig. 16c). Thus, we suggest that the

Fig. 16. Same as Fig. 5 except for DJF.
stronger southerly winds associated with the TECs advected warm and moist air from the south to the north, which resulted in the larger CAPE. The stronger low-level wind speed is also likely to contribute to the larger SREH of the TECs (Figs. 14a–c).

We note that the high-pressure system to the east of the TECs also contributes to the strong southerly winds. As the high-pressure system associated with the TECs is stronger than that associated with the NTECs, the zonal pressure gradient to the southeast of the cyclone center is also stronger, which results in stronger southerly winds there. The upper-level PV also displays a stronger ridge structure in the northeast region of the cyclone center (Figs. 16d–f). This suggests that the stronger high-pressure system has a deep structure that extends through the troposphere.

Our analysis suggest that the large-scale upward motion also contributes to the occurrence of tornadoes by destabilizing the troposphere as they do during MAM (Figs. 5g–i). A region of large-scale upward velocity at 600 hPa associated with the TECs extends over the northeast, southeast, and south regions of the cyclone center (Fig. 16g). The locations of tornadoes that developed in the south and southeast regions of the cyclone center correspond to the region of upward motion. Differences in the upward motion associated with the TECs and NTECs are statistically significant (exceeding the 95 % or 99 % confidence level) in the southeast region of the cyclone center (Fig. 16i).

The box and whisker plot of the maximum CAPE and EHI values shows noticeable differences between the TECs and NTECs (Fig. 17). The 75th percentile of CAPE for the TECs exceeds 250 J kg\(^{-1}\), but it is less than 170 J kg\(^{-1}\) for the NTECs. The 25th percentile of CAPE (90 m\(^2\) s\(^{-2}\)) for the TECs is comparable with the median value for the NTECs. For EHI, the 75th percentile for the TECs (about 0.1) exceeds the 90th percentile of the NTECs, and the median value for the TECs is greater than the 75th percentile of the NTECs. The means of the maximum CAPE and EHI for the TECs differ from those of the NTECs with statistical significance at 95 % confidence level. The box and whisker plots for the maximum of equivalent potential temperature at 950 hPa clearly show that environments around the centers of TECs are characterized by low-level moist and warm air, which contributes to larger CAPE (Fig. 17c). The difference in the mean of the maximum equivalent potential temperature between TECs and NTECs is statistically significant (95 % confidence level).

Fig. 17. Same as Fig. 6 except for (a) CAPE, (b) EHI, and (c) equivalent potential temperature at 950 hPa in DJF.
Comparison of tornadic extratropical cyclones between Japan and the United States

In this subsection, we describe the differences in the characteristics of TECs and their associated environmental parameters, which were derived from JRA-55, between Japan and the US during MAM when tornadoes associated with ECs occur most frequently in the latter. We used the same definition of TECs in the US as was used for Japan, except that they were detected in the region 110°–40°W, 30°–55°N during MAM from 1962 to 2011. By applying the same tracking algorithm, we detected 1098 TECs and their associated 5640 tornadoes using tornado data obtained from the Severe Weather Database compiled by the Storm Prediction Center at NOAA. Figure 18 shows the distribution of TECs and their associated tornadoes in the US. Majority of the TECs and their associated tornadoes occurred inland on the North American continent. In Japan, on the other hand, majority of TECs develop over the oceans and many of their associated tornadoes were observed along the coastal regions of the Japanese islands (Fig. 2).

We compared the composite fields of the TECs for Japan with those for the US. To compare the structures of the ECs of similar intensity between Japan and the US, 147 ECs with a minimum SLP of less than 992 hPa in the US were excluded from the composite analysis because TECs with an SLP lower than 992 hPa are hardly ever observed in Japan (Fig. 1). The composite fields for the environmental parameters, together with the geopotential height at a low level and kernel density estimates (Wilks 2006) for distributions of tornadoes with respect to the cyclone centers are shown in Fig. 19. Evidently, the horizontal scale of the Japanese TECs appears to be smaller than that in the US. SREH and CAPE values around the warm sector of the US TECs are larger than those from Japan (Figs. 19a, b). The tornadoes primarily occurred in the warm sector in both Japan and the US, although their area in the US is more widespread than that in Japan. The region in which SREH exceeds 150 m² s⁻² extends over the east of the cyclone center in the US. On the other hand, although SREH above 100 m² s⁻² is also found in the southeast region of the cyclone centers in Japan, there is no region where SREH exceeds 150 m² s⁻². A region with CAPE values between 100 and 350 J kg⁻¹ exists in the south–southeast region of the cyclone center in the US, whereas in Japan, CAPE values in that region are less than 100 J kg⁻¹ (Figs. 19c, d). As both CAPE and SREH are larger in the US than in Japan, EHI in the former is also noticeably higher in the southeast to south of the cyclone center (Figs. 19e, f). In that region, EHI is greater than 0.14 in the US but is less than 0.06 in Japan. Thus, the mesoscale environment in the US is more favorable for the occurrence of supercells and associated tornadoes.

To clarify why SREH is larger in the US than in Japan, we examined the distribution of the southerly winds at low levels (Fig. 20). Although the southerly wind at 900 hPa in Japan exceeds 14 m s⁻¹ and is stronger than that in the US, the region in which the southerly wind exceeds 10 m s⁻¹ is wider in the US than in Japan (Figs. 20a, b). The vertical cross section of the southerly wind along the lines A–A' and B–B' in Figs. 20a and 20b are shown in Figs. 20c and 20d, respectively. Near the surface (around 1000 hPa), the southerly wind is considerably weaker in the US than in Japan: the southerly wind near the surface exceeds 10 m s⁻¹ in Japan but is less than 6 m s⁻¹ in the US.
As a result, the vertical shear of the southerly winds in the US is stronger than that in Japan, resulting in larger SREH in the US. Note that Tochimoto and Niino (2016) showed that the vertical shear of the southerly winds contributes dominantly to 0–1 km SREH and causes its difference between outbreak cyclones and non-outbreak cyclones. The weaker southerly winds near the surface in the US may be the result of surface friction because most of the ECs in the US are located inland on the North American continent, whereas the

Fig. 19. Horizontal distributions of mesoscale environmental parameters in Japan (left panels) and the US (right panels): (a) and (b) SREH (color shading; m² s⁻²); (c) and (d) CAPE; (e) and (f) EHI. Contour lines indicate geopotential height at 900 hPa (m) with an interval of 20 m. Blue contour lines indicate kernel density estimates for distributions of tornado with respect to the TEC centers.
The majority of ECs around Japan occur over the seas where surface friction is lower (Figs. 20e, f).

The difference in CAPE between Japan and the US can be explained by the differences in temperature at both the low- and mid-levels. The vertical cross sections of the differences in temperature (Fig. 3d) and specific humidity (Fig. 19d) between Japan and the US along line A–A’ are shown in Fig. 21. Near the surface, the temperature in the US is at least 2 K warmer than that in Japan. In contrast, from the mid-
to upper-levels, the temperature in the US is more than 3 K colder than that in Japan. As the low-level specific humidity in Japan is greater than that in the US, the difference in CAPE between Japan and the US is caused by the temperature fields through the troposphere rather than by the water vapor fields.

4. Discussion

4.1 Seasonality of tornadic extratropical cyclones

To the best of our knowledge, this is the first study to have revealed the statistical characteristics of TECs and their seasonality together with their associated tornadoes in Japan. The distribution of CAPE associated with the structures of TECs varies with the seasons. The largest CAPE in SSON is associated with higher temperatures and increased amounts of water vapor at low levels compared with the other seasons. The higher temperature and larger amounts of water vapor are likely to be caused by the higher sea surface temperature compared to other seasons. In contrast, CAPE is smallest during DJF and NSON because the temperature is lower and there is less low-level water vapor than in other seasons. Chuda and Niino (2005) showed that CAPE in Japan displays strong seasonality, with the peak values occurring in summer, and it also decreases with increasing latitude.

Our comparison of the structures and environmental parameters of TECs and NTECs in each season indicates that the parameters or meteorological variables useful for distinguishing TECs from NTECs differ among the seasons. The distributions of upper-level PV accompanied with a cold air mass can cause significant differences in CAPE and may provide useful information for detecting TECs in MAM and NSON.

CAPE during DJF may also be a useful parameter for the detection of TECs, although its value is relatively small, which is somewhat similar to environments for tornadoes associated with quasi-linear convective systems in the US (Thompson et al. 2012). The larger CAPE for TECs during DJF was caused by the warmer and more humid low-level air advected along the periphery of the high-pressure system to the east of the cyclone center. Thus, the strong high-pressure system to the east is suggested to be an important element for a tornadogenesis associated with a TEC in DJF.

The results of this study also show that EHI may be a useful parameter for distinguishing TECs from NTECs around Japan in all seasons except MAM. Seko et al. (2009) showed that EHI was useful for accessing a potential for Saroma, Hokkaido tornado on 7 November 2006, which occurred in a warm sector of a TEC classified to NSON.

On the other hand, the present study suggests that SREH is less useful for distinguishing TECs from NTECs around Japan except during DJF. Although the regions where there are significant differences in SREH between TECs and NTECs are found in DJF, a considerable proportion of tornadoes do not collocate with these regions. In the US, SREH calculated between 0 and 1 km is considered to be a useful parameter for distinguishing between occasions when there is the potential for tornadic thunderstorms to develop and non-tornadic scenarios (Rasmussen 2003; Thompson et al. 2003), as well as between the potential for tornado outbreak events and periods when an outbreak is unlikely (Mercer et al. 2009, 2012; Shafer et al. 2009; Tochimoto and Niino 2016).

The environments shown in this study are somewhat similar to high-shear, low-CAPE (HSLC) environments that mainly appear for the cool season tornadoes in the southeastern US (Sherburn and Parker 2014; Sherburn et al. 2016). Sherburn et al. (2016) examined the composite HSLC environments and showed that the forcing of ascents for severe events were stronger than that for nonsevere events, which is similar to our results in MAM and DJF.

The horizontal resolution of the dataset may affect the mesoscale features, such as the veering of the wind with height and CAPE that can evolve rapidly in small time and space scales (e.g., Apsley et al. 2016; King et al. 2017; Markowski et al. 1998). Thus,
the values of environmental parameters obtained from reanalysis dataset should not be directly compared with those obtained from soundings even though the relative comparisons may still be useful. Our previous study (Tochimoto and Niino 2016) of the structure of ECs that caused tornado outbreaks and those that did not, clearly demonstrated the differences and suggested that the structure of ECs is important for providing a favorable background for the mesoscale environment of supercells and associated tornadoes.

We also examined the KHI (Sakurai and Kawamura 2008) for the TECs and NTECs for each season (not shown). The results suggest that KHI is not necessarily a more useful parameter than CAPE and EHI for distinguishing TECs from NTECs, even though values of KHI are large for TECs (not shown).

5. Summary

We have examined the climatology of the structure and environment of ECs that caused tornadoes (TECs) in Japan between 1961 and 2011. As TECs exhibit different seasonal characteristics including their tracks and the geographical distribution of associated tornadoes, they were separately examined for spring (MAM), autumn (SON), and winter (DJF).

The structures and environmental parameters associated with TECs were compared with those for non-tornadic ECs (NTECs). The characteristic differences between TECs and NTECs in each season may be briefly summarized as follows, where TECs that developed during SON were divided into those located to the north of 40°N (NSON) or to the south of 40°N (SSON) around the time of the tornado:

(i) MAM: TECs pass from the mainland of China to the Japanese islands through the East China Sea or the Yellow Sea. Many of the tornadoes occur in the warm sector of the TECs. TECs are accompanied with significantly stronger upper-level PV and colder mid-level temperatures than are seen in NTECs. The colder mid-level air in TECs results in larger CAPE values in the southeast region of the cyclone center. Stronger large-scale upward motion in that region for TECs is also associated with the upper-level high PV.

(ii) SSON: TECs follow the following two tracks: those passing from the Yellow Sea to the Sea of Japan and those from the mainland of China to the East China Sea. Tornadoes occur in the southwest, southeast, and northeast regions of the cyclone center. The stronger southerly winds associated with the more meridionally elongated structure of the TECs advect warm and moist air northward, and this creates an unstable atmosphere. The region in which CAPE and EHI are significantly larger develops to the east of the cyclone center for TECs, although the locations of about half of the tornadoes do not coincide with the region of large EHI.

(iii) NSON: TECs pass from north of the Korean Peninsula to Hokkaido. Majority of the EC-associated tornadoes that affect Hokkaido occur in NSON. CAPE and EHI values for TECs are significantly larger than those for NTECs. These features may be associated with the colder upper-level temperature associated with upper-level trough. On the other hand, the region of large SREH for TECs does not coincide with the locations of tornadoes. Thus, thermodynamically more unstable environments seem to be important for tornadoes in NSON.

(iv) DJF: Majority of the TECs move from the mainland of China to the East China Sea and the Yellow Sea. The majority of the tornadoes occur in the south and southeast regions of the cyclone center. The distributions of CAPE and EHI show significant differences between TECs and NTECs, and the region in which these parameters are large occurs near the locations of tornadoes. These differences are caused partly by the stronger high-pressure system to the east of the TEC center: the strong southerly winds between the TECs and the high-pressure system advect warm and moist air northward, thus creating a thermodynamically unstable atmosphere.

The differences in the structures of TECs and the environmental parameters during MAM between Japan and the US were also examined. The values of CAPE, SREH, and EHI of the US TECs were noticeably larger than those from Japan. The larger SREH in the US is caused by the stronger low-level vertical shear generated by the larger surface friction over land. The larger CAPE in the US can be attributed to the warmer temperatures near the surface caused by solar heating and lower temperatures at mid-levels. This may explain the lack of tornadoes stronger than EF4 in Japan (according to the statistics since 1961), and the statistics that the number of tornadoes per 10^4 km^2 per year in Japan is 0.54 (10^4 km)^-1 yr^-1 (Niino et al. 1997), which is about 40 % of that in the US.

In the present study, we have revealed significant features of TECs and the associated environmental parameters in Japan for each season. However, the physical mechanisms through which TECs are more favorable for tornadogenesis than NTECs remain to
be completely clarified. For instance, to what degree the high-pressure system to the east of TECs during DJF affects TECs and associated tornadogenesis is not entirely understood. Research is required for further understanding of the physical mechanisms and the detailed evolution of synoptic systems that causes an environment favorable for a tornadogenesis.

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Appendix: Comparison of SREH and CAPE with upper-air soundings

It is of interest to examine how the values of SREH and CAPE calculated from the JRA-55 dataset compare with those obtained from operational upper-air soundings made by the JMA. For this purpose, we used the sounding data from 1987 to 2007 from all 18 JMA stations. The JRA-55 parameters calculated at the four grid points nearest to the upper-air stations were interpolated to obtain their values at the sounding stations. The average values of the correlation coefficient between JRA-55 and the upper-level soundings for SREH and CAPE for all stations are 0.62 and 0.59, respectively. The largest correlation coefficient for SREH (CAPE) among the sounding stations is 0.84 (0.79) at Kagoshima (Ishigakijima) and the smallest is 0.003 (0.23) at Yonago (Akita).

Figure A1 shows scatter diagrams of CAPE and SREH between the upper-air soundings and JRA-55 for Ishigakijima (in the southwest of Okinawa Prefecture; see Fig. 2a) and Kagoshima (on the south of Kyushu Island; see Fig. 2), where the largest correlation coefficients were obtained for each parameter. Both SREH and CAPE obtained from JRA-55 are about half the value of the upper-air soundings. The average values of the coefficient of linear regression between the upper-air soundings and JRA-55 for SREH and CAPE are 0.4 and 0.29, respectively. The values of the regression coefficient for SREH (CAPE) vary from 0.001 (0.1) to 0.63 (0.56). Thus, both SREH and CAPE obtained from JRA-55 are smaller than those for the upper-air soundings. These differences in SREH and CAPE between JRA-55 and the soundings are partly caused by the horizontal resolution of JRA-55 (which is 100 km), where the vertical profiles of the thermodynamic and dynamical quantities are considered a horizontal average across the 100-km grid square. The horizontal interpolation of physical quantities at the nearest four grid point values of JRA-55 to the sounding stations may also be the cause of these differences, especially for those near the coastlines, for which some of the nearest grid points could be located over the oceans.

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