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Differences in Tropical Cyclone Tornado Activities and Key Tornadic Environments Between China and the United States

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Key Points:

- Lower TC tornado frequency in China are partly due to shorter, more southerly, and less recurving inland TC tracks
- The most thermodynamically and kinematically favorable regions in TC are mismatched in China but overlapped in the U.S
- The mismatch stems from southern TCs, whose lapse rate and relative humidity are both high in the southwest quadrant

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Abstract Tornadic tropical cyclones (TCs) in China occur at a similar frequency to those in the U.S., yet the number of TC tornadoes in China is only 16.5% of that in the U.S. This study reveals that one reason is that tornadic TCs in China have shorter track lengths, fewer recurving tracks, and more southerly locations when producing tornadoes. The other reason is TCs' less tornado-conducive environments in China. TC environments in China are more dynamically favorable but less thermodynamically conducive to tornadogenesis relative to the U.S. The composite impact is that the regions with the most favorable thermodynamic and kinematic conditions mismatch in China, with the former in the southwest quadrant and the latter in the northeast quadrant of TCs, whereas they overlap in the northeast quadrant in the U.S. and thus lead to a larger composite parameter. This mismatch in China primarily stems from tornadic TCs in southern China.

Plain Language Summary Tropical cyclones (TCs) in China produce tornadoes at a similar rate as those in the U.S., but China sees far fewer TC tornadoes overall. This study found two key reasons. First, TCs that spawn tornadoes in China tend to have shorter and less recurving paths, and stay farther south when producing tornadoes compared to U.S. storms. Second, the environment around TCs in China is less favorable for tornadoes. The best conditions for tornado formation—combining instability, moisture, and wind shear—are mismatched in China while collocated in the U.S. In China, the most unstable air is usually in the southwest quadrant of the TC, while the strongest wind shear is in the northeast. In the U.S., these factors overlap in the northeast quadrant, making tornadoes more likely. This mismatch in China is especially clear in southern TCs, where the necessary ingredients are split apart.

1. Introduction

Tropical cyclones (TCs) represent a significant environment conducive to tornado formation. TC tornadoes pose a distinct threat to life and property, typically occurring away from the TC center where other TC threats, such as strong winds and heavy rainfall, mainly occur. Despite accounting for approximately 3% of U.S. TC fatalities (Rappaport, 2014), TC tornadoes have received much less attention compared to other TC threats or mid-latitude tornadoes. This neglect may be attributed to several factors. Firstly, TC tornadoes are generally weaker, smaller, and shorter-lived compared to their mid-latitude counterparts, thus resulting less damage potential (Wen et al., 2024). Moreover, the miniature supercells, the primary parent storms of TC tornadoes, tend to be weaker, shallower, and shorter-lived than their midlatitude counterparts, and are often embedded within the rain bands of their parent TCs, posing significant challenges in detection and forecasting (Bai et al., 2017).

The U.S. has the largest frequency of TC tornadoes worldwide, followed by China. Both countries, situated in the middle latitudes, experience significant vertical wind shear, facilitating tornado formation. Additionally, their extensive coastlines render swathes of land vulnerable to TC strikes. Despite these similarities, the contrast in TC tornado frequency between the two countries is stark. The U.S. has an average of 65 TC tornadoes annually (Edwards & Mosier, 2022), whereas China sees a considerably lower average of 5 TC tornadoes per year (Bai et al., 2020).

Surprisingly, while the U.S. experiences fewer landfalling TCs on average—4 per year compared to China's average of 8—its tornado-generating efficiency per TC is notably higher, with an average of 12 tornadoes per TC in the U.S. compared to just 2 in China. Several factors may contribute to this discrepancy. Firstly, the flatter coastal and inland terrain of the U.S. may render it more susceptible to TC tornado genesis compared to China. Additionally, differences in environmental conditions and TC features could play an important role. Further investigation is needed to fully understand the impact of these factors on TC tornado frequency in both countries.

Differences in non-TC tornadoes and their environmental features between the U.S. and China have been examined by Zhou et al. (2022). They found that the yearly occurrence of non-TC tornado in China is only 5−10% of that in the U.S. This huge difference mainly stems from the much lower likelihood of multiple tornadoes occurring within a particular synoptic system during China's tornado season. Zhou et al. (2022) attributed this huge difference to the seasonal mismatch between favorable thermodynamic and dynamic conditions in China. In particular, the tornado incidence area in China features a lower significant tornado parameter (STP) due to the decreased vertical wind shear during its summer tornado season when instability is high enough, contrasting to the higher vertical shear observed in the U.S. tornado incidence area during its spring tornado season when instability is also high. Consistent results were also obtained by Zhang et al. (2023). However, it remains unclear whether these critical environmental differences apply to TC environments considering the proximity of TC seasons between the two countries.

This study aims to reveal the differences in TC tornadoes characteristics and the key tornadic environments that underlie the substantial discrepancy in TC tornado frequency between the U.S. and China from 2007 to 2021. This work utilizes tornado data sets alongside the fifth-generation ECMWF reanalysis (ERA5) data set.

2. Data and Methods

2.1. TC and TC Tornado Database

TC best-track data for the northwest Atlantic were obtained from the HURDAT2 database (Landsea & Franklin, 2013), available online at https://www.nhc.noaa.gov/data/#hurdat. The northwest Pacific TC best-track database was compiled by the China Meteorological Administration (Lu et al., 2021; Ying et al., 2014), available at https://tcdata.typhoon.org.cn.

Each TC's records begin from the onset of tropical depression and extend until the ending of either tropical depression or extratropical cyclone following transition. Tornado information within the contiguous U.S. was derived from NOAA's Storm Prediction Center (SPC) severe weather database, accessible at https://www.spc.noaa.gov/wcm/#data.

In the contiguous region of China, tornado information is mainly obtained from the Peking University Open Research Data Platform (Zhou et al., 2020), as well as from published papers on tornadoes in China, damage surveys conducted by local meteorological agencies, and reports archived through web searches. Quality control of the tornado records in China was performed by reviewing national and regional radar reflectivity mosaic images, available at http://www.weather.com.cn/radar/index2021.shtml, and removing tornado records without convective storm signatures. Following McCaul (1991), a TC tornado is defined when it occurs within 800 km from the center of its parent TC.

2.2. Environmental Parameters

The environmental parameters were calculated using the fifth-generation ECMWF (ERA5) reanalysis data (Hersbach et al., 2023a, 2023b), with a 1-hr interval and a horizontal resolution of $0.25° \times 0.25°$.

Several atmospheric parameters were composited over $20° \times 20°$ ranges centered by the TC center at tornado-producing times. These parameters include mixed-layer convective available potential energy (MLCAPE), entraining-CAPE (E-CAPE) (Sueki & Niino, 2016), 0−1-km storm-relative helicity (SRH1), 0−6-km vertical wind shear (SHR6), significant tornado parameter (STP) and entraining-STP (E-STP).

MLCAPE was calculated by lifting a parcel from a mixed layer within the lowest 100 hPa of the model vertical coordinate. E-CAPE accounted for entrainment effects using a one-dimensional Lagrangian parcel model (Romps & Kuang, 2010), assuming a parcel ascent rate of 1 m s^{-1} (Molinari et al., 2012) and a constant mass entrainment rate of 40% km^{-1}, following Bai et al. (2022).

For SRH1 calculation, storm motion was estimated using the method outlined by Bunkers et al. (2000). STP was computed following Thompson et al. (2003), utilizing a mixed-layer method within the lowest 100 hPa. E-STP was derived similarly to STP, but MLCAPE was replaced by E-CAPE.

Permutation testing, a statistical technique to assess differences between means of two distributions (Efron & Tibshirani, 1993), was employed for the environmental parameters. A significance level of $p = 0.05$ corresponds to the 95% confidence level. Given the unknown statistical distributions of the parameters examined in the present study, permutation testing was preferred over the *t*-test, as it does not necessitate variables to follow a normal distribution, unlike the *t*-test (Mercer et al., 2009).

3. Results

3.1. Features of TC Tornadoes and Their Parent TCs

In the 15-year period from 2007 to 2021, a total of 417 TCs occurred in the northwest Pacific, with 121 making landfall in China. Among these TCs, 59 produced 111 tornadoes in China, with 36 TCs generating only one tornado and 23 TCs generating more than one tornado. In comparison, 263 TCs occurred in the northwest Atlantic, with 59 making landfall in the U.S. Out of these, 62 TCs generated 742 tornadoes in U.S., with 18 TCs producing only one tornado and 44 TCs producing more than one tornado. These results underscore that TCs in the U.S. indeed exhibit a higher efficiency in producing tornadoes compared to those in China.

In China, TC tornadoes are predominantly observed along the coastline (Figure 1a), whereas in the U.S., they occur both along the coastline and far inland (Figure 1b). The spatial distribution of tornadoes relative to their parent TC centers differs apparently between China and the U.S. In China, TC tornadoes mainly occur in the northern half of the TC circulation, with a slight prevalence in the northeast quadrant (Figure 1c). In contrast, in the U.S., TC tornadoes substantially dominate the northeast quadrant (Figure 1d).

A similar diurnal variation in the number of TC tornadoes is observed in both China and the U.S., with a peak occurring at 15:00−18:00 local time (UTC+8) (Figure 2a). Additionally, the peak occurrence of TC tornadoes in China is observed in August, which is 1 month earlier than in the U.S (Figure 2b).

The differences in the location and frequency of TC tornadoes between China and the U.S. may be partly attributed to distinct characteristics in the tracks and locations of tornadic TCs. A majority of tornadic TCs in China exhibit southeast-northwest oriented tracks (Figure 1e), especially in southern China in monsoonal environment with large area of TC circulations over the ocean, while in the U.S., most of tornadic TCs have recurving tracks with large area of TC circulations over land (Figure 1f), which are conducive to tornado genesis (Verbout et al., 2007) possibly due to larger vertical shear resulting from recurving in front of westerly troughs. Consequently, this contributes to the higher frequency of TC tornadoes in the U.S. compared to China.

Furthermore, tornadic TCs in China generally have shorter tracks, with an average total length of 3,160 km and inland length of 259 km, in contrast to the U.S. average total length of 3,642 km and inland length of 1,017 km (Figure 2c). The shorter tracks of TCs in China may limit tornado genesis opportunity. Consequently, tornadic TCs in China predominantly generate tornadoes when their centers are near the coastline (Figure 1g), whereas in the U.S., tornadic TCs produce tornadoes both near the coastline and far inland (Figure 1h). As a result, the average intensity of TCs when producing tornadoes in China is stronger than that in the U.S, with the average minimum sea level pressures of 986 and 993 hPa, respectively (Figure 2d).

China's shorter and less recurving TC tracks may result from dominant subtropical high patterns and terrain. At tornado-producing times, the west Pacific subtropical high extends zonally (Figure 1e), steering TCs (averaging 24.6°N) via easterlies south of the high and limiting northward recurvature. Mountainous terrain in coastal China and Vietnam causes rapid dissipation. In contrast, U.S. TCs form farther north (31.4°N), west of a northeast-oriented Bermuda High and east of an adjacent westerly trough (Figure 1f), fostering pronounced northeast recurvature and sustained movement over the flatter terrain.

3.2. Comparison of Key Environmental Parameters of Tornadic TCs Between China and the U.S

Environmental parameters from the composite fields over the 5° × 5° area around the TC center are examined to explain the distinct tornado-generating efficiency of tornadic TC between China and the U.S. The composite distribution of mean sea level pressure shows that while producing tornadoes, composite TCs exhibit similar size

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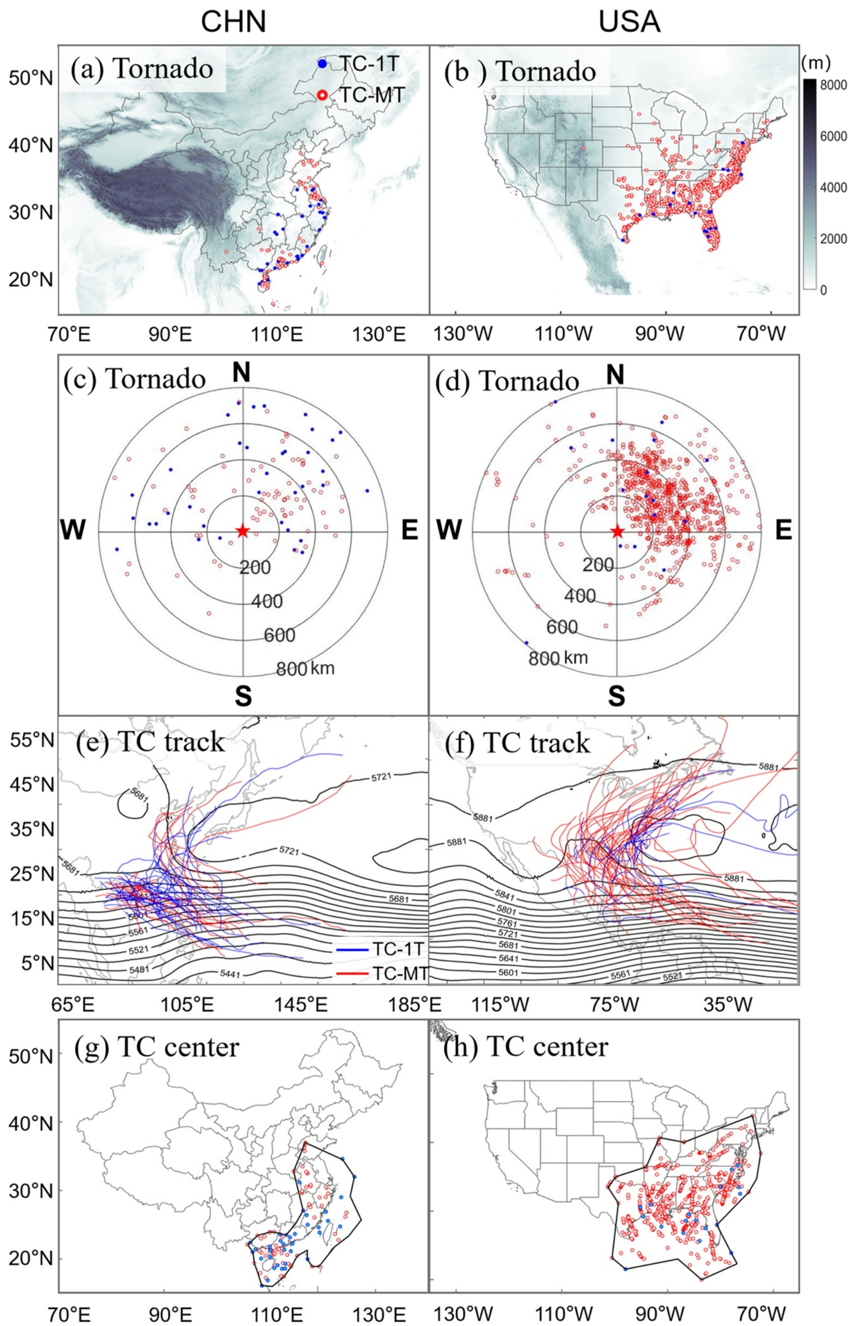

Figure 1. Distributions of TC tornadoes (dots) and terrain heights (shading) in (a) China and (b) the U.S. The locations of TC tornadoes (dots) relative to the center of their parent TC (red star) at the time of each tornado in (c) China and (d) the U.S. from 2007 to 2021 are shown on Earth-relative coordinates. The tornadic TC tracks of (e) China and (f) the U.S. are also displayed, with blue lines denoting tracks of TCs that generated only one tornado, and red lines denoting tracks of TCs that generated more than one tornado. The solid black contours in panels (e, f) denote the composite 500 hPa geopotential height (gpm) at tornado-producing times from 2007 to 2021 using ERA5 data. Panels (g, h) present distributions of TC centers (dots) when producing tornadoes in China and the U.S. Blue dots denote tornadoes generated by TCs that produced only one tornado, while red dots denote tornadoes generated by TCs that produced more than one tornado.

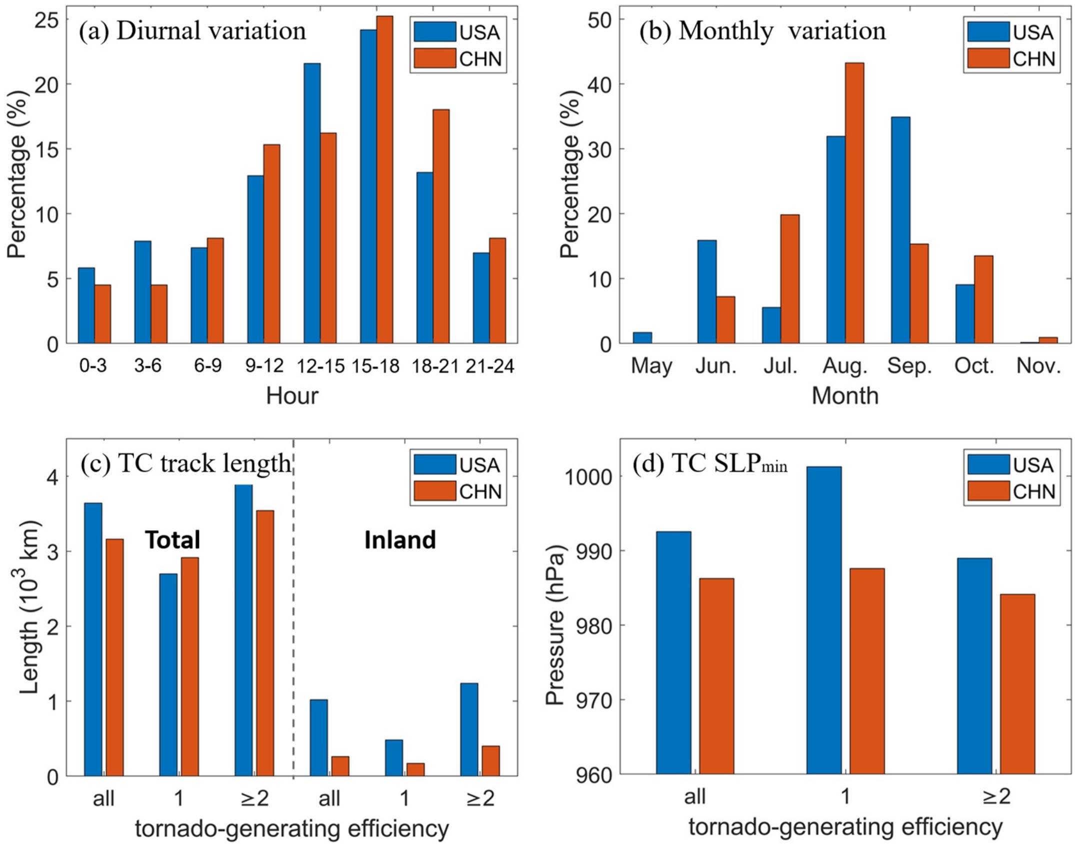

Figure 2. Variations of TC tornado occurrences in China and the U.S. from 2007 to 2021, depicted in panel (a) daily and (b) monthly frequency distributions. Also shown are (c) the average total track length (left) and inland track length (right), as well as (d) average minimum sea level pressure near the eyes of all tornadic TCs, for tornadic TCs collectively, those producing one tornado, and those producing more than one tornado in both China and the U.S. over the specific period.

between the two countries. However, they display apparently greater intensity in China (Figures 3a and 3b), aligning with the findings depicted in Figure 2d.

Tornadic TCs in the U.S. exhibit a more favorable thermodynamic environment than those in China. In the U.S., a region of substantial MLCAPE, peaking at 1,053 J kg^{-1}, is present in the southeast quadrant of tornadic TCs (Figure 3b). Conversely, MLCAPE in China peaks lower at 1,040 J kg^{-1} (Figure 3a). The distribution of E-CAPE, which strongly correlates with TC tornado occurrence, also shows a larger peak in the U.S. (71 J kg^{-1}) than China (67 J kg^{-1}), but with a different location. In the U.S., the primary high E-CAPE center is located in the northeast quadrant of TCs (Figure 3d), while in China, it is situated in the southwest quadrant (Figure 3c). Additionally, a secondary center of E-CAPE is observed in the northeast quadrant of TCs in China, albeit with a much smaller magnitude.

Regarding the dynamic condition, tornadic TCs in China offer a more conducive environment for tornado formation compared to those in the U.S. In China, SRH1 peaks exceeding 180 m^2s^{-2} are predominantly in the northern half of the TC circulation (Figure 3g), while SRH1 in the U.S. reaches a lower maximum value of 148 m^2s^{-2}, primarily in the northeast quadrant (Figure 3h). However, both countries show maximum values of SHR6 in the northeast quadrant (Figures 3e and 3f) with the maximum value in the U.S. (14.7 m s^{-1}) slightly larger than that in China (13.6 m s^{-1}), suggesting a larger potential for supercell genesis in U.S. TC environments.

Composite environments for TC tornado genesis favor the U.S. over China. In the U.S., the most favorable thermodynamic and kinematic conditions overlap in the northeast quadrant, while in China, the most favorable thermodynamic conditions occur in the southwest quadrant with the most favorable dynamic conditions in the northwest quadrant. This disparity leads to significant differences in composite parameter distribution. In the U. S., E-STP peaks in the northeast quadrant, whereas in China, it peaks in both northeast and southwest quadrants

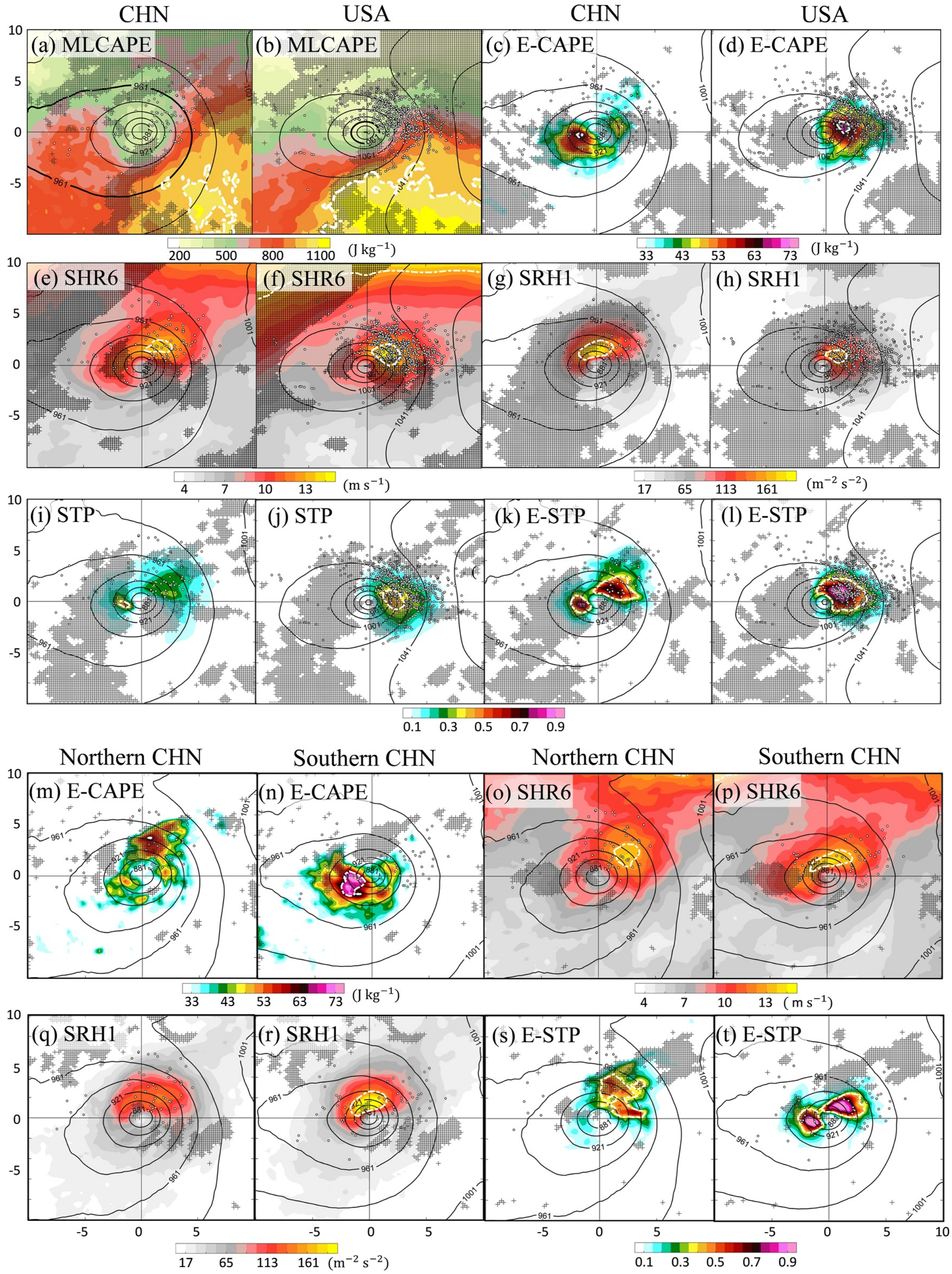

Figure 3. Horizontal distribution of (a, b) MLCAPE (J kg^{-1}), (c, d) E-CAPE (J kg^{-1}), (e, f) SHR6 (m s^{-1}), (g, h) SRH1 (m^2 s^{-2}), (i, j) STP, and (k, l) E-STP of all the tornadic TCs in China (denoted by CHN) and the U.S. (denoted by USA) from 2007 to 2021. The black contour denotes the composite mean sea level pressure, with 961 hPa highlighted in bold. The white lines represent contours with value of 1,025 J kg^{-1}, 65.5 J kg^{-1}, 13 m s^{-1}, 149 m^2 s^{-2}, 0.4, and 0.4 for MLCAPE, E-CAPE, SHR6, SRH1, STP, and E-STP, respectively. The differences in parameters between the U.S. and China are statistically significant at the 95% confidence level over the area shaded with a "plus" symbol. (m–t) are as (c–h, k, l) for northern TCs and Southern TCs in China from 2007 to 2021. The white lines represent contours with value of 65.5 J kg^{-1}, 10 m s^{-1}, 101 m^2 s^{-2}, and 0.4 for E-CAPE, SHR6, SRH1, and E-STP respectively.

but with smaller magnitude and coverage. The maximum E-STP values are 0.9 and 1.0 in China and the U.S (Figures 3k and 3l), respectively. The area covered by STP and E-STP values exceeding 0.4 is notably smaller in China than in the U.S (Figures 3i–3l). Consequently, tornadic TCs in China offer a less conducive environment for tornado formation compared to those in the U.S., which is the key environmental reason for the lower tornado-generating efficiency of tornadic TCs in China. In addition, Figures 3i–3l also show that E-STP covers more tornadoes than STP with high value, and thus is more useful for tornado forecasting.

3.3. Reasons for the Mismatch of Environments of Tornadic TCs in China

To find out the reason for the mismatch between thermodynamically and dynamically favorable conditions of tornadic TCs in China, the composite parameters of tornadic TCs in China are divided into two parts: southern TCs and northern TCs, considering the average latitude of TC centers when producing tornadoes in China is apparently south of those in the U.S. Those TCs that produce tornadoes while centered south of 25°N were classified as southern TCs (Total 37 southern TCs producing 62 tornadoes); otherwise, they were classified as northern TCs (Total 24 northern TCs producing 49 tornadoes).

The mismatch between thermodynamically and dynamically favorable conditions of tornadic TCs in China are primarily from southern TCs. The most favorable thermodynamic conditions are distributed in the southwest quadrant of southern TCs (Figure 3n), while the most favorable dynamic conditions are in the north of TC centers (Figures 3p and 3r). However, both thermodynamically and dynamically favorable conditions of northern TCs are located in the northeast quadrant (Figures 3m–3o and 3q).

In order to understand why the maximum value of E-CAPE is located in the southwest quadrant in southern TCs while the maximum value of E-CAPE is located in the northeast quadrant in northern TCs, we compared the distribution of MLCAPE and relative humidity for the southern and northern TCs of China (Figure 4), considering that the magnitude of E-CAPE is mainly determined by the basic magnitude of MLCAPE and relative humidity which mainly determines the amount of entrainment. The results show that in northern TCs, the MLCAPE is higher in the northeast than southeast quadrant (Figures 4a and 4b), whereas the relative humidity (column average RH from 1,000 to 100 hPa) is much higher in the northeast quadrant than in the southeast quadrant likely due to rich moisture supply from the ocean, which may have resulted in the higher E-CAPE in the northeast quadrant. However, in the southern TCs, the relative humidity in the southeast quadrant is quite close to that in the northeast (Figures 4e and 4f), while the MLCAPE in the southwest quadrant is much higher than that in the northeast quadrant likely due to a warmer near surface temperature, which may have led to the larger E-CAPE in the southeast quadrant. Considering the similar moisture in terms of either mixing ratio at 925 hPa or the column precipitable water (Figure 4c vs. Figure 4d, Figure 4g vs. Figure 4h), the differences of the MLCAPE between the northeast and southwest quadrants for the southern and northern TCs are possibly due to the different lapse rate between 1,000 and 700 hPa.

Overall, the primary environmental driver for the substantial difference in the formation efficiency of TC-spawned tornadoes is possibly a large overlapping extent between the maximum values of E-CAPE and SRH1. The maximum E-CAPE and SRH1 in the U.S. not only overlap but also are quite large in magnitude. Even though the northern TCs in China are similar to TCs in the U.S. in the better overlapping between E-CAPE and SRH1 in the northeast quadrant, the magnitudes of SRH1 and E-CAPE are much smaller than TCs in the U.S. Similar to the northeast quadrant of northern TCs in China, the U.S. TCs have the largest maximum E-CAPE in the northeast quadrant due to a larger relative humidity (Figures 4i–4l) likely owning to rich moisture supply form the ocean. However, SRH1 and E-CAPE are both dominated by Southern TC in China (Figures 3m, 3n, 3q, and 3r). Although the southern TCs in China have larger maximum SRH1 and E-CAPE than TCs in the U.S., they, however, are generally mismatched. Consequently, both northern and southern TCs in China have smaller E-STP values relative to those in the U.S (Figures 3l–3s and 3t), and thus a lower formation efficiency of TC-spawned tornadoes.

4. Summary and Discussion

This study compared the features of TC tornadoes as well as their parent TCs between China and the U.S. Key tornadic environments of TCs between the two countries were also examined using the ERA5 reanalysis data from 2007 to 2021.

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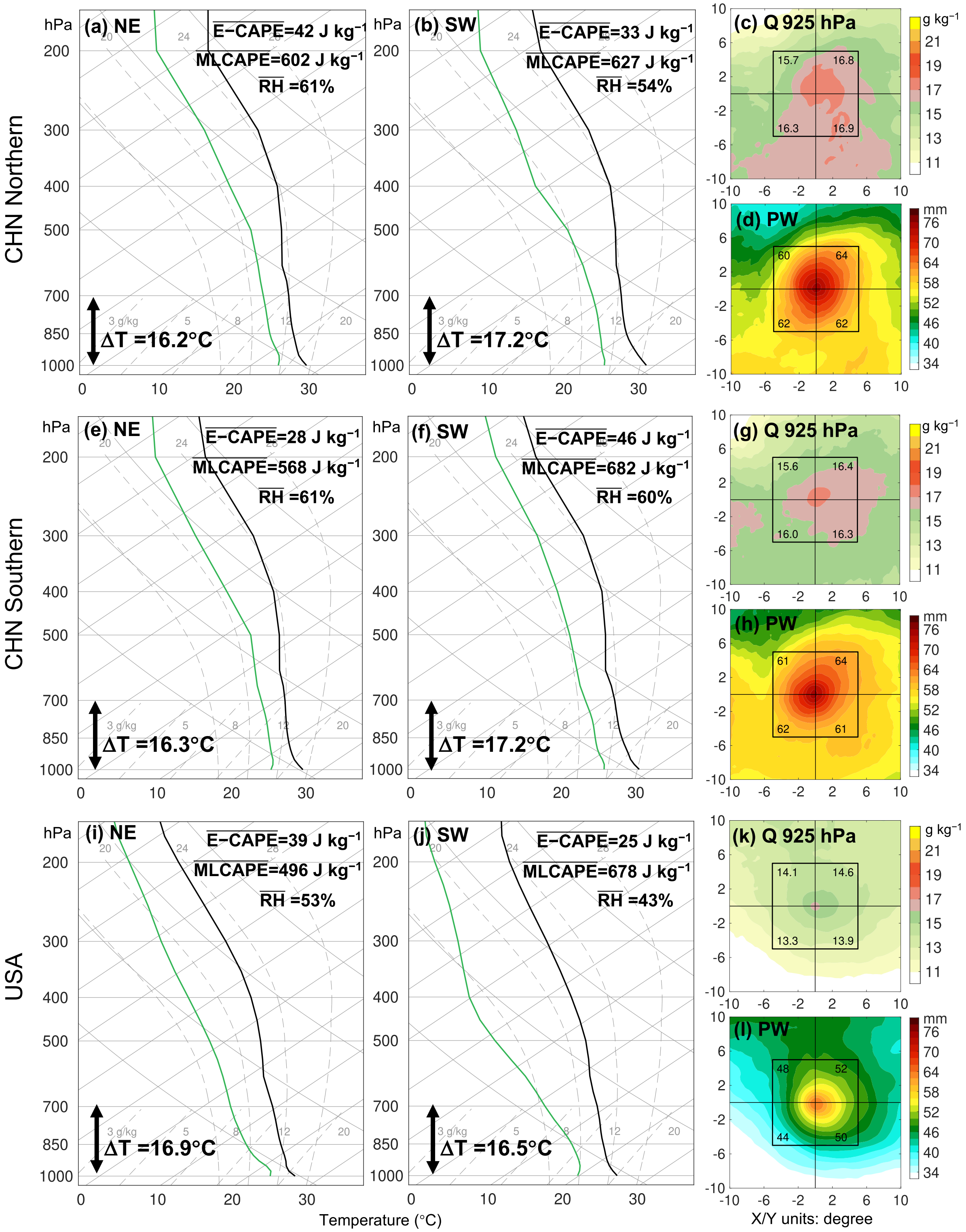

Figure 4. Vertical profiles of temperature (°C) and dew point (°C) averaged over the 5° × 5° area around the TC center in the (a) northeast (NE) and (b) southwest (SW) quadrants of the northern TCs in China. The corresponding temperature differences between 1,000 and 700 hPa are given in the lower left corner. Also given are the corresponding E-CAPE, MLCAPE and column average RH from 1,000 to 100 hPa in the upper-right corner. The horizontal distribution of water vapor mixing ratio (g kg^{-1}) at 925 hPa and column precipitable water (mm) are given in panels (c, d) with the average for the four quadrants over the 5° × 5° area around the TC centers given for references. (e–h) are as (a–d) but for the southern TCs in China. (i–l) are as (a–d) but for TCs in the U.S.

Results show that TCs in the U.S. have much higher tornado generating efficiency than in China. From 2007 to 2021, 59 TCs in northwest Pacific produced 111 tornadoes in China, while 62 TCs in northwest Atlantic produced 742 tornadoes in the U.S. One reason for this large disparity is the shorter track lengths, less recurving tracks, and located more south of tornadic TCs in China when producing tornadoes, which provide less baroclinic environment and less opportunity for tornadogenesis, in comparison to tornadic TCs in the U.S. The differences in the TC tracks are possibly due to their different locations relative to subtropical highs and westerly troughs as well as different terrain roughness.

On the other hand, tornadic environments of TCs in China were found less conducive than those in the U.S. The results showed that the regions with the most beneficial thermodynamic and dynamic conditions overlap in the northeast quadrant of parent TCs in the U.S., while the two beneficial regions situated in two different quadrants of TCs in China. As a result, tornadic TCs in the U.S. have higher composite parameters, including STP and E-STP, suggesting environments more conducive to the formation and development of tornadoes. The mismatch between thermodynamically and dynamically beneficial conditions of tornadic TCs in China are mainly due to the TCs in southern China, in which the maximum E-CAPE was observed in the southwest quadrant due to a larger lapse rate with a similar relative humidity relative to the northeast quadrant where dynamic condition is more favorable. The substantial difference in the formation efficiency of TC-spawned tornadoes between China and the U.S. is more related to the overlapping extent between the maximum values of E-CAPE and SRH1 relative to pure thermal or dynamic factors.

In addition to differences in the magnitude of E-STP, China may have much smaller flat high-E-STP area. In the U.S., widespread flat terrain and more northerly recurving TCs expose inland areas in the northeast quadrant to tornado-favorable conditions. In China, flat areas are much less, tornadic TC tracks tend to be near the coast, keeping the northeast quadrant mostly oceanic, and the southeast quadrant of southern TC mostly over the ocean, further limiting tornado potential.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The ERA5 data are available at Hersbach et al. (2023a, 2023b). Tropical cyclone best-track data are available at https://www.nhc.noaa.gov/data/#hurdat and https://tcdata.typhoon.org.cn. U.S. tornado information are available at https://www.spc.noaa.gov/wcm/#data and China tornado information is available at Zhou et al. (2020).

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