1. Introduction

Under the joint influence of warm water and a summertime monsoon trough, the western North Pacific (WNP) is the most active ocean basin in the world for tropical cyclones (TCs). The landfall of TCs brings about a series of natural disasters, causing significant damage and loss of life along coastal areas. The destructiveness and socioeconomic impact of TCs are not only related to the scale of maximum wind speed but also to the outward extension of the tangential wind field, which is generally characterized by the TC outer size (Powell and Reinhold 2007; Irish et al. 2008; Matyas 2010; Zhai and Jiang 2014; Paredes et al. 2021). In operational monitoring and early warnings, the radius of gale-force winds is the most used practical measure of outer size based on the available data (e.g., Sampson et al. 2017; Knaff et al. 2021). In operational monitoring and early warnings, the radius of gale-force winds is the most used practical measure of outer size based on the available data (e.g., Sampson et al. 2017; Knaff et al. 2021).

TC outer size (hereinafter referred to as size for convenience) varies significantly with ocean basin, season, and year (Brand 1972; Merrill 1984; Cocks and Gray 2002; Kimball and Mulekar 2004). Globally, WNP TCs have the largest average size and widest size distribution, while TCs over the eastern North Pacific are the smallest (e.g., Chavas and Emanuel 2010; Knaff et al. 2014; Chan and Chan 2015). Within the WNP basin, TCs in the South China Sea tend to be relatively small, while large TCs are more likely to occur east of Taiwan and the Philippines (e.g., Yuan et al. 2007; Chan and Chan 2018). Therefore, as an initial step, this study investigates the distribution and variation characteristics of TC size over the WNP region on the decadal time scale.

Further investigation revealed that over the W-NWP, the genesis position of LTC_{EC} migrated equatorward during the second epoch, leading to a longer TC lifetime before landfall. Also, the increase of background relative vorticity and moisture associated with the southward migration is conducive to larger initial vortices. For TCs originating from the E-WNP, the change in the active area of TC passages reduced the frequency of TCs affecting the Chinese coast. Moreover, the growth of TC size during the intensification stage was significantly suppressed, lowering the occurrence probability of extremely large TCs. Changes in the large-scale thermodynamic environments between the two epochs were explored. Increased static stability and decreased convective available potential energy are possible factors limiting TC size increase.

KEYWORDS: North Pacific Ocean; Tropical cyclones; Decadal variability; Climate change
There are prominent interannual and decadal variations in the genesis frequency, intensity, and active regions of TCs over the WNP. On the decadal time scale, with the climate regime shift associated with the phase reversal of the PDO around the year 1998 and the La Niña–like warming pattern in the northwestern Pacific Ocean, the characteristics of TC activity have undergone differential changes over the eastern and western parts of the WNP (Park et al. 2014; Hsu et al. 2014; Choi et al. 2015; Wang et al. 2015; J. Zhao et al. 2018). In the southeast quadrant, there was a low-level anticyclonic anomaly and the corresponding increase in vertical wind shear, which significantly reduced the annual genesis number over this region and decreased the frequency of TC occurrence south of 20°N (e.g., Liu and Chan 2013; Hsu et al. 2014; He et al. 2015; J. Zhao et al. 2018). In the northwest quadrant, the increase of SST, the deepening of warm surface water, and the increase of relative humidity not only favored TC genesis but also increased the occurrence frequency of rapid intensification and intense storms (e.g., Choi et al. 2015; Wang et al. 2015; Wu et al. 2018; H. Zhao et al. 2018). Correspondingly, the location of TC lifetime maximum intensity migrated northward and closer to the coastal area (e.g., Park et al. 2014; Wang and Toumi 2021; Zhao et al. 2022). In terms of TC movement, there was an abrupt reduction in TC passages over the South China Sea, while the dominant TC track that travels northwest to affect the coastal areas of East Asia was enhanced. This is primarily due to a cyclonic anomaly in the large-scale steering flow centered over the southeastern China, which is characterized by the westerly anomaly over the South China Sea and the southerly anomaly east of Taiwan and the Philippines (e.g., Wu et al. 2005; Tu et al. 2009; He et al. 2015; Shan and Yu 2021; Guo and Tan 2022).

Due to the influence of the climate regime shift and possibly the long-term warming trend, TC activities pose an increasing threat to the coast of East Asia (Park et al. 2014; Mei and Xie 2016; Wang and Toumi 2021; Basconcello and Moon 2022). Changes in TC intensity and precipitation along the coastal regions of East Asia are receiving increasing attention (e.g., Park et al. 2011; Choi and Kim 2019; Li et al. 2017; Liu and Wang 2020; Liu et al. 2020; Gao et al. 2021). Li et al. (2017) and Liu et al. (2020) investigated TCs making landfall over China in recent decades and found that the frequency and intensity of landfalling TCs over East China have increased, making the destructive potential of landfalling TCs increase. Liu and Wang (2020) found that from 1980 to 2017, the precipitation brought by landfalling TCs increased in East China and decreased over South China. With TCs passing offshore included in the analyses, Gao et al. (2021) demonstrated that the upward trend of TC precipitation is an overall feature along the southcoast of China during the past four decades. Meanwhile, various characteristics of TCs affecting the Korean Peninsula and Japan showed similar changes to the landfalling TCs over East China (Park et al. 2011; Choi and Kim 2019).

In the context of significant changes in climate conditions and characteristics of TC activity during the recent decades, the following questions naturally arise: How did the distribution of TC size change over the WNP basin, especially in the coastal regions of East Asia? What are the main physical factors and processes contributing to the TC size changes? Investigation of these two issues is of great importance for deepening the understanding of the variations in landfalling TCs and disaster response and risk management. In this study, we examine the epochal changes in the outer size of landfalling TCs affecting the Chinese coast from 1977 to 2020 and attempt to understand the possible causes of the variations in TC size distribution. We divided the analysis period into two epochs: 1977–98 (E1) and 1999–2020 (E2). Section 2 describes the data and methods used in the study. Section 3 investigates the changes in the size distribution of landfalling TCs over East China and South China and explores the underlying factors and physical processes that may affect TC size. Finally, the results of this work are summarized in section 4. The linkage between TC size change and long-term climate variability and the implications for TC size in a warmer climate are also discussed.

2. Data and methods

a. Data

The primary TC data analyzed in this study were from the best-track data compiled by the Regional Specialized Meteorological Center Tokyo–Typhoon Center of the Japan Meteorological Agency (JMA) and extracted from the International Best Track Archive for Climate Stewardship dataset version 4 (Knapp et al. 2010, 2018), including the 3-hourly TC center positions, the maximum sustained wind speed, the longest and shortest rain radii (R30). The arithmetic mean of R30 along the major and minor axis was used to represent TC size. In addition, the monthly mean atmospheric data from the fifth-generation European Centre for Medium-Range Weather Forecasts reanalysis (ERA5; Hersbach et al. 2020), which has a refined horizontal resolution of 0.25° × 0.25°, were used to examine the large-scale environmental fields and their variations. The monthly mean SST data were also obtained from the ERA5 dataset.

The JMA makes full use of all available observations in the analysis of R30, such as surface synoptic network, ship, buoy, scatterometers (QuikSCAT and ASCAT before and after 2007), and more recently, the low-level atmospheric motion vectors derived from Himawari-8/9 satellite images (e.g., Muroi 2018; Takeuchi 2018). Consistencies across datasets and between adjacent times are also considered. Before the advent of satellite scatterometers in 1999, the determination of R30 could only rely on surface in situ observations and weather map analyses, which may introduce subjectivity and uncertainty due to the sparseness of oceanic surface wind measurements, especially over the eastern part of the WNP (Landsea and Franklin 2013; Knaff et al. 2021). However, given the much more stable evolution of TC size relative to TC intensity (e.g., Kilroy et al. 2016; Schenkel et al. 2018), the good density of meteorological observations...
stations along the coast of East Asia and on islands offshore can continuously collect information on surface wind fields during TC passages and thus provide a reliable basis for utilizing the JMA wind radii in the study of landfalling TCs over these regions (e.g., Takagi and Wu 2016).

Considering the uncertainties in the estimation of TC wind structure (e.g., Song and Klotzbach 2016; H.-J. Kim et al. 2022), the 34-kt wind radii (R34) data compiled by the Joint Typhoon Warning Center (JTWC) and Shanghai Typhoon Institute of China Meteorological Administration (STI/CMA) were used to confirm the robustness and reliability of the results. Time series analysis was also carried out to check the inhomogeneity issues associated with the evolution of observing platforms (Fig. S1 in the online supplemental material). The results suggest that over the western part of the WNP, there is no spurious trend and structural breaks in the time series of the annual medians of TC size. In contrast, for TCs originating from the eastern part of the WNP, there might be an abrupt change point associated with the use of satellite scatterometers. Nevertheless, we cannot rule out the possibility that such abrupt change was due to natural interdecadal variability since the change point is very close to the time of the PDO phase change. The results of this study can be revisited when more reliable datasets of TC size are available in the future.

b. Method

This study focuses on the TCs formed over the WNP and making landfall over Chinese mainland, excluding Taiwan and Hainan Island, from June to October 1977–2020. Here, a landfalling TC refers to the TC that passes through the coastline at least once during its lifetime. For TCs making multiple landfalls, only the first landfall was considered. The timing and location of TC landfall were derived from the TC best-track data provided by STI/CMA, which has higher accuracy and completeness due to the coverage of the meteorological station network and the use of multiple types of observation data sources (Ying et al. 2014). In subsequent analyses, we only included the TC cases with their best-track age at landfall greater than 1 day and less than 14 days. Here, best-track age is defined as the time since the genesis of a TC (first reaching tropical storm intensity). TCs with an age of less than 1 day have little change in size, while TCs with an age of longer than 14 days are rare (only two cases) and not representative due to their complex tracks. Including these TC cases in the analyses does not affect the statistics and conclusions of this study.

Before a TC makes landfall, the strong winds and heavy precipitation in its outer-core region already have a severe impact on the coastal area. Therefore, the size of a landfalling TC analyzed in this paper is defined as the average R30 value during the 24 h before landfall. For the convenience of calculation, the endpoints of this 24-h period are rounded back to the nearest 3 h according to the actual landfalling time. Considering the uncertainty of intensity estimation among different agencies and the representativeness of TC size during landfall, only TC cases with at least seven valid R30 records in the JMA best-track data within the 24 h before landfall were retained (a total of 214 cases).

Figures 1a and 1b show the landfall locations and the monthly frequency distribution for all the TC cases. According to the landfall latitude, these TCs were divided into two groups, landfalling TCs over East China and South China, denoted by LTC\textsubscript{EC} and LTC\textsubscript{SC}, respectively. Here we follow the 23.5°N dividing latitude of Sparks and Toumi (2021), which makes the two groups with similar numbers of cases. Moreover, the Pearson correlation coefficient of the annual number of TC landfalls between the two groups reaches a minimum. Similar latitudes have been used as the boundary between East China and South China in other studies (e.g., Li et al. 2017; Liu and Wang 2020; S.-H. Kim et al. 2022).

c. Statistical significance testing

Four types of statistical significance testing are utilized in this study. First, given the nonnormal distribution of TC data (e.g., intensity, lifetime, and size), we conduct the comparison of median values and standard deviations using the nonparametric Wilcoxon rank-sum test and Levene test, respectively. Second, the chi-square test is used to statistically compare changes in percentages. Third, the similarities between two distributions of TC characteristics are evaluated using two-sample Kolmogorov–Smirnov testing. Finally, the statistical differences in mean values of meteorological variables and TC passage frequencies are determined by the two-sample Student’s t test.

3. Results

a. Spatiotemporal variations

The size distribution of the landfalling TCs is positively skewed (Fig. 1c), with a median of 326.4 km and a standard deviation of 139.0 km. The landfalling size was mainly concentrated in the 200–500-km range, accounting for 74.8% of all cases. TCs with landfalling sizes larger than 500 km accounted for about 10% and are referred to as extremely large landfalling TCs in the following.

An interesting feature is that these extremely large landfalling TCs clustered in the two periods of 1990–97 and 2011–19 (Fig. 2), resulting in larger mean sizes than adjacent periods. In the time series of the annual mean size, there is an upward trend from 1977 to 1997 (at the 95% confidence level using a Mann–Kendall trend test and the Sen’s slope is 6.3 km yr\textsuperscript{−1}). This increasing trend is primarily related to the occurrence of very large landfalling TCs in the 1990s, e.g., Polly (1992), Herb (1996), and Winnie (1997). No noticeable long-term change can be identified from the year 1998. Based on the above characteristics, the analysis period is divided into two epochs of equal length: 1977–98 (E1) and 1999–2020 (E2). The results of the subsequent analyses are not particularly sensitive to the division year (figure not shown).

Figure 3 displays the size distribution of LTC\textsubscript{SC} and LTC\textsubscript{EC} during the E1 and E2 periods. The size of LTC\textsubscript{SC} is mainly concentrated in the range of 100–400 km, with a median value of around 300 km. There were no significant differences in the
number of landfalling TCs and the size distribution over South China between the two epochs (Figs. 3a,b). The proportion changes in each size interval did not exceed 5% (Fig. 3c). Compared with LTCSC, the median size of LTCEC is larger. The difference in the median size is statistically significant using a Wilcoxon rank-sum test at the 95% confidence interval during E1 and the 99% confidence interval during E2 (Table 1). The number and size distribution of LTCEC changed remarkably. Compared with the former epoch, the number of LTCEC in E2 increased by more than a quarter (Figs. 3d,e). The peak of the size distribution of LTCEC fell between 200 and 300 km during E1 and shifted to 400–500 km during E2. At the same time, the proportion of extremely large landfalling TCs decreased from 17.8% to 8.8%. The proportion of TCs with landfalling size below 300 km also decreased from 37.8% to 28.1% (Fig. 3f). These changes led to a notable increase in the median and a statistically significant decrease in the variance of the size distribution of LTCEC (using a Levene variance test at the 99% confidence interval, see Table 1).

From the above results, we found that during the E2 period: 1) the size distribution of LTCEC was narrower; 2) the difference in the median sizes between LTCSC and LTCEC became more significant than the E1 counterpart. To examine the robustness of these two phenomena, the corresponding results using size estimates from STI/CMA and JTWC are given in Table 1 for comparison. The R34 data released by

![Fig. 1](image_url)
STI/CMA is based on the correlation between TC size and the radial profile of infrared brightness temperature and covers the period from 1981 to 2016 (Lu et al. 2017). The STI/CMA size dataset also shows that the difference between the landfalling sizes over East China and South China increases and becomes more significant; the size variance over East China decreased significantly during the E2 period. However, the standard deviation of size distribution in the STI/CMA dataset is much smaller than the JMA R30, which might be related to the different data and algorithms for size estimation. Next, the R34 data from the JTWC best-track dataset were used for further comparison. The R34 data released by JTWC covers the period from 2001 to 2020, which is close to the E2 period in this study. It can be seen from Table 1 that both the difference in the median sizes between LTCSC and LTCEC and the size variance of LTCEC in the JTWC dataset are closer to the results with the JMA dataset, although in general, the R34 value of JTWC is slightly smaller (Song and Klotzbach 2016; H.-J. Kim et al. 2022).

The outer size of a TC is related to its initial vortex size at the time of genesis and the duration of the subsequent intensification phase over the sea surface (e.g., Cocks and Gray 2002; Lee et al. 2010; Chan and Chan 2012). For landfalling TCs, the genesis location cannot only determine the upper limit of TC development time through the length of the track but also affects the initial vortex size of TC due to the different environmental characteristics. Hence, the genesis location may profoundly impact the size of landfalling TCs. The geographical distribution of TC genesis density over the WNP and the genesis positions of the landfalling TCs are shown in Fig. 4. During the E1 period, three high-value centers can be identified in the distribution of TC genesis density over the WNP, located over the South China Sea, between 120° and 140°E, and to the east of 140°E, respectively. These centers largely remained in place during the E2 period, with no apparent change in the center over the South China Sea. Instead, the center between 120° and 140°E shifted eastward and extended southeastward, and the center to the east of 140°E moved northward. The genesis positions of LTCSC were consistently concentrated in the band extending southeastward from the South China Sea to about 145°E during both the E1 and E2 periods (Figs. 4a,b). Therefore, the genesis location of LTCSC was not sensitive to the change in the overall distribution of TC genesis over the WNP, which may be related to the characteristic westward-moving track of LTCSC (see Fig. 1a). For LTCEC, the genesis positions closely followed the three centers of TC genesis over WNP, but their latitudinal distribution was relatively scattered (Figs. 4c,d). Compared with E1, the mean genesis location of LTCEC between 120° and 140°E migrated southeastward during the E2 period. There was no significant change in the genesis location of LTCEC in the vicinity of the remaining two centers of TC genesis density over the WNP.

To diagnose the link between the change of genesis location and the size change of LTCSC, the entire WNP basin was divided into three subregions according to the three centers of TC genesis frequency: the South China Sea area (west of 120°E), the western portion of WNP (W-WNP, 120°–140°E), and the eastern portion of WNP (E-WNP, east of 140°E). Table 2 groups LTCSC according to their genesis subregions and different ranges of landfalling size. It can be revealed that only a few cases of LTCSC were from the South China Sea, which accounts for less than 10%. About 60% of LTCSC formed over the W-WNP, and the landfalling size is most frequently distributed within the 300–500-km range. For LTCSC,
originating from the W-WNP, the proportion of TCs with landfalling sizes less than 300 km decreased during E2, and that of landfalling TCs between 300 and 500 km increased significantly. The proportion of extremely large landfalling TCs (with sizes larger than 500 km) did not change significantly. For LTC$_{EC}$ originating from the E-WNP, the extremely large TCs decreased considerably during the E2 period, while the proportion of other size ranges did not change much.

Based on the above results, it can be concluded that two aspects caused the narrower size distribution of LTCEC during E2: 1) the landfalling size of LTC$_{EC}$ formed over the W-WNP shifted to a larger size between 300 and 500 km; and 2) the significant reduction of the extremely large landfalling TCs formed over the E-WNP. The former is also responsible for the more significant difference in the median sizes between LTC$_{EC}$ and LTC$_{SC}$ in the absence of notable changes in the size distribution of LTC$_{SC}$ during E2. In addition, the changes

Table 1. Standard deviation of the size of landfalling TCs over East China and the difference in the median size between East China and South China in two epochs divided at 1998/99 derived from different sources of size estimation. The nonparametric Levene test and the Wilcoxon rank-sum test are used for detecting significant changes in the variance between the two epochs and the difference in the median between East China and South China groups. The corresponding $p$ values for each statistical test are shown in parentheses.

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</tr>
</thead>
<tbody>
<tr>
<td>EC standard deviation (km)</td>
<td>187.2 ($p &lt; 0.01$)</td>
<td>104.6</td>
<td>50.8 ($p &lt; 0.1$)</td>
<td>34.9 ($p &lt; 0.1$)</td>
<td>73.1 ($p &lt; 0.1$)</td>
</tr>
<tr>
<td>EC minus SC median difference (km)</td>
<td>40.0 ($p &lt; 0.05$)</td>
<td>74.0 ($p &lt; 0.01$)</td>
<td>13.1 ($p &gt; 0.1$)</td>
<td>33.1 ($p &lt; 0.1$)</td>
<td>62.7 ($p &lt; 0.05$)</td>
</tr>
</tbody>
</table>
in the size of LTC\textsubscript{EC} generated over the W-WNP in the later epoch may be related to the systematic change in the genesis location. Still, this connection is not apparent for LTC\textsubscript{EC} formed over the E-WNP. Therefore, LTC\textsubscript{EC} originating from the W-WNP and E-WNP will be analyzed separately to explore the possible mechanisms leading to the size change of landfalling TCs.

b. Possible explanations

1) W-WNP

The box-and-whisker plots in Fig. 5 compare the genesis latitude, TC age at landfall, and TC age at the lifetime maximum intensity of LTC\textsubscript{EC} during the E1 and E2 periods. For LTC\textsubscript{EC} formed over the W-WNP, the median of genesis latitude shifted 3.15° latitude southward in E2, passing the Wilcoxon rank-sum test at the 95% confidence level (Fig. 5a). The overall southward shift of the genesis location increased the total distance traveled by TCs before making landfall over East China, resulting in a 0.87-day increase in the median TC age at landfall (Fig. 5c). Past studies have pointed out that over the WNP, the TC-favorable environment was displaced northward and toward the coastal area in the recent decades (e.g., Park et al. 2014; Liu and Chan 2022; Zhao et al. 2022). It is clear from Fig. 5e that the median intensification duration of LTC\textsubscript{EC} originating from the W-WNP has increased by 1.13 days (passing the Wilcoxon rank-sum test at the 95% confidence level). Numerical simulation studies have found that TCs generally grow in size during the intensification and mature stages under favorable conditions due to the internal convective

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TABLE 2. Percentages of landfalling TCs over East China originating from three subregions of the western North Pacific and in different size ranges. The left and right numbers in parentheses after the subregion name are the counts of landfalling TCs over East China originating from this source during the E1 and E2 periods, respectively. Boldface values indicate that the change in proportion between the two epochs passes the chi-square test at the 90% confidence level.

<table>
<thead>
<tr>
<th>Subregion</th>
<th>R30 ≤ 300 km</th>
<th>300 &lt; R30 ≤ 500 km</th>
<th>R30 &gt; 500 km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E1</td>
<td>E2</td>
<td>E1</td>
</tr>
<tr>
<td>South China Sea (4/4)</td>
<td>4.4%</td>
<td>5.3%</td>
<td>4.4%</td>
</tr>
<tr>
<td>West WNP (25/38)</td>
<td>20.0%</td>
<td>12.3%</td>
<td>26.7%</td>
</tr>
<tr>
<td>East WNP (16/15)</td>
<td>13.3%</td>
<td>10.5%</td>
<td>13.3%</td>
</tr>
</tbody>
</table>
FIG. 5. Box-and-whisker plots of the (a),(b) genesis latitude, (c),(d) TC age at landfall, and (e),(f) TC age at the time of lifetime maximum intensity of landfalling TCs over East China originating from the (left) W-WNP and (right) E-WNP subregions during the E1 and E2 periods. The differences in medians ($\Delta M$) and the corresponding $p$ values (using a Wilcoxon rank-sum test) are indicated in each panel.
activity and the boundary layer processes (Smith et al. 2009; Fudeyasu and Wang 2011; Kilroy et al. 2016). Therefore, the increase in TC lifetime, especially the duration of the intensification phase, is conducive to the increase and maintenance of TC size (e.g., Chan and Yip 2003; Chan and Chan 2012), which in turn translated to the size change of LTCEC. Compared with the W-WNP, the differences in the medians of TC age at landfall and TC age at the lifetime maximum intensity of LTCEC formed over the E-WNP were opposite in sign and insignificant (Figs. 5b,d,f).

Changes in the genesis location of TCs could also modify the distribution of initial vortex size. The percentage change in the initial size of LTCEC formed over the W-WNP in different size intervals is given in Fig. 6a. In E2, the percentage of cases with an initial size smaller than 300 km decreased by 15.3%. In comparison, the percentage of cases in the 300–500-km range increased by 20.7%, indicating that the initial size of LTCEC originating from the W-WNP also shifted to larger size values. To diagnose the relationship between the changes in genesis location and size distribution of the initial TC vortex, Fig. 6b shows the percentage of all TCs formed in different latitudes over the W-WNP. Over this region, the frequency of TC genesis reached a maximum in the range of 15°–20°N (the average position of the WNP summer monsoon trough), and its latitudinal distribution (in a 5° latitude interval) is virtually the same over the two epochs (not shown). For LTCEC, the percentage distribution of genesis location with latitude exhibits a systematic southward shift in E2, which is consistent with the results in Fig. 5a. Specifically, the frequency of TC genesis during the E1 period reached a peak value in the range of 20°–25°N, but the peak shifted to the range of 15°–20°N during the E2 period. The southward movement of the mean genesis position of LTCEC forming in the W-WNP is likely to be related to the abrupt northward shift of TC tracks in the recent epoch (e.g., Wu et al. 2005; Tu et al. 2009; He et al. 2015; Shan and Yu 2021), since a change in the predominant TC track east of Taiwan and the Philippines will change the source region of landfalling TCs over East China. Figure 6c demonstrates the proportion changes of LTCEC with an initial vortex size greater than 300 km and less than or equal to 300 km and the dependence with latitude. The results indicate that the increase of TCs with an initial size larger than 300 km mainly occurred south of 20°N, while the decrease of TCs with an initial size less than or equal to 300 km mainly occurred north of 20°N. In other words, the southward movement of the mean genesis position of LTCEC originating from the W-WNP is also related to larger initial storms.

To further understand the relationship between initial vortex size and the variation in the genesis location of TCs over the W-WNP, Fig. 7 shows the average spatial distribution of the outgoing longwave radiation and 850-hPa flow field from July to September, as well as the distribution of the longitudinal-mean 850-hPa relative vorticity and the 700-hPa relative humidity with latitude. Here we used the mean environmental fields over the peak season instead of the entire period of June–October, because nearly 90% of LTCEC occurred during July–September. Climatologically, the summer monsoon trough extends southeast from the South China Sea to the position of (10°N, 147°E), and the WNP subtropical high controls the region north to the monsoon trough. Such a configuration leads to significant variations of the large-scale environmental fields with latitude. Specifically, between 10° and 20°N of the W-WNP, the background relative vorticity reaches a positive maximum, and the water vapor content is abundant. However, in the W-WNP region north of 20°N, both the relative vorticity and relative humidity decreased rapidly with the increase of latitude. Therefore, for the same synoptic-scale pre-TC disturbances, the area controlled by the WNP monsoon trough is more favorable to the development of deep convection and the import of environmental angular momentum, facilitating the formation of TCs with larger initial size (Liu and Chan 2002; Hill and Lackmann 2009; Knaff et al. 2014). Conversely, small-size storms or the so-called “midget typhoons” are more likely to occur in the region north of 20°N over the W-WNP (e.g., Arakawa 1952; Brand 1972).
In summary, the genesis location of LTC$_{EC}$ originating from the W-WNP was displaced toward the equator to a region with higher relative vorticity and water vapor content during the E2 period, which was conducive to the increase of initial vortex size and would likely correspond to larger TCs at landfall.

A binary linear regression model was established using the least squares method to assess the contribution of the variations in initial vortex size and TC age at landfall on the size change of LTC$_{EC}$. To expand the sample size, the training set of the model included all the landfalling TCs generated over the W-WNP (using only the samples of landfalling TCs over East China does not qualitatively change the conclusion). The results show that the correlation coefficient between the size of LTC$_{EC}$ obtained by the linear regression model and the actual value reaches 0.81 (Fig. 8a). Figures 8b and 8c compare the proportion changes of LTC$_{EC}$ derived from the regression model and the actual value in different size intervals. The proportion of LTC$_{EC}$ formed over the W-WNP decreased by 18.8% in the 200–300-km range and increased by 16.8% in the 400–500-km range, while the proportions of the remaining size intervals did not change significantly (Fig. 8b). The linear regression model is able to reproduce such changes, showing the proportion in the 200-300 km range decreasing by 18.8% and the proportion in the 400-500-km range increasing by 14.2% (Fig. 8c). The above results suggest that the changes in

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**Fig. 7.** (a) The spatial distribution of the average outgoing longwave radiation (shaded; unit: W m$^{-2}$) and the flow field at 850 hPa and over the western North Pacific from July to September 1977–2020. The red dashed line indicates the average axis position of the summer monsoon trough. (b),(c) The distribution of the longitudinal-mean (from 120° to 140°E) 850-hPa relative vorticity and 700-hPa relative humidity (solid black line) with latitude. The gray shadings denote the range of ±1 standard deviation.
the initial size and TC age at landfall due to the overall shift in the genesis location dominated the size change of \( \text{LTCEC} \) originating from the W-WNP.

2) E-WNP

From the perspective of conditional probability, the decrease in extremely large \( \text{LTCEC} \) formed over the E-WNP in the E2 period was affected by two factors: 1) the change in the occurrence probability of extremely large TCs originating from the E-WNP subregion and 2) the change in the frequency of landfalling TCs along the southeastern coast of China.

The impact of changes in TC track on the landfalling frequency was investigated first. Due primarily to the influence of seasonal variation of the WNP subtropical high on TC tracks, the landfalling TCs formed over the E-WNP mainly occur in July and August (more than three-quarters of all the cases from June to October). Moreover, we found that all the extremely large landfalling TCs coincidentally occurred in August. Figure 9 shows the spatial distributions of track density for TCs formed over the E-WNP and the epochal changes in July and August, respectively. The TC track density is calculated as the average number of TC occurrences per year in each 2.5\(^\circ\) \times 2.5\(^\circ\) latitude-longitude grid box. To exclude the influence of TC translation speed, each TC is counted only once in a grid box.

Two prevailing TC tracks can be identified from the distribution of track density in July: one mainly affects the sea areas south and southeast of Japan; the other affects the South China Sea region along a westward path during E1 and approaches the southeast coast of China along a northwestern path during E2 (Figs. 9a,c). Overall, the magnitude of TC track density in July was relatively small, and there was no systematic change in the distribution of track density along the coast of China between the two epochs (Fig. 9e). Over the E-WNP subregion, the number of TCs formed in August was significantly higher than that in July. From the distribution of track density during August of the E1 period (Fig. 9b), one can easily identify a band with a high track density value extending from 10°N, 145°E to 25°N, 120°E. This corresponds to a prevailing TC track moving northwestern from the southwest corner of the E-WNP, mainly affecting the eastern coast of China or recurving to affect the Korean Peninsula and Japan. However, this prevailing track shifted northeast during the E2 period, primarily because the genesis location of TCs over the E-WNP subregion shifted systematically to the east, and the heading was more northward. From the difference in the distribution of track density, it appears that compared with the E1 period, TC activity over the coastal regions of East China is significantly reduced, while TC activity along the southern coast of Japan increased significantly (Fig. 9f). Correspondingly, the number of landfalling TCs over China (East China) in August decreased from 11 (10) cases in E1 to 6 (6) cases in E2.

Next, we examine the change in the growth characteristics of TC size during the E2 period. Previous observational and numerical modeling studies have suggested that the initial vortex size influences the expansion rates of TC size (e.g., Cocks and Gray 2002; Lee et al. 2010; Xu and Wang 2010a). TCs with larger initial sizes can import more angular momentum and accelerate the increase of size (Chan and Chan 2014; Martinez et al. 2020). To minimize the effect of initial size, we evaluate the subsequent evolution of TC size by the ratio of the TC size at the time of lifetime maximum intensity to the initial size and refer to this ratio as cyclone expansion factor (CEF). Figure 10 displays the CEF distribution corresponding to the \( \text{LTCEC} \) originating from the W-WNP and E-WNP, respectively. The results show that for \( \text{LTCEC} \) formed over the W-WNP sub-region, the CEFs of extremely large TCs are generally consistent with those of other TCs. This indicates that the size increases of \( \text{LTCEC} \) formed over the W-WNP were similar. The initial vortex size is the dominant factor determining whether the vortex can develop into an extremely large storm. For the \( \text{LTCEC} \) originating from the E-WNP, their CEF values were generally higher than those from the W-WNP (the median difference passes the Wilcoxon rank-sum test at the 99% confidence level), which is related to longer TC lifetime and duration of the intensification phase (e.g., Chan and Yip 2003; Chan and Chan 2012; see also Figs. 5c–f). Except for Typhoon Soudelor (2015), the CEF
values of extremely large landfalling TCs from the E-WNP were all above the upper quartile (2.34) of the overall CEF distribution, indicating that TCs formed over the E-WNP need to undergo a significant growth process to maintain a huge size at landfall. Notably, 7 out of the 8 LTCEC from the E-WNP with CEF higher than 2.34 formed during the E1 period. Therefore, the decrease in CEF value may be the other key reason besides the variations in the TC activity for the reduction in LTCEC of extremely large size during the E2 period.

To further investigate whether the CEF of TCs formed over the WNP changed systematically, Fig. 11 shows the cumulative distribution function of CEF for TCs during the E1 and E2 periods. Compared with the former epoch, the CEF distribution of TCs formed over both the W-WNP and E-WNP subregions in E2 shifted toward small values (both passing a two-sample Kolmogorov–Smirnov test at the 99% confidence level). More specifically, the CEF distribution of TCs originating from the W-WNP was concentrated in a narrow range of smaller values. There was only a minor reduction in the medians between the two epochs. In contrast, the CEF distribution of TCs formed over the E-WNP has changed significantly, especially in the range of large CEF values. For example, the proportion of CEF above 2.34 decreased sharply from 31.8% in E1 to 8.6% in E2. Such a decrease indicates that the size expansion of the E-WNP TCs following their genesis was significantly suppressed in E2.

Finally, we attempt to understand the possible reasons for the decrease of CEF during the E2 period from a large-scale thermodynamic environment perspective. Numerical simulation results indicated that rainbands and convective activity outside the TC primary eyewall are the essential internal process driving the size expansion (e.g., Hill and Lackmann 2009; Wang 2009). The net upward mass transport and diabatic heating produced by rainbands and deep convection can excite a secondary circulation in the outer-core region, which imports angular momentum through the low-level inflow, strengthening TC outer winds.

FIG. 9. Spatial distributions of track density of TCs formed in (left) July and (right) August over the E-WNP during the (a),(b) E1 and (c),(d) E2 periods and (e),(f) their differences. The black dots in (e) and (f) indicate the grid boxes within which the difference in the mean track density between the two epochs passes the Student’s t test at the 90% confidence level.
Increasing the atmospheric and sea surface temperature difference (hence the enthalpy flux) and decreasing the static stability is favorable for the enhancement of rainbands and convective activity, and thus the growth of TC size (e.g., Xu and Wang 2010b; Stovem and Ritchie 2016; Shen et al. 2000; Ma et al. 2019).

Figure 12 shows the changes in SST, the sea–air temperature difference, and the atmospheric thermodynamic parameters, including the tropospheric static stability, convective available potential energy (CAPE), convective inhibition, and the midlevel relative humidity between the two epochs. Among them, the sea–air temperature difference is represented by the difference between SST and 1000-hPa air temperature; the tropospheric static stability refers to the difference in potential temperature between 300 and 900 hPa (Sharmila and Walsh 2018); and the midlevel relative humidity refers to the mass-weighted 600–850-hPa-averaged relative humidity (Wang and Toumi 2019; Martinez et al. 2020). In the ERA5 reanalysis, CAPE is proportional to the difference between the environmental saturated equivalent potential temperature and the equivalent potential temperature of the parcel. The calculation of this parameter assumes that the parcel does not mix with the surrounding air and that the ascent is pseudoadiabatic.

During the E2 period, SST warms throughout the WNP region, with the most significant increase in the midlatitudes (Fig. 12a). As the tropical SST increases, the moist convection acts to stabilize the tropospheric lapse rate, with warming occurring faster in the upper troposphere than the near-surface (IPCC 2021). Thus, compared to the magnitude of the increase in SST, the change in the sea–air temperature difference is smaller. The significant increase only covers the region between 10° and 40°N east of 140°E (Fig. 12b). For the landfalling TCs which move westward or northwestward, the insignificant change in sea–air temperature difference along their tracks may have a limited influence on the expansion of TC size. In most WNP regions south of 20°N, the static stability increased significantly, and CAPE decreased significantly (Figs. 12c,d). These two changes have inhibitory effects on TC convection and hence the increase of TC size.

**FIG. 10.** Boxplots of cyclone expansion factor for landfalling TCs over East China formed over the W-WNP and E-WNP (only showing the median and the interquartile range). The numbers in parentheses at the bottom are the count of TC cases from the W-WNP and E-WNP. The difference in median (ΔM) and the corresponding p values (using the Wilcoxon rank-sum test) are indicated in the upper-left corner. Gray + markers highlight the extremely large TCs with landfalling sizes over 500 km.

**FIG. 11.** Cumulative distribution function of cyclone expansion factor for all TCs formed over the (a) W-WNP and (b) E-WNP subregions from June to October during the E1 (gray) and E2 (black) periods. The black dashed line marks the value of 2.34, corresponding to the upper quartile for landfalling TCs over East China originating from the E-WNP in Fig. 10.
When the TC genesis position is farther offshore, the convective processes within the TC are suppressed for longer. In addition, the changes in static stability and CAPE show a certain degree of zonal asymmetry; that is, the change amplitude is more prominent in the southeast corner of WNP. These two factors may negatively impact the size increase of TCs originating from the E-WNP.

Like SST, there was an overall increase in the midlevel relative humidity, with the most significant increases occurring in the area of 15°–25°N, 135°–165°E (Fig. 12f). The impact of environmental moisture on TC size evolution is not consistent across different simulation studies, depending on the specific setting of water vapor distribution (e.g., Hill and Lackmann 2009; Wang and Toumi 2019; Martinez et al. 2020). Hill and Lackmann (2009) emphasized the favorable role of high environmental relative humidity on TC size. Wang (2009) showed that TC size is sensitive to the diabatic heating/cooling rates in the outer rainbands and pointed out that higher relative humidity might be conducive to larger TCs. More recently, Wang and Toumi (2019) suggested that the midlevel dry air in the ambient atmosphere facilitates the development of radial gradient of latent heating and hence the secondary circulation when it does not seriously invade the TC inner core, especially during the TC intensification period. Y. Li et al. (2022) found through composite analysis that in the North Atlantic, rapidly growing TCs do have more pronounced environmental dry air intrusion than non-rapidly-growing TCs.

In summary, the warming of SST during the E2 period did not cause significant changes in sea–air temperature difference in the active region of TCs affecting the Chinese coast, while the increase of atmospheric static stability and the decrease of CAPE were two fundamental changes that may inhibit the convective activity within TCs and hence the size increase. Especially for TCs formed over the E-WNP, the process of size increase may have slowed down more significantly than their W-WNP counterparts due to longer track length...
and larger change amplitudes of static stability and CAPE over the southeast WNP. Based on the available results, we are uncertain whether the increase in the midlevel relative humidity inhibits TC growth. Well-designed numerical experiments may help answer this question in the future.

4. Summary and discussions

This study investigated the changes in the size distribution of TCs landing over South China and East China during the past 44 years. The results show that the size distribution of landing TCs over South China during the later epoch (1999–2020) was virtually unchanged compared to the previous epoch (1977–98). However, the size distribution of landing TCs over East China was narrower during the later epoch. Also, the difference in the median sizes of landing TCs between East China and South China was more significant. According to the partition of genesis location, the change in the size distribution of landing TCs over East China mainly came from the joint influence of two aspects: the size of landing TCs formed over the W-WNP (120°–140°E) subregion shifted to a larger size range of 300–500 km, and a significant decrease in the extremely large TCs originating from the E-WNP subregion (east of 140°E).

Further analyses show that over the W-WNP, the genesis location of the landing TCs over East China generally migrated southward during the second epoch. Thus, on the one hand, the peak frequency of the genesis location of the landing TCs over East China moved southward from 20°–25°N to 15°–20°N, where the WNP summer monsoon trough with higher relative vorticity and relative humidity dominated and was conducive to the increase of the initial vortex size. On the other hand, the southward shift of the mean genesis location resulted in an increase in both TC lifetime and the duration of intensification before landfall. The increase in the initial vortex size and TC lifetime caused the landing TCs over East China originating from the W-WNP to have a larger size. The characteristic changes in the size distribution can be reproduced using a binary linear regression model.

Over the E-WNP, the genesis location of TCs in August moved eastward during the second period. The dominant TC track that previously approached China along a northwest direction turned northward and eventually affected the Korean Peninsula and Japan. Moreover, we found that the size increase of TCs originating from the E-WNP was significantly inhibited during the intensification phase, which reduced the occurrence probability of extremely large landing TCs. Comparing the large-scale thermodynamic environments between the two periods shows that CAPE decreased and static stability increased significantly over most areas of the WNP south of 20°N. At the same time, the sea–air temperature difference did not change significantly in the region of frequent passages of landing TCs. Such changes in these environmental factors are likely unfavorable to the development of rainbands/convection and the secondary circulation within TCs, thereby inhibiting the inward transport of angular momentum and expansion of TC size.

Changes in the sizes of landing TCs are closely related to the PDO and the associated climate regime shift. First, with the reversal of the PDO phase in 1998, the southerly wind anomaly in the large-scale steering flow field led to the abrupt northward shift of TC tracks east of the Philippines–Taiwan (e.g., Wu et al. 2005; Tu et al. 2009; He et al. 2015; Shan and Yu 2021) and therefore the equatorward migration of the genesis location of TCs making landfall over East China. Second, the 1990s was an active period of TC genesis and multiple TC events over the WNP; after 1998, the frequencies of TC genesis and multiple TC events decreased significantly (e.g., Liu and Chan 2013; Hsu et al. 2014; Schenkel 2016; Ren et al. 2020). In addition to the changes in the large-scale thermodynamic environment discussed above, the variability of multivortices interaction and merger was responsible for the occurrence of some huge landing TCs in the 1990s and the reduced variance in the sizes of landing TCs during the second epoch (figure not shown). Third, the PDO and anthropogenic warming displaced the TC-favorable environment northward (e.g., deepened warm surface water and reduced vertical wind shear; see Fig. S2 in supplemental material), which was conducive to the intensification and maintenance of TC vortices over the East Asian coast (Park et al. 2014; Choi and Kim 2019; Liu and Chan 2022; Zhao et al. 2022).

Previous studies reported a nonlinear relationship between TC intensity and size, showing that there is a systematic increase in TC size with intensity for storms weaker than about 90 kt but sizes are comparable for storms with higher intensities (e.g., Wu et al. 2015; Knaff et al. 2016). Therefore, for landing TCs examined here, a better correlation between the averaged intensity and size before landfall can be expected. Our results indicate that the intensities of the landing TCs over East China also increased, primarily related to the storms originating from the W-WNP (see Figs. S3–S5 and Table S1). Although there was an increase in the lifetime maximum intensity for all the TCs making landfall over East China, the storms originating from the E-WNP reached the maximum intensity far from the coast, thus having less impact on the landfall intensity. We also found that the difference in the averaged intensities before landfall between East China and South China was more statistically significant in the later epoch. However, unlike TC size, there is no change in the variance of TC intensity between the two epochs, suggesting that TC intensity only partly impacted the landing size.

The ability to estimate the TC size has improved rapidly during the last two decades, while in earlier years, there was greater uncertainty in subjective estimations of TC size due to the lack of satellite observations and numerical model products, especially in the eastern region of WNP far from the East Asian coast (Chan and Chan 2018; Knaff et al. 2021). Therefore, it is necessary to further verify the findings of this study by using more dynamically consistent and objectively analyzed datasets of TC size. Combining high-resolution reanalysis data, TC wind field models, and machine learning methods may help solve this issue (e.g., Schenkel et al. 2017; Bian et al. 2021; Chavas et al. 2015; Zhuo and Tan 2021). Nevertheless, the suppression of TC size increase during the intensification stage during the later epoch found here in this study seems to be in line with the results of recent works on the long-term change of TC precipitation.
and cloud depth/fraction (e.g., Guzman and Jiang 2021; Tu et al. 2021; Lai and Toumi 2023), which collectively indicates that there has been a systematic weakening trend of the inner-core deep convection of TCs.

The results obtained in this study also have implications for understanding the climatology of TC size in a warmer climate system. Previous projections of future TC activity derived from dynamic downscaling methods suggested that TC size would increase in a future, warmer climate among all TC basins except for WNP (Knutson et al. 2015). This means that for WNP, certain thermodynamic factors and related processes may exist to limit the expansion of TC size. How do a decrease in CAPE and an increase in static stability brought by an adjustment of the troposphere in response to SST warming affect the TC internal processes to limit the TC size? Over the western part of the WNP, where the midlevel ambient air is already very humid, does a further increase in relative humidity limit or promote the expansion of TC size? Answers to these questions will help to understand possible changes in the distribution of TC size in future climates. Moreover, the expansion of the tropics will also shift the average location of TC genesis poleward (e.g., Sharmila and Walsh 2018), which increases the risk of TCs affecting higher latitudes. Still, the lifetime of landfalling TCs in some coastal regions may be shortened, which is also one of the possible factors limiting the TC size.

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