Entraining CAPE for Better Assessment of Tornado Outbreak Potential in the Warm Sector of Extratropical Cyclones

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ABSTRACT

Convective available potential energy (CAPE) is known to lack skill in discussing the environments of tornadic and nontornadic storms, or those of tornado outbreaks and nonoutbreaks. In this paper, a composite analysis of extratropical cyclones that caused 15 or more tornadoes [outbreak cyclones (OCs)] and 5 or fewer tornadoes [nonoutbreak cyclones (NOCs)] in the United States in April and May between 1995 and 2012 shows that entraining-CAPE (E-CAPE), which considers the effects of the entrainment of environmental air, is useful in the analysis of the environments of OCs and NOCs. E-CAPE in the warm sector of OCs is larger than that in the warm sector of NOCs (statistically significant at the 95%–99% level). Moreover, the regions with large E-CAPE for both OCs and NOCs are more closely correlated with the locations of tornadoes than those with large CAPE. The larger E-CAPE near the center in the warm sector of OCs is due to greater moisture at low and midlevels that results from advection by strong southerly winds and synoptic-scale ascent, respectively. The composite analysis also shows that E-EHI, E-SCP, and E-STP, for which traditional CAPE used in the energy helicity index (EHI), supercell composite parameter (SCP), and significant tornado parameter (STP) is substituted by E-CAPE, are more strongly correlated with tornado locations than are the original EHI, SCP, and STP, respectively.

1. Introduction

Tornado outbreaks often occur in the warm sector of extratropical cyclones (ECs) in the United States (e.g., Newton 1967; Hamill et al. 2005). In the warm sector, southerly winds in the lower troposphere and westerly winds in the upper troposphere provide strong veering vertical shear, and the warm moist air advected from the south creates unstable stratification, resulting in favorable conditions for supercells and associated tornadoes. However, not all ECs cause tornado outbreaks. Tochimoto and Niino (2016, 2017) investigated the

differences in the structure and environment between ECs that caused tornado outbreaks [hereafter outbreak cyclones (OCs)] and those that did not [hereafter nonoutbreak cyclones (NOCs)]. They showed that storm-relative environmental helicity (SREH) is a useful parameter in distinguishing between OCs and NOCs. They also showed that convective available potential energy (CAPE) shows significant differences between OCs and NOCs, especially in the region south of the cyclone center. The distribution of CAPE, however, did not necessarily map onto the region in which many tornadoes occurred. Other studies of the environment of tornadoes also showed that CAPE is not very skillful in distinguishing between tornadic and nontornadic storms (e.g., Edwards and Thompson 2000; Monteverdi et al. 2003; Thompson et al. 2003), or between tornadic outbreaks and nontornadic outbreaks (e.g., Shafer et al. 2009; Mercer et al. 2012).

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Although previous literature related to idealized numerical simulations of supercells indicates that midlevel dry air contributes to reducing the intensity of supercells via entrainment (Gilmore and Wicker 1998; James and Markowski 2010; Honda and Kawano 2015), the effects of the entrainment of environmental air are not included in traditional estimates of CAPE. Sueki and Niino (2016) showed that including the effect of the entrainment of environmental air in CAPE [entraining-CAPE (E-CAPE); Molinari et al. 2012] results in greater skill in distinguishing tornadic and nontornadic typhoons, and in estimating the potential for tornadoes. Their study suggests that the midlevel lapse rate and the moisture in typhoons can also be important for supercell development. Motivated by their study, we examine here whether E-CAPE can also be useful for discriminating between OCs and NOCs, as well as for estimating the potential for EC-associated tornado development.

The remainder of this paper is organized as follows. The data used in this study and our analysis methods are described in section 2. The results of applying E-CAPE to OC and NOC environments are presented in section 3, and these results are discussed in section 4. Finally, a summary is given in section 5.

2. Data and methods

The data used for the composite study were the Japanese 55-year Reanalysis (JRA-55; Kobayashi et al. 2015), which provides 6-hourly gridpoint values with a 1.25° horizontal grid spacing on 37 vertical levels. We targeted ECs that spawned tornadoes in the United States in April and May between 1995 and 2012, which is the same period as studied by Tochimoto and Niino (2016). Tornado data were obtained from the Severe Weather Database (<https://www.spc.noaa.gov/publications/mccarthy/f-scale.pdf>) produced by the Storm Prediction Center at the National Oceanic and Atmospheric Administration (NOAA). Our definitions of OCs and NOCs follow Tochimoto and Niino (2016) and are briefly summarized here for convenience. First, synoptic-scale ECs were detected using Hodges's tracking method (Hodges 1994, 1995, 1999). Second, tornadic ECs were defined as ECs that were accompanied by tornadoes within 3 h of the JRA-55 6-hourly analysis time. Third, tornadic ECs that were accompanied by 15 or more tornadoes during the 24 h between 0900 UTC on one day and 0900 UTC on the following day were defined as OCs, while those accompanied by 5 or fewer tornadoes during the same 24 h were defined as NOCs. We detected 55 OCs and 41 NOCs in the present study. The number of OCs and NOCs in each year, together with the number of tornadoes associated with OCs and NOCs, are listed in Table 1.

TABLE 1. Numbers of OCs and NOCs over the study period. The numbers of tornadoes associated with OCs and NOCs are shown in brackets, where the numbers before and after the slash are the sum of tornado counts for the entire lifetime of the cyclones and that for the 24-h period around the KT, respectively.

Year	No. of OCs (tornado)	No. of NOCs (tornado)
1995	5 (215/162)	0 (0/0)
1996	2 (96/75)	9 (27/22)
1997	1 (29/22)	3 (11/9)
1998	3 (131/100)	4 (21/15)
1999	4 (161/108)	5 (24/15)
2000	2 (38/32)	3 (27/15)
2001	3 (109/78)	4 (16/14)
2002	3 (78/52)	1 (2/2)
2003	5 (300/186)	1 (5/5)
2004	1 (20/20)	2 (8/5)
2005	1 (35/23)	2 (10/4)
2006	3 (156/135)	2 (2/2)
2007	2 (55/38)	0 (0/0)
2008	5 (247/146)	1 (2/2)
2009	3 (62/55)	1 (1/1)
2010	2 (63/57)	1 (5/5)
2011	9 (1001/723)	0 (0/0)
2012	1 (95/79)	2 (8/6)
Total	55 (2889/2091)	41 (170/122)

To check the dependence of our results on the objective analysis datasets used, we also completed similar composite analysis using the National Centers for Environmental Prediction Climate Forecast System Reanalysis (NCEP-CFSR; Saha et al. 2010) and the NCEP Climate Forecast System, version 2 (NCEP-CFSv2; Saha et al. 2014), operational analysis. The former covers the period between January 1979 and March 2011, and the latter covers from April 2011 to the present. These datasets provide gridpoint values with a 0.5° horizontal grid spacing on 37 vertical levels. We used the same analysis period with these datasets as with JRA-55.

Composite analysis was used to identify the differences in E-CAPE between OCs and NOCs. In this analysis, the physical variables were simply superposed with respect to the EC center, which was defined by the vorticity maximum at 900 hPa. The key time (KT) was defined as the time at which the largest number of tornadoes occurred within 24 h (from -12 to $+12$ h). As described by Tochimoto and Niino (2016), the KTs for more than 90% of OCs and NOCs are 1800 and 0000 UTC. A permutation test (Efron and Tibshirani 1993), which is a statistical technique used to determine if the means of two distributions are different, was performed on the meteorological variables. In what follows, p values of 0.1, 0.05, and 0.01 correspond to the 90%, 95%, and 99% confidence levels, respectively.

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

FIG. 1. Horizontal distributions of CAPE and E-CAPE for the composite fields at the key time (KT), where color shading shows percentages of maximum value of CAPE for (a) OCs, (b) NOCs, and (c) p values for differences in CAPE between OCs and NOCs. (d)–(f) As in (a)–(c), but for E-CAPE. Contour lines in (a), (b), (d), and (e) indicate geopotential height at 900 hPa with an interval of 20 m, and those in (c) and (f) show differences in CAPE and E-CAPE between OCs and NOCs. Note that the contour intervals in (c) and (f) are 200 and 20 J kg^{-1} , respectively. Blue dots indicate the locations of tornadoes with respect to the cyclone center. The labels on the axes are in degrees relative to the cyclone center.

$$\text{CAPE} = g \int_{\text{LFC}}^{\text{LNB}} \frac{T_v(z) - \bar{T}_v(z)}{\bar{T}_v(z)} dz, \quad (1)$$

where z is the height, $T_v(z)$ is the virtual temperature of the parcel, $\bar{T}_v(z)$ is the virtual temperature of the environment, g is acceleration due to gravity, and LFC is the level of free convection. Note that the thermodynamic

state of the initial parcel to be lifted was given by the average over the lowest 1-km layer.

E-CAPE was calculated by considering the effect of entrainment, based on a one-dimensional Lagrangian parcel model (Romps and Kuang 2010). We assumed that condensates immediately fall from the parcel and did not consider latent heating associated with the

freezing of liquid water. We also followed [Molinari et al. \(2012\)](#) in assuming that the parcel ascends at a rate of 1 m s^{-1} and entrains environmental air at a constant mass entrainment rate ε . Here, we used an ε value of $20\% \text{ km}^{-1}$, following [Sueki and Niino \(2016\)](#).

We additionally examined the effect of entrainment on the energy helicity index (EHI; [Hart and Korotky 1991](#)), supercell composite parameter (SCP; [Thompson et al. 2002, 2003](#)), and significant tornado parameter (STP; [Thompson et al. 2002, 2003](#)) by replacing CAPE in these parameters with E-CAPE. The conventional EHI combines SREH ([Davies-Jones et al. 1990](#)), which is calculated between heights of 0 and 1 km, with CAPE as follows:

$$\text{EHI} = \frac{\text{SREH} \times \text{CAPE}}{1.6 \times 10^5}. \quad (2)$$

We defined the entraining energy helicity index (E-EHI) as follows:

$$\text{E-EHI} = \frac{\text{SREH} \times \text{E-CAPE}}{1.6 \times 10^5} \frac{\text{CAPE}_{\max}}{\text{E-CAPE}_{\max}}, \quad (3)$$

where $\text{CAPE}_{\max}$ ($\text{E-CAPE}_{\max}$) is the maximum value of CAPE (E-CAPE) in each composite field of OCs and NOCs. The factor $\text{CAPE}_{\max}/\text{E-CAPE}_{\max}$ was included in Eq. (3) to allow a comparison between the distributions of EHI and E-EHI on an equitable basis, because E-CAPE is about 10 times smaller than CAPE.

The conventional SCP is defined as follows:

$$\text{SCP} = \frac{\text{MUCAPE}}{1000} \times \frac{0 - 3 \text{ km SREH}}{100} \times \frac{\text{BRN shear}}{40}, \quad (4)$$

where MUCAPE is CAPE calculated for most unstable parcels, 0–3-km SREH is SREH between 0 and 3 km, and BRN shear is the bulk Richardson number shear, which is defined as the difference between the density-weighted mean winds at 0–6 km and at 0–500 m.

In this paper, we introduced E-SCP as follows:

$$\text{E-SCP} = \frac{\text{E-MUCAPE}}{1000} \times \frac{\text{MUCAPE}_{\max}}{\text{E-MUCAPE}_{\max}} \times \frac{0 - 3 \text{ km SREH}}{100} \times \frac{\text{BRN shear}}{40}, \quad (5)$$

where $\text{MUCAPE}_{\max}$ ($\text{E-MUCAPE}_{\max}$) is the maximum of MUCAPE (E-MUCAPE) in each composite field for OCs and NOCs. Note that SCP was developed to describe the environment favorable for supercells, but not necessarily for tornadic supercells.

Furthermore, the conventional STP is defined as follows:

TABLE 2. Correlation coefficients between the PDF of tornado locations and environmental parameters for OCs.

Parameters without entrainment		Parameters with entrainment	
CAPE	0.40	E-CAPE	0.77
		E-CAPE10	0.64
		E-CAPE30	0.83
EHI	0.68	E-EHI	0.82
SCP	0.76	E-SCP	0.85
STP	0.75	E-STP	0.86

$$\text{STP} = \frac{\text{CAPE}}{1000} \times \frac{\text{SHR6}}{20} \times \frac{\text{SREH}}{100} \times \frac{(2000 - \text{MLLCL})}{1500}, \quad (6)$$

where SHR6 is the magnitude of the bulk shear vector between the surface and 6 km, and MLLCL is the mean layer lifting condensation level. In this paper, we also introduced E-STP as follows:

$$\text{E-STP} = \frac{\text{E-CAPE}}{1000} \times \frac{\text{CAPE}_{\max}}{\text{E-CAPE}_{\max}} \times \frac{\text{SHR6}}{20} \times \frac{\text{SREH}}{100} \times \frac{(2000 - \text{MLLCL})}{1500}. \quad (7)$$

We will compare the composite fields of E-EHI, E-SCP, and E-STP with the conventional EHI, SCP, and STP, respectively, in the next section. Note that the factor $\text{CAPE}_{\max}/\text{E-CAPE}_{\max}$ for E-EHI, E-SCP, and E-STP was not included in the permutation tests.

3. Results

a. Horizontal distribution of CAPE and E-CAPE

[Figures 1a–c](#) show the composite fields of the conventional CAPE for OCs and NOCs. There are significant differences in CAPE between OCs and NOCs, especially at more than 500 km south of the cyclone center. The maximum value of the composite field for OCs is 1207 J kg^{-1} ($x = 1.25^\circ$, $y = -7.5^\circ$), and that for NOCs is 707 J kg^{-1} ($x = 1.25^\circ$, $y = -2.5^\circ$). However, the region with large CAPE does not necessarily correspond to the region where tornadoes are concentrated. Although a considerable fraction of tornadoes for OCs occurs in the warm sector, and within 5° of the cyclone center, the region of large CAPE is more than 500 km south of the cyclone center. The region in which differences between OCs and NOCs are statistically significant is also located 500–1000 km south of the cyclone center. This is not surprising because the various factors, such as convective initiation, level of free convection, and vertical shear,

Relative humidity & equivalent potential temperature

FIG. 2. Zonal-vertical cross sections of relative humidity (color shading; %) and equivalent potential temperature (red solid lines; K) along lines (a) A–A' and (b) B–B' in Fig. 1a, and (c) C–C' and (d) D–D' in Fig. 1b. The labels on the abscissa are in degrees.

can affect the occurrence of supercells and associated tornadoes.

In contrast, the distributions of E-CAPE show good agreement with the locations of the tornadoes (Figs. 1d,e). The region in which E-CAPE is large is within 5° of the cyclone center for both OCs and NOCs. To quantitatively compare the effectiveness of the environmental parameters in expressing the potential for tornadoes, we examined the correlation coefficients between environmental parameters and a probability density function (PDF)

of tornado locations, which we calculated using a kernel density estimate with an assumption of a Gaussian kernel (Wilks 2006; Table 2). The correlation coefficient between the PDF of the tornado locations and E-CAPE (0.77) is larger than that between the PDF and CAPE (0.40). In addition, E-CAPE for OCs is significantly greater than that for NOCs, and the region in which the difference between OCs and NOCs is significant is located in the warm sector close to the cyclone center (Figs. 1d–f). Note that E-CAPE is much smaller than

Specific humidity at 950 hPa

FIG. 3. As in Fig. 1, but for specific humidity (color shading; g kg^{-1}) at (a)–(c) 950 hPa and (d)–(f) 750 hPa. Contour lines in (d) and (e) are geopotential height at 750 hPa. Note that the contour intervals in (c) and (f) are 0.5 and 0.2 g kg^{-1} , respectively.

CAPE because the former considers the effects of entrained environmental air.

The reason why E-CAPE is large in the warm sector close to the cyclone center is similar to the explanation given by Sueki and Niino (2016) for tropical cyclones. Zonal-vertical cross sections of relative humidity and equivalent potential temperature along

the lines A–A' and B–B' in Fig. 1a are shown in Figs. 2a and 2b, respectively. Along line B–B', which is about 1000 km south of the cyclone center where CAPE is large, the relative humidity at midlevels is lower (Fig. 2b) than that along line A–A' (Fig. 2a). The relative humidity between 700 and 400 hPa, about 500 km east of the OC center, is less than 30% along line B–B', while that along

Vertical pressure velocity at 750 hPa

FIG. 4. Horizontal distributions of vertical pressure velocity at 750 hPa for (a) OCs and (b) NOCs (color shading: Pa s^{-1}), and (c) that of p values for differences between OCs and NOCs. Contour lines in (a) and (b) indicate geopotential height at 900 hPa with an interval of 20 m, and those in (c) show differences in the vertical pressure velocity between OCs and NOCs with a contour interval of 0.1 Pa s^{-1} . The labels on the axes are in degrees relative to the cyclone center.

line A–A' is greater than 45% (Fig. 2b). Thus, the buoyancy of an air parcel along line B–B' (A–A') is reduced more (less) by entraining environmental air with relatively low (high) equivalent potential temperature, resulting in smaller (larger) values of E-CAPE. Although a similar feature is also found in the cross sections for NOCs (Figs. 2c and 2d), relative humidity at low- and midlevels along C–C' is lower than that seen in OCs (Fig. 2a). These differences result in differences in E-CAPE between OCs and NOCs, as discussed below.

b. Important factors resulting in differences in E-CAPE between OCs and NOCs

Figure 3 shows the horizontal distributions of specific humidity at 900 and 750 hPa for OCs and NOCs. As described by Tochimoto and Niino (2016), OCs have significantly greater low-level moisture than NOCs (Figs. 3a–c). This, together with the midlevel moisture fields (Figs. 3d–f), contributes to the difference in E-CAPE between OCs and NOCs. The specific humidity at midlevels shows statistically significant differences between OCs and NOCs in the warm sector, resulting in the differences in E-CAPE. On the other hand, temperature fields show no significant differences between OCs and NOCs (not shown).

The difference in low-level moisture between OCs and NOCs in the region of large E-CAPE is caused mainly by the difference in the strength of the low-level southerly winds, which advect moist air northward (Tochimoto and Niino 2016). On the other hand, horizontal advection appears to contribute little to midlevel moisture in that region, because there is more moisture there than in the south. This suggests that the higher specific humidity at the midlevels is likely to be caused by vertical advection. In fact, the synoptic ascent in the warm sector of OCs is significantly stronger than that for NOCs (Fig. 4), and the region with cyclone-scale ascents corresponds well to the region of large midlevel moisture. We also calculated the vertical advection of moisture at midlevels and confirmed that it is predominantly positive in the warm sector for OCs and notably larger than that for NOCs (Fig. 5).

c. Energy helicity index using CAPE and E-CAPE

Here, we compare the composite fields for EHI and E-EHI between OCs and NOCs (Fig. 6). Note that the factor of $\text{CAPE}_{\text{max}}/\text{E-CAPE}_{\text{max}}$ is about 9.5 for OCs and 7.8 for NOCs. The difference in EHI between OCs and NOCs is statistically significant in the region southeast of the cyclone center: the maximum value of EHI for

FIG. 5. Composite fields for (a) vertical and (b) horizontal advection [$\text{g kg}^{-1} (6\text{h})^{-1}$] of specific humidity at 750 hPa at KT - 6 for OC. Contour lines indicate geopotential height (m) at 750 hPa.

OCs is 1.12, while that for NOCs is 0.57 (Figs. 6a,b). However, the locations of the tornadoes near the cyclone center for OCs (between $y = -2.5^\circ$ and 0.0°) are not necessarily covered by the region with large EHI (Fig. 6a). The region in which EHI is larger than 0.8 lies between $x = -2.5^\circ$ and 5.0° , $y = -9.0^\circ$ and -2.5° .

The E-EHI values larger than 0.8 for OCs are found between $x = -2.0^\circ$ and 4.0° , $y = -7.5^\circ$ and -1.0° (Fig. 6d). This region shows greater consistency with the locations of tornadoes than that of EHI. The correlation coefficient of 0.82 for E-EHI is larger than that of 0.65 for EHI (Table 2). The difference in E-EHI between OCs and

NOCs is statistically significant in the region southeast of the cyclone center (Fig. 6f). Note that although arguments remain regarding the physical meaning of EHI for supercells and tornado potential (Doswell and Schultz 2006), defining E-EHI by Eq. (3) allows us to formally compare EHI with E-EHI. The results of the comparison demonstrate the usefulness of E-CAPE. Note that the criterion $\text{E-EHI} = 1$ for the conveniently defined E-EHI is not equivalent to the criterion $\text{EHI} = 1$, and may not have a discriminating power as the latter. Thus, further research is required to determine appropriate criteria for E-EHI before it can be practically tested for operational use.

FIG. 6. As in Fig. 1, but for (a)–(c) EHI and (d)–(f) E-EHI. Red dots indicate the locations of tornadoes with respect to the cyclone center. Note that the contour interval in (c) and (f) is 0.2.

Shafer et al. (2010) showed that the region in which environmental parameters have large values is wider for severe weather outbreaks (primarily major tornado outbreaks) than that for less significant outbreaks. Figure 7 shows box-and-whisker plots of an area that exceeds the threshold value of 0.1 for E-EHI around the EC centers ($15^{\circ} \times 15^{\circ}$) for OCs and NOCs. The area for OCs tends to be wider than that for NOCs, indicating that environments of OCs are associated with wider regions favorable for the occurrence of supercells and tornadoes.

Figure 8 shows box-and-whisker plots for the maximum of CAPE, E-CAPE, EHI, and E-EHI in the $10^{\circ} \times 10^{\circ}$ area around the centers of the OCs and NOCs. Note that the factor of $\text{CAPE}_{\text{max}}/\text{E-CAPE}_{\text{max}}$ is not included here in the calculation of E-EHI. In both CAPE and E-CAPE, the 25th percentile value for OCs is larger than that for the median value of NOCs. Thus, both CAPE and E-CAPE seem to be useful for discriminating between OCs and NOCs. Both EHI and E-EHI also show good discrimination between OCs and NOCs (e.g., the 25th percentile values of EHI and E-EHI for OCs are larger than their

FIG. 7. Box-and-whisker plots for the area in which E-EHI exceeds the threshold value of 0.1 for OCs and NOCs. The shaded box indicates the range for the 25th–75th percentiles, and the whiskers indicate that for the 10th–90th percentiles. Median values are marked by the black horizontal line within each shaded box.

median values for NOCs). However, it seems that the discriminatory powers of E-CAPE and E-EHI are not especially improved when compared with CAPE and EHI, respectively.

d. Supercell composite parameter and significant tornado parameter with entrainment effects

In this subsection, we examine whether E-SCP and E-STP are more useful for estimating tornado outbreak potential than are the original SCP and STP parameters. Composite fields of SCP and E-SCP are shown in Fig. 9. Note that $\text{MUCAPE}_{\text{max}}/\text{E-MUCAPE}_{\text{max}}$ is about 5.8 for OCs and 7.7 for NOCs. Larger values of SCP and E-SCP for OCs exist in the east and southeast regions of the OC center compared with those for NOCs. The maximum value of E-SCP ($x = 4.0^\circ$, $y = 0^\circ$) is located to the north of that for SCP ($x = 3.0^\circ$, $y = -3.0^\circ$). For both SCP and E-SCP, differences between OCs and NOCs are statistically significant in the east and southeast region of the cyclone center (95%–99% confidence level). Although both SCP and E-SCP are useful parameters for distinguishing between OCs and NOCs, the correlation coefficient for E-SCP is 0.85, which is larger than the 0.75 obtained for SCP (Table 2), indicating that E-SCP is more closely correlated with the spatial distribution of tornadoes.

FIG. 8. Box-and-whisker plots of maximum (a) CAPE, (b) E-CAPE, (c) EHI, and (d) E-EHI within 10° of the center of OCs and NOCs. The shaded box indicates the range of the 25th–75th percentiles, and the whiskers indicate that for the 10th–90th percentiles. Median values are marked by the black horizontal line within each shaded box.

FIG. 9. As in Fig. 6, but for (a)–(c) SCP and (d)–(f) E-SCP. Note that the contour interval in (c) and (f) is 0.1.

The box-and-whisker plots for the maximum of SCP and E-SCP in the $10^{\circ} \times 10^{\circ}$ area around the centers of the OCs and NOCs show that both SCP and E-SCP are useful for discriminating OCs and NOCs: the 25th percentile values for OCs are larger than those for NOCs. On the other hand, there is a less clear advantage in using E-SCP for distinguishing between OCs and NOCs compared with SCP (Fig. 10). This is probably because MUCAPE is used in the calculation of SCP. The box-and-whisker plots for E-SCP, where it is calculated with E-CAPE instead of E-MUCAPE, show some improvement in discriminating between OCs and NOCs

compared with SCP, SCP with MLCAPE (Fig. 10c), and E-SCP with E-MUCAPE [i.e., the 25th percentile and 10th percentile values of E-SCP with E-MLCAPE for OCs are larger than the median value for NOCs (Fig. 10d)]. However, E-SCP with E-MUCAPE or E-MLCAPE are not very useful in discriminating between OCs and NOCs than are SCP with MUCAPE.

The composite fields of STP and E-STP also show significant differences between OCs and NOCs in the east and southeast region of the cyclone center (Fig. 11). However, the region in which E-STP exceeds 0.7 shows greater consistency with tornado locations compared

FIG. 10. As in Fig. 8, but for (a) SCP, (b) E-SCP, (c) SCP with MLCAPE, and (d) E-SCP with E-MLCAPE.

with that of STP. In fact, the correlation coefficient for E-STP is 0.86, which is larger than the 0.76 obtained for STP (Table 2), indicating that E-STP is more closely correlated with the spatial distributions of tornadoes. Furthermore, E-STP for OCs is larger than STP in the east and southeast region of the cyclone center where a considerable fraction of the tornadoes occur (Fig. 12).

Box-and-whisker plots for the maximum of STP and E-STP are shown in Fig. 13. For E-STP (STP), the median and 10th percentile values for OCs are larger (smaller) than the 90th percentile and median values of NOCs, respectively. Thus, E-STP is likely to be more effective in discriminating between OCs and NOCs.

e. E-CAPE for other seasons

Tornado outbreaks also occasionally occur in the warm sector of ECs in other seasons, such as autumn

[September–November (SON)] and winter [December–February (DJF)]. Thus, we examined the effectiveness of E-CAPE for tornado outbreaks in SON and DJF. To exclude tropical cyclones in SON, cyclones that crossed 27.5°N from the south were not used in this study. The number of OCs in SON and DJF were 22 and 13, respectively. Figure 14 shows the composite fields of CAPE and E-CAPE for OCs in SON and DJF.

Large values of CAPE in SON are evident more than 1000 km south of the cyclone center. Therefore, as most tornadoes occur within 1000 km of the cyclone center, CAPE is not well correlated with tornado locations. On the other hand, large values of E-CAPE in the composite fields are found in the southeast region of the cyclone center, and thus tornado locations are more closely correlated with E-CAPE (Fig. 14c). The correlation coefficient between the PDF of tornado locations and E-CAPE is 0.59, which is notably larger than the 0.14 for that between the PDF and CAPE.

FIG. 11. As in Fig. 6, but for (a)–(c) STP and (d)–(f) E-STP. Note that the contour interval in (c) and (f) is 0.3.

In DJF, large values of CAPE exist between $y = -1000$ and -500 km, more than 1200 km south of the cyclone center (Fig. 14b). The CAPE distribution is not well correlated with tornado locations because most tornadoes occur within 500 km of the cyclone center. On the other hand, the composite fields of E-CAPE, which is large in the southeast region of the cyclone center, show better consistency with the tornado locations in DJF (Fig. 14d). The correlation coefficient of 0.77 for E-CAPE is notably larger than that of 0.26 for CAPE. Although the sample number for OCs is too small to investigate the effectiveness of E-CAPE with statistical confidence, these results seem to suggest

that E-CAPE is also useful for examining tornado outbreak potential in SON and DJF, in addition to April and May.

4. Discussion

a. Dependence on entrainment rate

Sueki and Niino (2016) found that E-CAPE with $\varepsilon = 20\% \text{ km}^{-1}$ best explains the temporal and spatial distributions of typhoon-associated tornadoes, and we have so far assumed the same entrainment rate. Sueki (2017) recently made a large eddy simulation of a typhoon-associated minisupercell and found the entrainment rate

FIG. 12. Difference between E-STP and SCP for OC.

to be about $15\%–20\% \text{ km}^{-1}$. However, many of the storms associated with tornado outbreaks in the warm sector of ECs are likely to be classic supercells, and may not have the same entrainment rate as minisupercells associated with tropical cyclones. Thus, we have also examined the dependence of E-CAPE on the entrainment rate for our set of ECs.

Figure 15 shows the composite fields for E-CAPE with $\varepsilon = 10\% \text{ km}^{-1}$ (E-CAPE10) and with $\varepsilon = 30\% \text{ km}^{-1}$ (E-CAPE30) for OCs and NOCs. For OCs, the large

values of E-CAPE10 are located about 500 km southeast of the cyclone center (Fig. 15a). It is this region where the difference in E-CAPE10 between OCs and NOCs is remarkable (Fig. 15c). However, this region shows less consistency with the tornado locations near the cyclone center (between $y = -2.5^\circ$ and 0° ; cf. Fig. 1d for E-CAPE). In fact, the correlation coefficient between the PDF of the tornado locations and E-CAPE10 (0.64) is smaller than that between the PDF and E-CAPE (0.77; Table 2). On the other hand, the region with large values of E-CAPE30 in the warm sector is located closer to the cyclone center and covers the region in which most tornadoes occur (Figs. 15d–f). The correlation coefficient between the PDF and E-CAPE30 (0.83) is slightly larger than that between the PDF and E-CAPE (0.77; Table 2), showing that E-CAPE30 has better consistency with the tornado locations. However, the region in which differences between OCs and NOCs are statistically significant for E-CAPE30 is much narrower than that for E-CAPE10 and E-CAPE. Therefore, a value for ε of 20% seems to be more appropriate for distinguishing OCs from NOCs than using values of 30% or 10%. To reliably estimate the entrainment rate, however, it will be necessary to perform a large eddy simulation of supercells in various environments.

b. Dependence of the results on the objective analysis dataset

To examine the degree to which the present results depend on the objective analysis dataset used, we compare the composite fields of E-CAPE obtained from the JRA-55 and NCEP-CFSR/CFSv2 datasets (Fig. 16). Note that the EC tracks used here are the same as those detected with JRA-55. Although the values of E-CAPE

FIG. 13. As in Fig. 8, but for (a) STP and (b) E-STP.

FIG. 14. Horizontal distribution of CAPE and E-CAPE in SON and DJF for the composite fields at KT. Color shading in (a) [(b)] and (b) [(d)] shows the percentage of maximum value of CAPE [E-CAPE] for OCs in SON and DJF, respectively. Blue dots are the same as those in Fig. 1. Note that contour lines indicate geopotential height at 900 hPa.

for NCEP-CFSR/CFSv2 tend to be about 1.5 times larger than those for JRA-55, the overall distributions of E-CAPE are similar between JRA-55 and NCEP-CFSR/CFSv2. In addition, differences in E-CAPE between OCs and NOCs are statistically significant in the southeast region of the cyclone center (95%–99% confidence level; not shown). Thus, the distribution of E-CAPE derived from the JRA-55 data seems to be robust for exploring the environments of tornado outbreaks associated with ECs, although its absolute

values may need some adjustment when different datasets are used.

5. Summary

Our composite analysis of extratropical cyclones that caused tornado outbreaks (OCs) and those that did not (NOCs) has shown that CAPE including the effects of entrainment of environmental air (E-CAPE) is more useful in examining the differences between OCs from

E-CAPE10

E-CAPE30

FIG. 15. As in Figs. 1d–f, but for (a)–(c) E-CAPE10 and (d)–(f) E-CAPE30. Note that the contour intervals in (c) and (f) are 50 and 5 J kg^{-1} , respectively.

NOCs than is traditional CAPE. The distributions of E-CAPE are more closely correlated with tornado locations compared with the original CAPE, and E-CAPE at these locations for OCs is significantly larger than that for NOCs. We have also shown that the distributions of E-EHI, E-SCP, and E-STP in which traditional CAPE is substituted by E-CAPE are more closely correlated with tornado locations than the original parameters EHI,

SCP, and STP, respectively. These results show that tornado potential might be better predicted if E-CAPE is considered, although detailed quantitative criteria for parameters containing E-CAPE need to be determined based on rigorous statistical studies before they can be used operationally.

The difference in E-CAPE between OCs and NOCs is caused mainly by the difference in moisture fields at the

FIG. 16. Composite fields of E-CAPE for OCs for (a) NCEP-CFSR/CFSv2 and (b) JRA-55. Note that contour lines indicate geopotential height at 900 hPa.

low and midlevels. Low- to midlevel specific humidity in the warm sector for OCs is significantly larger than for NOCs, resulting in larger E-CAPE for OCs. It is suggested that the larger specific humidity at midlevels for OCs is caused by vertical advection that results from upward motion associated with upper-level troughs and a warm conveyor belt.

Although the present study focused on tornado outbreaks associated with extratropical cyclones, E-CAPE can be a useful parameter for assessing the tornado potential of more general environments. Examining its usefulness for environments other than extratropical and tropical cyclones, and the calculation of E-CAPE and other parameters for individual tornadoes using very high-resolution numerical weather prediction (i.e., a grid spacing of 4 km or less) are important subjects for future research. Furthermore, an examination of the applicability of E-CAPE to more general environments such as severe hail/wind, lightning, and convective initiation will be of great interest. Regarding the practical use of E-CAPE and environmental parameters incorporating E-CAPE, it would be important to determine exact criteria for examining environments of tornadoes and other severe local storms for individual datasets such as upper-air soundings and objective analysis datasets.

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