

• Original Paper •

Growing Threat of Rapidly-Intensifying Tropical Cyclones in East Asia[※]

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ABSTRACT

This study examines the long-term change in the threat of landfalling tropical cyclones (TCs) in East Asia over the period 1975–2020 with a focus on rapidly intensifying (RI) TCs. The increase in the annual number of RI-TCs over the western North Pacific and the northwestward shift of their genesis location lead to an increasing trend in the annual number of landfalling RI-TCs along the coast of East Asia. The annual power dissipation index (PDI), a measure of the destructive potential of RI-TCs at landfall, also shows a significant increasing trend due to increases in the annual frequency and mean landfall intensity of landfalling RI-TCs. The increase in mean landfall intensity is related to a higher lifetime maximum intensity (LMI) and the LMI location of the landfalling RI-TCs being closer to the coast. The increase in the annual PDI of East Asia is mainly associated with landfalling TCs in the southern (the Philippines, South China, and Vietnam) and northern parts (Japan and the Korean Peninsula) of East Asia due to long-term changes in vertical wind shear and TC heat potential. The former leads to a northwestward shift of favorable environments for TC genesis and intensification, resulting in the northwestward shift in the genesis, RI, and LMI locations of RI-TCs. The latter provides more heat energy from the ocean for TC intensification, increasing its chances to undergo RI.

Key words: tropical cyclone landfall, tropical cyclone intensity, climate change, rapid intensification

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Article Highlights:

- The threat of rapidly intensifying tropical cyclones making landfall along the coast of East Asia shows a significant increasing trend.
- The location of lifetime maximum intensity is closer to the coast, resulting in a higher annual mean landfall intensity.
- The long-term changes in vertical wind shear and tropical cyclone heat potential are the major factors responsible for the above changes.

1. Introduction

Tropical cyclone (TC) landfall poses a severe threat to coastal areas and the variability and long-term changes of landfalling activity in East Asia have received much attention in the recent decade. Park et al. (2014) showed that the threat of intense TCs to East Asia has increased over the period 1977–2010 because the locations of maximum intensity have moved closer to East Asian coastlines, resulting in an increase in landfall intensity over east China, Korea, and Japan. Mei and Xie (2016) showed a long-term increase in the lifetime peak intensity of landfalling typhoons that

strike East and Southeast Asia over the period 1977–2014, hence suggesting an increasing threat to these regions. Guan et al. (2018) examined the landfalling TCs with the lifetime maximum intensity (LMI), of at least typhoon intensity, in East and Southeast Asia between 1974 and 2013 and found an increasing trend in the annual mean landfall intensity due to an increase in the intensification rate.

Tropical cyclone (TC) rapid intensification (RI) is defined as a significant increase in TC intensity over a short time, and represents another important issue in TC studies and has always been a great challenge to forecasting. The variations and long-term change of RI over the western North Pacific (WNP) have been examined by some studies. Zhao et al. (2018) showed a significant increase in the proportion of RI-TCs over the WNP since 1998. Song et al. (2020) found a significant increase in RI magnitude (24 h intensity change of an RI event) during 1979–2018, which is related

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to an increase in the number of strong RI events [24 h intensity increase of at least 50 kt (kt; where 1 kt = 0.51 m s⁻¹)]. Song et al. (2021) showed a significant upward trend in the average LMI of RI-TCs, which is linked to a significant increase in the mean intensification rate.

These studies generally examined the landfalling activity and RI separately but very few studies have focused on those landfalling TCs that have undergone RI before landfall (hereafter referred to as landfalling RI-TCs). The maximum intensity attained by an RI-TC is usually high (Lee et al., 2016) and the risk of damage at TC landfall is therefore higher. Moreover, the time available for typhoon preparation and evacuation is usually short especially for those that strengthen just before landfall. The high risk of a landfalling RI-TC and the relatively poor skill in forecasting RI events pose a significant challenge for operational forecasting. Therefore, a better understanding of the variations of landfalling RI-TCs is very important and this study is an attempt to investigate the long-term change in the landfalling RI-TCs and the associated influence on the coastal areas of East Asia.

The remainder of this paper is organized as follows: Section 2 describes the data and methodology employed in this study. The long-term changes in RI-TCs and their possible impact on the coastal areas of East Asia are given in section 3. The large-scale environmental conditions responsible for these changes are presented in section 4. Section 5 gives the summary and discussion.

2. Data and methodology

2.1. Data

The TC best-track dataset is acquired from the Joint Typhoon Warning Center, which includes 6-hourly TC positions and intensities (measured as 1-min maximum sustained wind speed). Because routine satellite observations of TCs began in 1975, only TCs occurring in the period 1975–2020 are examined. In this study, only the TCs with the 1-min-average maximum sustained wind > 34 kt are considered.

It is well known that TC development and intensification are primarily controlled by dynamic factors such as the heat content of the ocean and vertical wind shear (VWS). The VWS is estimated as the magnitude of the difference between the 200- and 850-hPa zonal and meridional winds, which are extracted from the ECMWF ERA5 reanalysis dataset (Hersbach et al., 2020). The horizontal resolution of this dataset is 0.25° × 0.25°. Monthly mean oceanic temperature data (1980–2017) from the Simple Ocean Data Assimilation (with 0.5° × 0.5° horizontal resolution and 50 vertical layers) (Carton et al., 2018) are used to estimate the TC heat potential (TCHP), which is a measure of the ocean heat content contained in water warmer than 26°C. Some studies have reported that the TCHP can affect TC intensity and intensification (Wada and Usui, 2007; Wada and Chan, 2008). Following Leipper (1967), the TCHP is estimated by

$$\text{TCHP} = c_p \rho \int_{D_{26}}^0 [T(z) - 26] dz,$$

where ρ is the density of seawater (1026 kg m⁻³), c_p the specific heat capacity of the seawater at constant pressure (4178 J kg⁻¹ °C⁻¹), D_{26} is the depth of the 26°C isotherm, and $T(z)$ is the in situ temperature.

2.2. Methodology

Landfall is defined as a TC with its center passing over the coastline of East Asia. An RI event is defined if the 24-h intensity change is ≥ 30 kt (Kaplan and DeMaria, 2003). A TC can undergo multiple RI events (i.e. the whole process > 24 h) and an RI process can consist of consecutive RI events. An RI-TC is defined as a TC with at least one RI event. A landfalling RI-TC is then defined as an RI-TC that makes landfall along the coast of East Asia. If a landfalling RI-TC has multiple landfalls, only the landfall with an RI process immediately prior to it is considered. For example, an RI-TC undergoes an RI over the WNP and makes landfall in the Philippines and it is considered as a landfalling RI-TC in the Philippines. It may go on to enter the South China Sea (SCS) and make another landfall in south China or Vietnam. If it undergoes another RI over the SCS, it is considered as a landfalling RI-TC in south China or Vietnam. Otherwise, the second landfall is not counted.

The life cycle of a landfalling RI-TC consists of a sequence of stages including genesis, RI, LMI, and landfall. A set of parameters are used to describe these stages. The genesis location is defined as the position at which a TC first reaches an intensity of 25 kt. The RI locations are defined as the positions at which a TC undergoes its RI, which are a set of 6-hourly positions spanning from the beginning to the end of the RI. Following Liu and Chan (2019), the location of LMI of a TC is estimated as the position at which it last attains its LMI. This definition is different from that of Kossin et al. (2014), which is the position at which the TC first attains its LMI. The LMI location based on the present definition is usually closer to the coast of East Asia and is believed to have a better representation of the distance between the LMI location and landfall point (Liu and Chan, 2019). It should be noted that if an RI-TC has multiple landfalls, the LMI location for the second landfall is the position at which it attains the maximum intensity after its second RI. Thus, the LMI location for a second landfall in South China or Vietnam is usually located over the SCS. The landfall intensity is estimated as the 6-hourly intensity at, or just prior to, landfall. To have a better measure of the destructive potential at landfall, the power dissipation index (PDI), estimated as the cube of the wind speed at landfall (Emanuel, 2005), is defined. The annual PDI, which is the sum of the PDI at landfall of each landfalling TC, depends on both the number and intensity of these TCs and is considered as the parameter measuring the “total” destructiveness in a year (Liu and Chan, 2017).

The Mann-Kendall test (Mann, 1945) is used to test the statistical significance of the trend of a time series. This non-parametric test can be used on data with an unknown

sample distribution and is minimally affected by outliers. Relative weight analysis is used to estimate the relative importance of each factor based on its contribution to the *R*-squared values (percentage of the variance explained by the factors) obtained from multiple linear regression when the factors are correlated to each other.

3. Variations in RI-TCs

3.1. Temporal variations in RI-TCs

During 1975–2020, there were 470 RI-TCs over the

WNP, representing an annual mean of 10.2 and its time series shows an obvious upward trend, which is significant at the 90% confidence level (Fig. 1a). The interannual variation is large, ranging from 4 in 1978 to 18 in 2015. Out of the 470 RI-TCs, 289 make landfall along the coast of East Asia. The mean annual number of landfalling RI-TCs is 6.3 and its time series also shows a significant upward trend (confidence level of 99%) (Fig. 1b), which is partly related to the upward trend of the annual number of RI-TCs as suggested by the high correlation ($r = 0.61$) between the two time series.

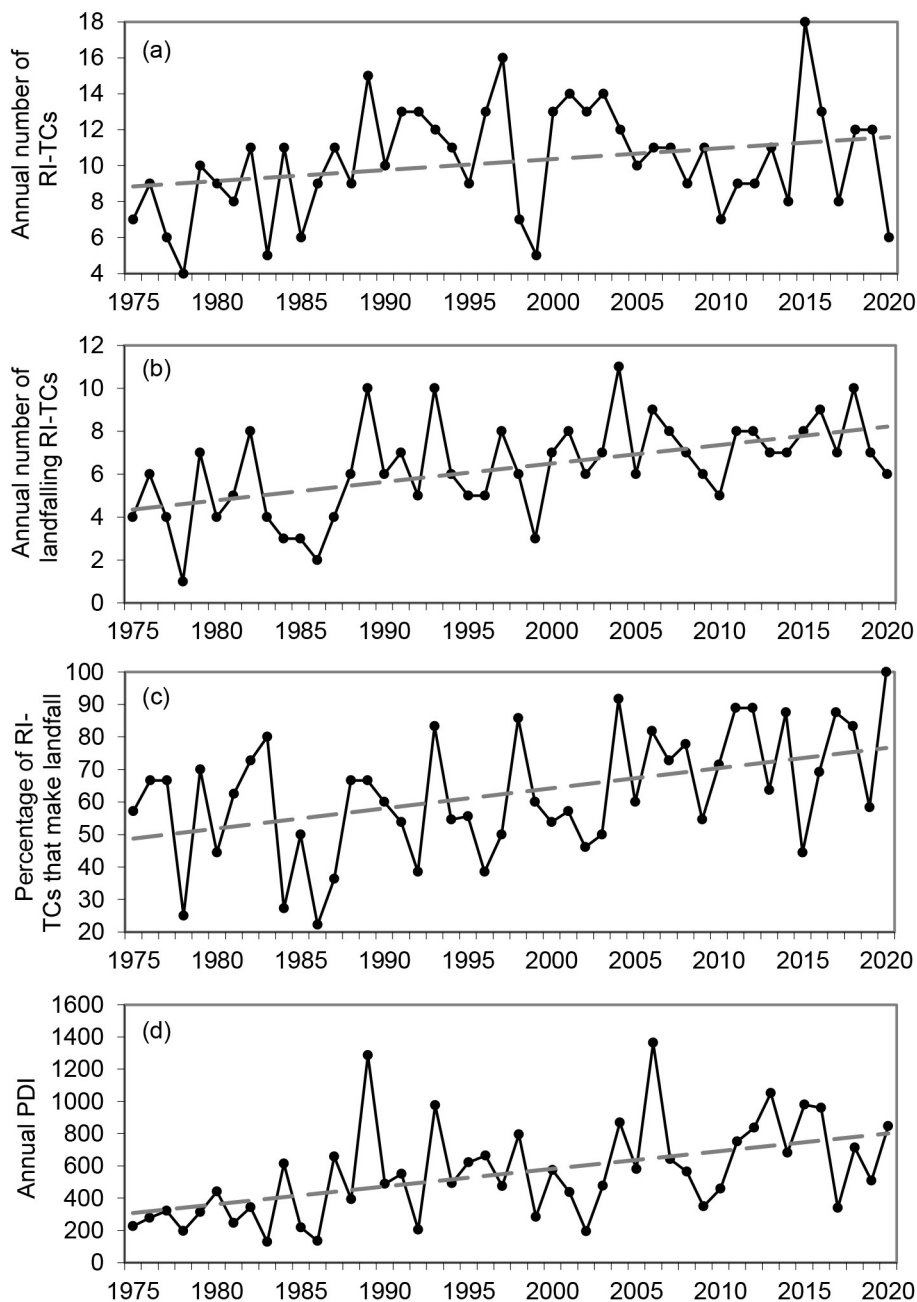


Fig. 1. Time series of (a) the annual number of RI-TCs, (b) the annual number of landfalling RI-TCs, (c) percentage of RI-TCs that make landfall, and (d) annual PDI (units: 10^4 kt^3). The dashed lines indicate the linear trends.

To remove the effect of the overall RI-TC activity on the number of landfalling RI-TCs, the variation in the percentage of RI-TCs that make landfall is examined. On average, 62.7% of the RI-TCs make landfall along the coast of East Asia and the percentage shows a gradual increase as indicated by its significant upward trend (confidence level of 99%) (Fig. 1c). The lowest percentage (22.2%) is found in 1986, with only 2 out of the 9 RI-TCs making landfall. In 2020, all the RI-TCs made landfall along the coast of East Asia, giving a percentage of 100%, which was the highest during the study period. These results demonstrate that the increase in the annual number of landfalling RI-TCs is not only related to the increase of RI-TCs over the entire WNP but also the percentage of these TCs making landfall. Guan et al. (2018) also found an increase in the percentage of TCs with at least typhoon intensity making landfall during 1974–2013. The correlations of the landfalling RI-TCs frequency with the total RI-TCs frequency and percentage of RI-TCs that make landfall are similar (correlation coefficients being 0.61 and 0.62, respectively), and the relative weight analysis shows that their contributions to the R -squared values of the multiple regression model are also similar (49.8% and 50.2%, respectively), suggesting that the two factors are of equal importance in controlling the annual number of landfalling RI-TCs.

To better understand the change in the percentage of RI-TCs that make landfall, it is useful to investigate the characteristics of the RI-TCs with and without landfall. An examination of the tracks of non-landfalling RI-TCs shows that most of these TCs follow the recurving track, move towards the ocean southeast of Japan and dissipate over water without landfall (not shown). Only a few move towards the coast of East Asia and dissipate over water without landfall. Therefore, the percentage of RI-TCs that make landfall partly depends on the genesis location and the subsequent track. Normally, a TC that forms further to the west has a higher chance to make landfall. Indeed, the percentage of landfalling RI-TCs is significantly correlated with the annual mean longitude of genesis location of all RI-TCs (including both landfalling and non-landfalling) ($r = -0.48$, confidence level of 95%). In addition, the mean genesis longitude of landfalling RI-TCs (141.5°E) is further to the west than that of non-landfalling RI-TCs (150.9°E) and the difference is significant at the 99% confidence level. The latitude and longitude of genesis location of all RI-TCs show an increasing trend (confidence level of 98%) and a decreasing trend (confidence level of 97%), respectively, indicating a northwestward shift in genesis location (Figs. 2a and 2b), consistent with the result from Zhao et al. (2018). A similar trend in genesis location is found for landfalling RI-TCs. However, no trend is detected for the genesis longitude of non-landfalling RI-TCs, suggesting that the genesis locations of non-landfalling RI-TCs are generally confined to a longitudinal band and a westward shift in genesis location will, therefore, increase the chances for an RI-TC to make landfall.

While the chances of an RI-TC making landfall is partly related to the genesis longitude, the actual number of landfalling RI-TCs also depends on the total number of RI-TCs over the WNP. As discussed above, the annual number of landfalling RI-TCs is highly correlated with the total number of RI-TCs ($r = 0.61$) but its correlation with the mean genesis longitude is less significant ($r = -0.20$). Using these two factors as predictors for the annual number of landfalling RI-TCs, the multiple regression model gives a correlation of 0.70, and the contributions of the total number of RI-TCs and mean genesis longitude to the R -squared values are 84.4% and 15.6%, respectively. Thus, the upward trend in landfalling RI-TCs is mainly due to the increase in RI-TCs over the WNP and the role of the northwestward shift in genesis location is to increase the percentage of RI-TCs that make landfall along the coast of East Asia.

The annual number of landfalling RI-TCs along the coast of East Asia has been shown to have a significant increasing trend. To better measure the destructive potential in coastal areas, the annual PDI, which depends on both landfall frequency and intensity, is also examined. The annual PDI shows a significant increasing trend at the 99% confidence level (Fig. 1d), indicating an increasing threat posed by RI-TCs to the coastal areas of East Asia. The climatological mean of the annual PDI is $554.9 \times 10^4 \text{ kt}^3$. Over the study period, the annual PDI has increased by 160%. The interannual variation of annual PDI is very large, with the lowest value ($127.7 \times 10^4 \text{ kt}^3$) in 1983 and the highest value ($1363.7 \times 10^4 \text{ kt}^3$) in 2006. Mei and Xie (2016) showed that the increase in the intensity of landfalling typhoons is due to enhanced intensification rates. Guan et al. (2018) also examined the PDI at land, defined as the sum of PDI when the TC center is over land for each TC, and found an increasing trend over the period 1974–2013. Our result is therefore consistent with that of Guan et al. (2018) although the definitions of PDI are different and only the RI-TCs are considered in the present study.

The increasing trend of the annual PDI is obviously related to the increase in the annual number of landfalling RI-TCs. Since the annual PDI also depends on landfall intensity, the contribution of landfall intensity to the long-term change of annual PDI is investigated. The time series of annual mean landfall intensity also shows an increasing trend (Fig. 3a), but it is not significant (confidence level of 82%). It should be noted that there was only one landfalling RI-TC in 1978, making landfall in the Philippines with an intensity of 125 kt and giving an exceptionally high annual mean landfall intensity. If this year is excluded in the trend analysis, the confidence level rises to 92%, which is statistically significant. Therefore, the increase in annual mean landfall intensity could contribute to the increasing trend of annual PDI.

The annual PDI is significantly correlated with the annual number of landfalling RI-TCs and annual mean landfall intensity (correlation coefficients being 0.66 and 0.53, respectively, both are significant at the 99% confidence

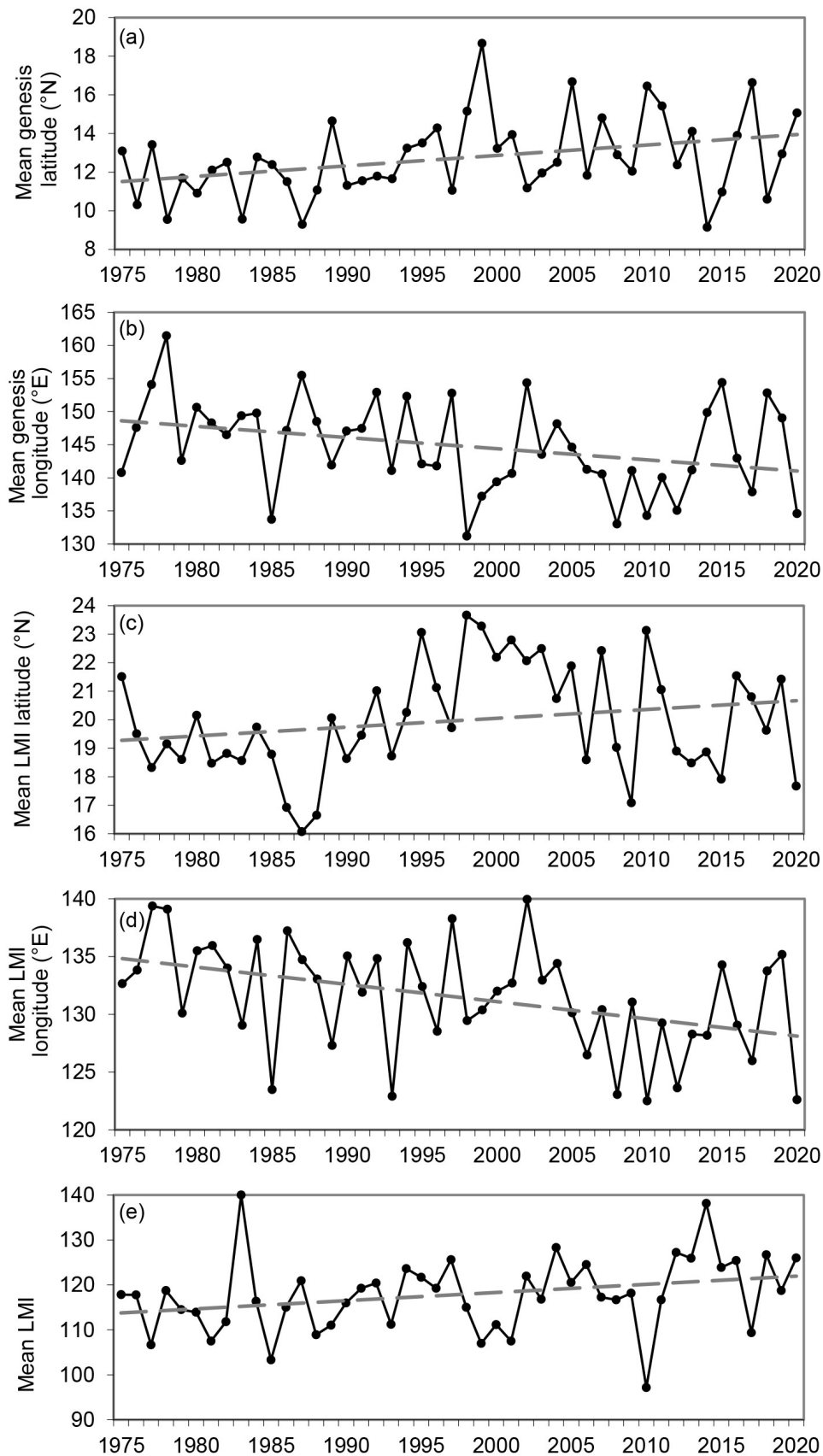


Fig. 2. Time series of the mean (a) latitude and (b) longitude of genesis location and the mean (c) latitude and (d) longitude of LMI location and (e) the mean LMI (units: kt) of RI-TCs (including both landfalling and non-landfalling). The dashed lines indicate the linear trends.

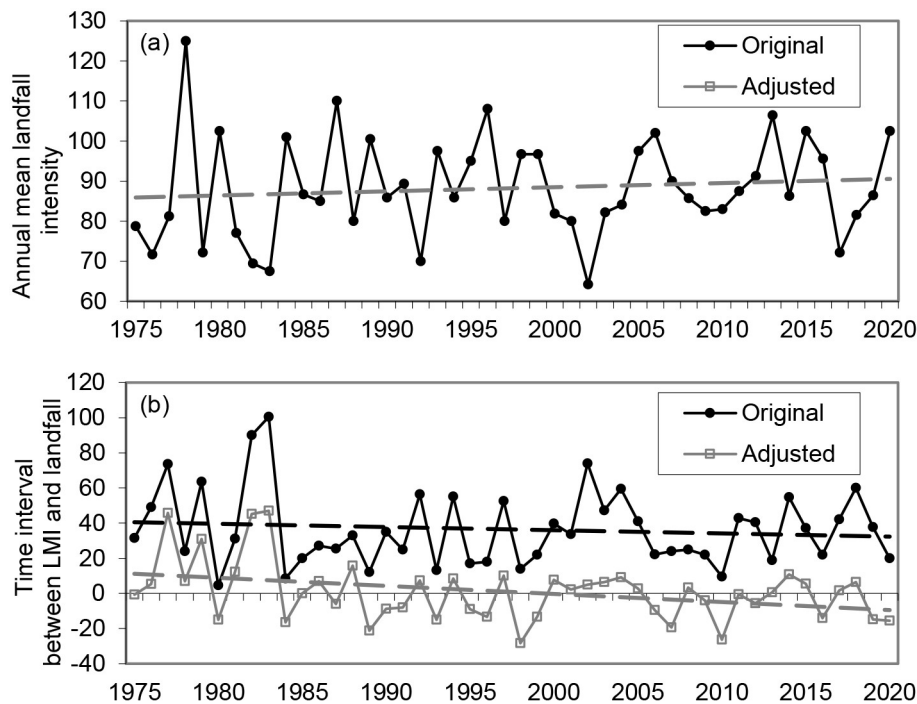


Fig. 3. Time series of (a) the annual mean landfall intensity (units: kt) and (b) the time interval (units: h) between LMI occurrence and landfall (original and adjusted). The dashed lines indicate the linear trends.

level). Using these two factors as predictors for the annual PDI, the multiple regression model gives a correlation of 0.92 and their contributions to the *R*-squared values are 59.1% and 40.9%, respectively. Thus, the increasing trend of annual PDI is mainly due to the increase in the annual frequency of landfalling RI-TCs, with the increase in annual mean landfall intensity playing a secondary role.

The intensity at landfall may be related to the LMI location of a landfalling RI-TC. If the LMI occurs close to the coast, weakening may not be significant during the time between LMI and landfall so that the intensity at landfall may be close to its LMI. In some cases, a TC actually attains its LMI near its landfall so that the landfall intensity is equal to the LMI. This situation is usually found for those RI-TCs making landfall in the Philippines. Thus, an RI-TC with its LMI location close to the coast may pose a severe threat to the coastal area. In contrast, a TC with its LMI location far away from the coast may substantially weaken before making landfall so that the intensity at landfall is lower. Therefore, the long-term change in LMI location may exert a significant influence on the landfall intensity and hence the annual PDI. Indeed, the trend analysis of the LMI occurrence of RI-TCs (both landfalling and non-landfalling) shows an increasing trend in latitude (confidence level of 79%) and a decreasing trend in longitude (confidence level of 99%), indicating a possible northwestward shift in the LMI location (Figs. 2c and 2d), consistent with the results from the previous studies (Park et al., 2014; Zhao et al., 2018; Wang and Toumi, 2021). This implies that the LMI location has moved closer to the coast of East Asia, which may partly explain the increase in landfall intensity. Park et al.

(2014) also showed that the LMI location of TCs with at least tropical storm intensity has moved closer to East Asian coastlines over the period 1977–2010, which is the main reason for the increase in landfall intensity over East China, Korea, and Japan. In addition, the annual mean LMI of RI-TCs also shows a significant increasing trend (confidence level of 99%) (Fig. 2e), which may contribute to the increase in landfall intensity. Song et al. (2021) also found a similar trend, which is primarily linked to a significant increase in the mean intensification rate prior to the LMI.

To further investigate the possible relationship between LMI location and landfall intensity, the variation in the time interval between LMI occurrence and landfall (the time when LMI occurs minus time at landfall) is examined. A shorter time interval generally implies an LMI location closer to the coast. The landfall intensity is negatively correlated with the time interval ($r = -0.51$) suggesting that the landfall intensity is generally higher if the LMI location is closer to the coast. The trend analysis shows an insignificant trend in the annual mean time interval (Fig. 3b). The average LMI location of landfalling RI-TCs is near (19.4°N, 126.4°E), which is close to the coast of the Philippines and Taiwan Island, but far away from the coasts of Japan, the Korean Peninsula, and East China. The LMI usually occurs at a lower latitude because a TC generally experiences higher VWS and cooler water as it moves northward, leading to weakening. Therefore, the mean time intervals between LMI occurrence and landfall for the TCs making landfall in Japan, the Korean Peninsula, and East China (69.0 h, 77.3 h, and 54.9 h, respectively) are longer than those making landfall in the Philippines and Taiwan Island (16.4 h and 23.9 h respectively).

The mean time intervals for South China and Vietnam (21.4 h and 17.3 h, respectively) are also shorter because the LMI is usually located over the SCS. Thus, the annual mean time interval depends on the preferred landfall regions in that year. A year with a higher portion of TCs making landfall in the northern domain generally yields a longer mean time interval.

For example, the mean time interval in 1983, which consists of four landfalling RI-TCs (Japan: 2; East China: 1; South China: 1), is 100.5 h. In contrast, the mean time interval is generally shorter for a year in which the preferred landfall regions are to the south. A typical example occurred in 1980 when the four landfalling RI-TCs had a southern bias (the Philippines: 2; Taiwan Island: 2), thus resulting in a very short mean time interval (4.5 h). To remove this effect, the anomaly of the time interval for a region is obtained by subtracting the time interval from the climatological mean corresponding to that region. The time series of the adjusted time interval, which should reflect the actual change in the time interval between LMI occurrence and landfall, shows a significant decreasing trend (confidence level of 93%) (Fig. 3b). In other words, the time interval has actually shortened, leading to a higher landfall intensity.

To investigate the changes of annual PDI in different regions, the East Asia region is divided into three sub-regions and the landfalling TCs are accordingly grouped as south TCs (South China, Vietnam, and the Philippines), middle TCs (East China and Taiwan Island), and north TCs (Japan and the Korean Peninsula). The annual PDI of south TCs shows a significant upward trend (confidence level of 99%), which is related to the increasing trends of the annual frequency (confidence level of 86%) and the annual mean landfall intensity (confidence level of 97%), suggesting that the latter is the dominant factor (Table 1). A significant upward trend (confidence level of 99%) is also found for north TCs, which is mainly due to the increase in annual frequency (confidence level of 99%). The role of landfall intensity is minimal, as no trend exists in the annual mean landfall intensity. The trend in the annual PDI of middle TCs (confidence level of 63%) is not as significant as those of south and north TCs. It can be concluded that the increase in annual PDI in East Asia is mainly due to the increasing frequency of RI-TCs making landfall in the southern (South

China, Vietnam, and the Philippines) and northern parts (Japan and the Korean Peninsula) of East Asia and the increase in annual mean landfall intensity for the former also plays an important role.

3.2. Changes in characteristics of RI-TCs

The important stages of a landfalling RI-TC include genesis, RI, LMI, and landfall. It is useful to investigate the spatial distribution of the trends in each of these stages of RI-TCs (both with landfall or without landfall) and their possible impacts on the annual PDI. The major genesis area of RI-TCs is near (5°–15°N, 130°–160°E) and the spatial distribution of genesis frequency shows a decreasing trend in the southeastern part of the WNP (5°–10°N, 145°–180°E) and an increasing trend north and northwest of the major genesis area, indicating a northwestward shift in genesis location (Fig. 4a), which is consistent with the increasing trend (northward shift) in mean genesis latitude and the decreasing trend (westward shift) in mean genesis longitude of RI-TCs (see Figs. 2a and 2b). The shift of genesis location towards the coast of East Asia increases the chance of an RI-TC to make landfall and hence the percentage of landfalling RI-TCs as indicated by the significant correlation between the mean genesis longitude and the percentage of RI-TCs that make landfall ($r = -0.48$, confidence level of 95%). Indeed, such an increase in genesis frequency leads to an increasing frequency of the RI-TCs that form at higher latitudes and follow the recurving path towards Japan and the Korean Peninsula or a straight path towards Taiwan Island and east China (Fig. 4b). An increasing frequency of RI-TCs moving across the SCS and making landfall in south China is also observed. These results are consistent with the upward trend in the annual number of landfalling RI-TCs along the coast of East Asia (see Table 1).

Because of the upward trend in the annual frequency of RI-TCs, the frequency of occurrence of RI should increase and the spatial distribution of RI occurrence shows an increasing trend in most parts of the WNP (Fig. 4c). Such trends are more significant over the SCS, northeast of Taiwan Island, and southeast of Japan, which are outside the major RI region (10°–23°N, 123°–150°E). This implies a westward and northward expansion of the RI region and a higher frequency of RI-TCs undergoing RI near the coast of East

Table 1. Linear trends of the annual PDI, the annual number of RI landfalling TCs, the annual mean landfall, and the time interval between LMI and landfall intensity for all TCs, north TCs, middle TCs, and south TCs (see text for the definitions). Percentages in the parenthesis are the confidence levels, with those $\geq 90\%$ in bold.

	Annual PDI	Annual number of landfalling RI-TCs	Annual mean landfall intensity	Time interval between LMI and landfall
All TCs	Upward (99%)	Upward (99%)	Upward (82%)	Downward (98%)
North TCs	Upward (99%)	Upward (99%)	Upward (24%)	Downward (37%)
Middle TCs	Upward (63%)	Upward (48%)	Upward (66%)	Downward (39%)
South TCs	Upward (99%)	Upward (86%)	Upward (97%)	Downward (95%)

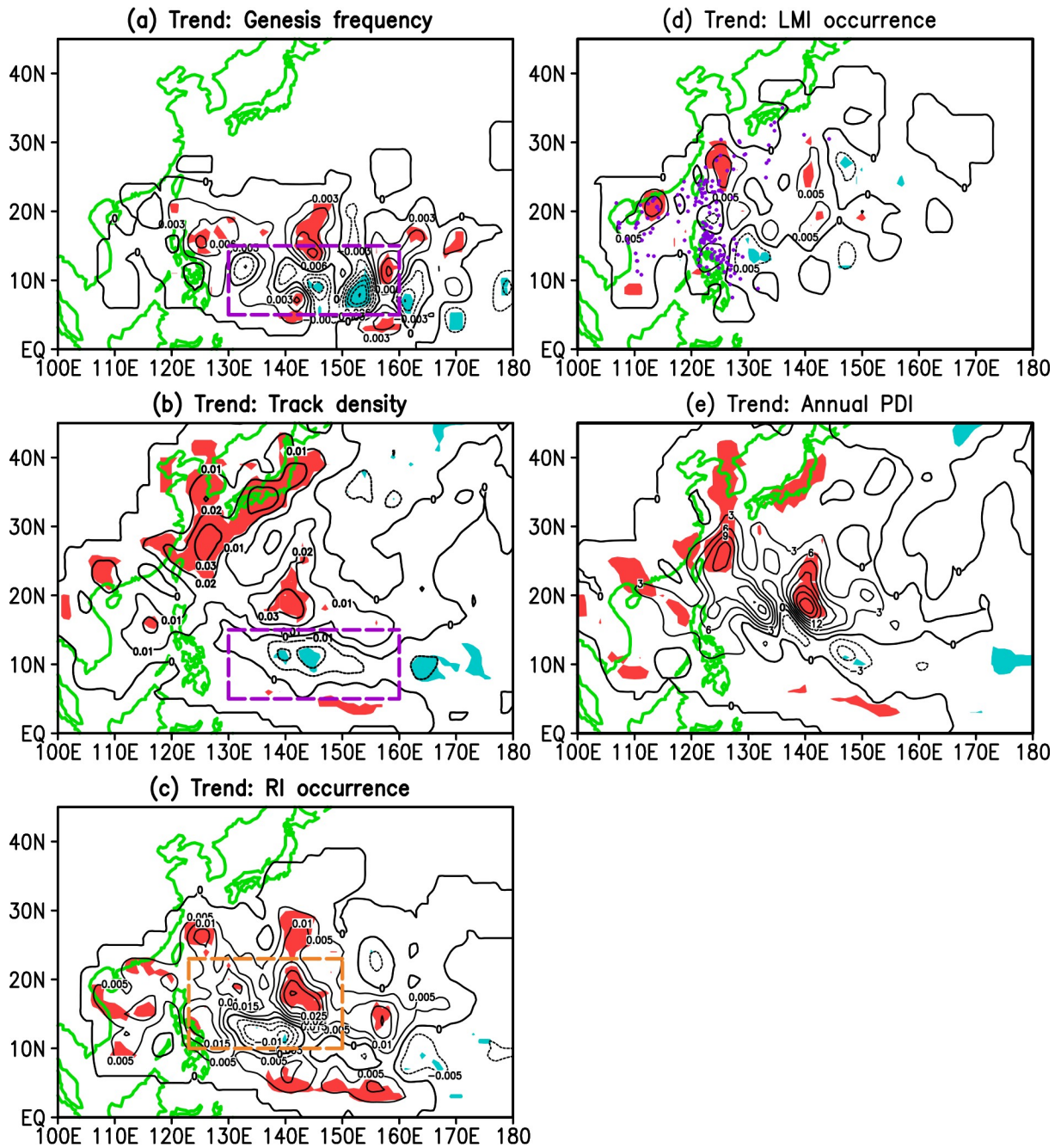


Fig. 4. Spatial distribution of the linear trends in (a) genesis frequency, (b) track density, (c) RI occurrence, (d) LMI occurrence, and (e) annual PDI (units: $kt^3 yr^{-1}$) of RI-TCs (including both landfalling and non-landfalling). Red and blue shadings indicate the areas with positive and negative trends significant at the 90% confidence level respectively. The purple dashed rectangular box in (a) and (b) and the orange dashed rectangular box in (c) indicate the major area for genesis and RI occurrence respectively. The purple dots in (d) indicate the LMI locations of all the landfalling RI-TCs with the time interval between LMI occurrence and landfall ≤ 24 h occurring between 1975 and 2020.

Asia. The increasing trend in the RI occurrence also implies an increasing trend in the RI-TCs attaining the maximum intensity near the coast of south China and Vietnam (Fig. 4d). Liu and Chan (2020) also found an increase in maximum landfall intensity near the south China coast during 2012–18, which is related to the increase in the annual frequency of the RI-TCs making landfall in south China. An increasing trend in LMI occurrence is also observed near

East China.

To further examine the impact of the change of LMI location on annual PDI, the landfalling RI-TCs with a short time interval between LMI occurrence and landfall (≤ 24 h) is examined. This type of landfalling RI-TC is of particular importance because it may make landfall shortly after the occurrence of LMI, leaving very little time for typhoon preparation and evacuation. The areas with the increasing trend

in LMI occurrence generally coincide with the major region of the occurrence of these RI-TCs (Fig. 4d). Thus, the westward shift in LMI locations leads to an increasing frequency of the landfalling RI-TCs with a short time interval between LMI occurrence and landfall (confidence level of 91%) (Fig. 5a) as well as an increase in their mean landfall intensity (confidence level of 99%) (Fig. 5b), leading to the higher annual PDI in these regions (Fig. 4e). Note also the increasing trend in annual PDI near the coast of Japan and the Korean Peninsula, which is largely related to the increasing frequency of RI-TCs affecting these regions.

4. Environmental conditions

The results from section 3 suggest a significant increasing trend of the annual PDI along the coast of East Asia associated with landfalling RI-TCs, which is related to the increase in the annual frequency of RI-TCs over the WNP and the shift of the LMI location towards the coast of East Asia. The possible causes of these changes are investigated in this section by examining the seasonal mean VWS and TCHP. The main season for landfalling RI-TCs is between May and November, which represents 94% of the annual number of landfalls, therefore the environmental conditions averaged between May and November are examined.

4.1. Vertical wind shear

The development of an RI-TC consists of the processes of genesis and RI, and a weak VWS environment provides a favorable condition for both processes. The correla-

tion map between the annual number of RI-TCs and VWS shows negative correlations extending from the southeastern part of the WNP to its northwestern part, which covers the northeast quadrant of the major genesis region and the north quadrant of the major RI region (Fig. 6a). Thus, the large-scale VWS is an important factor controlling the annual number of RI-TCs over the entire WNP. For the correlation map between the VWS and annual PDI, a small area of negative correlation is found in the northwestern part of the WNP (Fig. 6b) and the correlation between the mean VWS in this region and annual PDI is -0.42 (confidence level of 95%). A weak VWS environment (low VWS values) in this region allows the TC to undergo RI in the area northwest of the major RI region, resulting in a LMI location closer to the coast and hence a higher annual PDI.

Positive trends in VWS are found in the southeastern part of the WNP but the magnitude is small (Fig. 6c). A large area of negative trend is found in the northwestern part of the WNP and the northern part of the SCS which coincides with the area that has a negative correlation between the VWS and annual PDI. The decreasing VWS in these regions provides for a more efficient environment for TC intensification. Thus, the atmospheric environment is more favorable for TCs undergoing RI, which might explain the increasing trend in the annual frequency of RI-TCs. The northwestward shift in favorable atmospheric environments is also consistent with the observed northwestward shift in the genesis location, RI location, and LMI of RI-TCs. In addition, the weaker VWS over the northern part of the SCS may be responsible for the increasing frequency of TCs under-

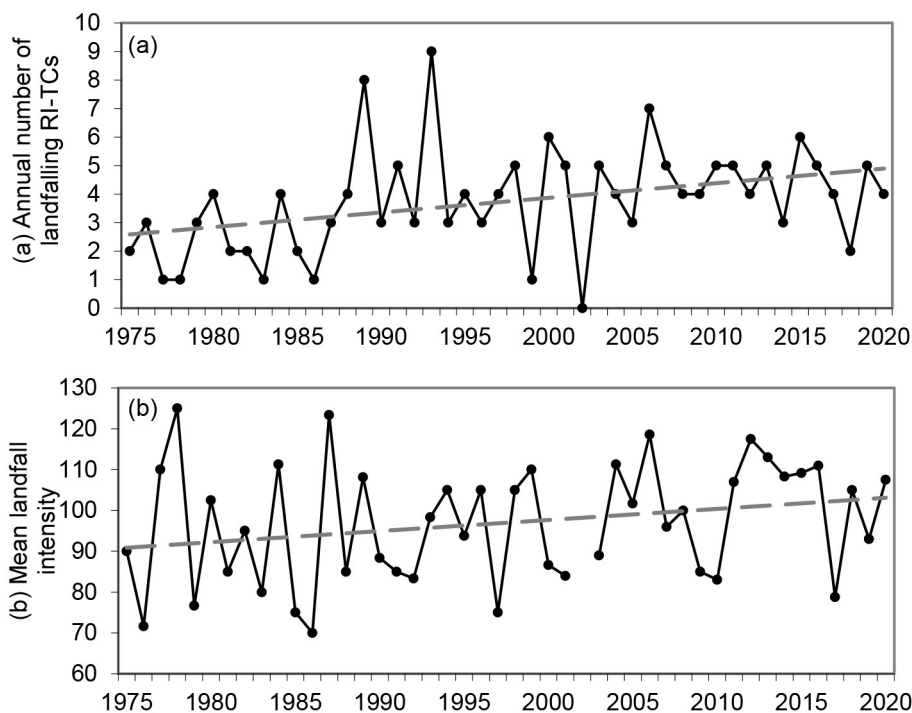


Fig. 5. Time series of (a) the annual number and (b) annual mean landfall intensity (units: kt) of the landfalling RI-TCs with the time interval between LMI occurrence and landfall ≤ 24 h. The dashed lines indicate the linear trends.

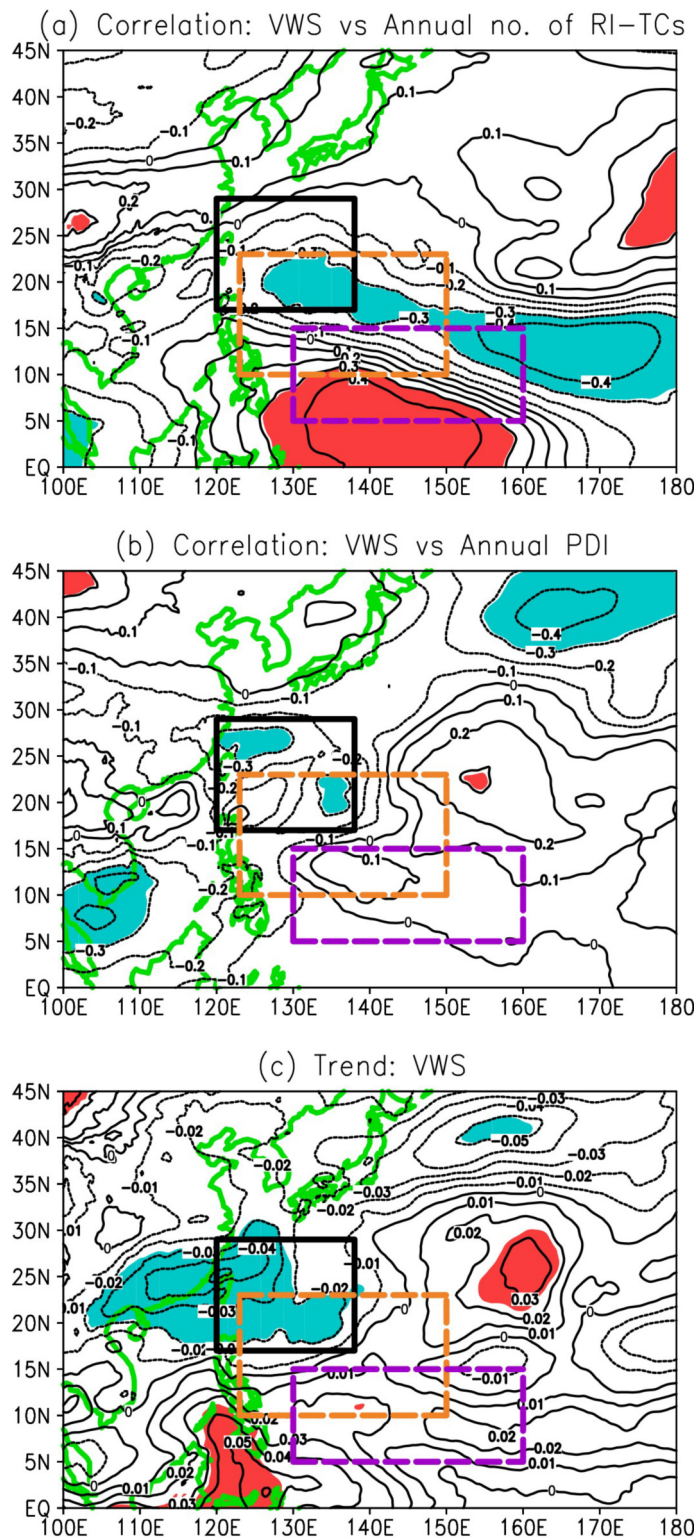


Fig. 6. Correlation maps (a) between the VWS and annual number of RI-TCs and (b) between the VWS and annual PDI. (c) Spatial distribution of the linear trends in VWS (units: $\text{m s}^{-1} \text{ yr}^{-1}$). Red and blue shadings indicate the areas with positive and negative correlation/trend significant at the 90% confidence level respectively. The purple and orange dashed rectangular boxes indicate the major genesis region and major RI region respectively. The black solid rectangular box represents the area with a significant correlation between the VWS and annual PDI.

going RI over the SCS, which is related to the increase in the annual PDI for the southern TCs.

4.2. TCHP

Because TCHP data are only available between 1980 and 2017, the analysis is performed for the period

1980–2017. The correlation map between the TCHP and annual number of RI-TCs reveals the pattern associated with El Niño–Southern Oscillation (ENSO), with positive correlations in the equatorial Central and East Pacific (Fig. 7a). Indeed, the annual number of RI-TCs is significantly correlated with the May–Nov Niño3.4 index ($r = 0.52$), with more

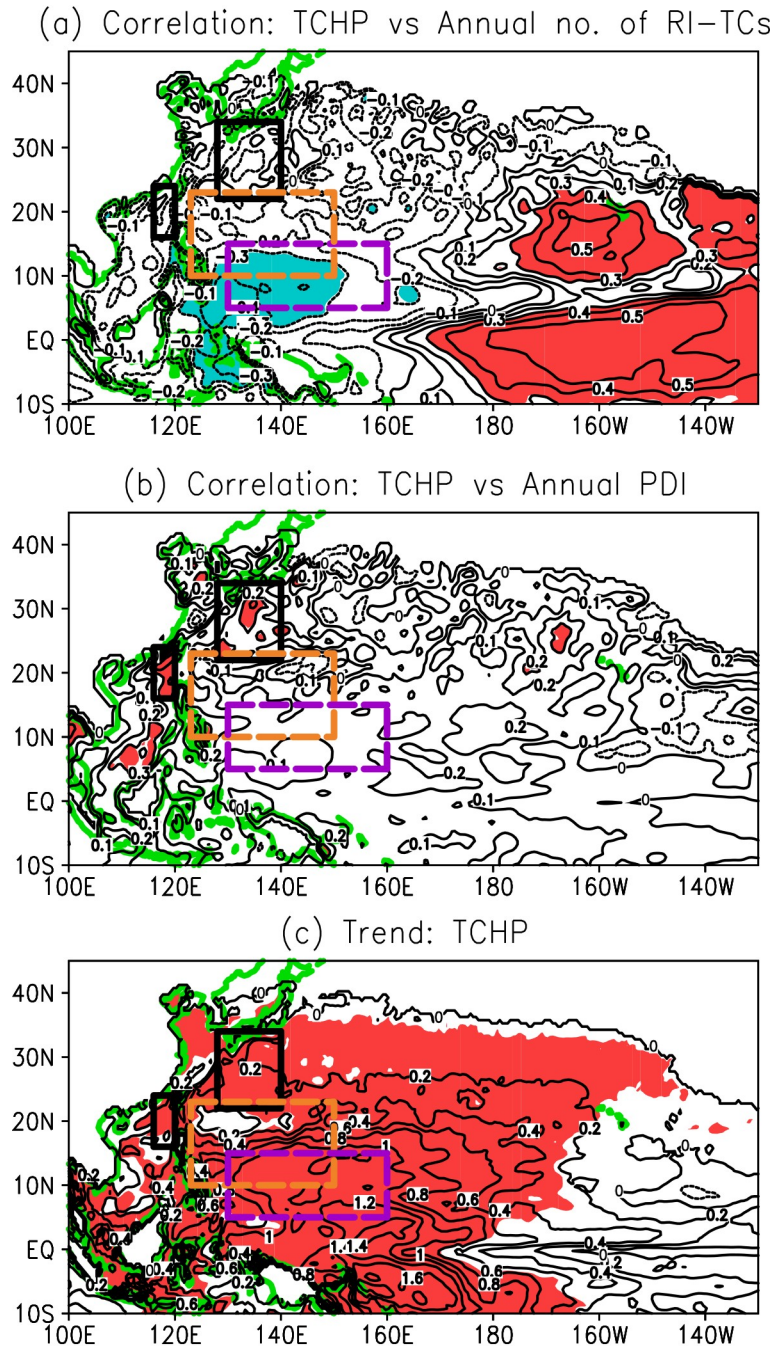


Fig. 7. Correlation maps (a) between the TCHP and annual number of RI-TCs and (b) between the TCHP and annual PDI. (c) Spatial distribution of the linear trends in TCHP (units: $\text{kJ cm}^{-2} \text{yr}^{-1}$). Red and blue shadings indicate the areas with positive and negative correlation/trend significant at the 90% confidence level respectively. The purple and orange dashed rectangular boxes indicate the major genesis region and major RI region respectively. The black solid rectangular boxes represent the area with a significant correlation between the TCHP and annual PDI.

(fewer) RI-TCs in an El Niño (La Niña) year. The correlation map for the annual PDI is quite different, with the positive correlations extending from the ocean south of Japan to the SCS (Fig. 7b). The correlation between the mean TCHP in these regions and annual PDI is 0.35, which is statistically significant at the 95% confidence level. No significant correlation is found in the equatorial Central and East Pacific, suggesting that ENSO has no impact on the annual PDI. Thus, the annual number of RI-TCs is largely related to the ENSO while the annual PDI is partly controlled by the TCHP near the coast of East Asia.

Positive trends in TCHP are found in most parts of the WNP, especially the ocean east of the Philippines (Fig. 7c). However, the increase in TCHP in the tropical WNP may not be related to the increase in annual PDI (see Fig. 7b) because the TCHP in this area is generally high enough for RI and a further increase in TCHP may not lead to an increase in annual PDI. Instead, the increase in TCHP near the coast of East Asia may partly explain the recent increase in annual PDI. Climatologically, the TCHP in the SCS and ocean south of Japan is generally lower and hence a lower frequency occurrence of RI. However, the recent increase in TCHP in these regions provides more heat energy from the ocean for TC intensification and supports a TC undergoing RI. An increasing trend in RI occurrence is therefore found in these regions (see Fig. 4b). The higher heat energy over the SCS, which increases the chance of a TC to undergo RI, results in a higher number of RI-TCs over the SCS and hence resulting in the increase in annual PDI for south TCs. The higher TCHP also provides more heat energy for TCs undergoing RI in the northwestern part of the WNP, resulting in an increasing trend of annual PDI for north TCs. Tropical cyclone heat potential (TCHP) has been shown to be the factor responsible for the increases in RI events (Wang et al., 2015), annual mean LMI (Song et al., 2021), and annual mean landfall intensity (Guan et al., 2018). Our results further demonstrate its role in the increase in annual PDI associated with landfalling RI-TCs. The increase in TCHP may be related to the recent strengthening of the easterly trade winds, which pile up warm surface ocean water towards the WNP main development region (Merrifield and Maltrud, 2011; Pun et al., 2013).

5. Summary and discussion

5.1. Summary

This study examines the long-term change in the threat of landfalling TCs in East Asia over the period 1975–2020 with a focus on the RI-TCs. The annual number of RI-TCs over the WNP shows a significant increasing trend. The mean genesis location of the RI-TCs shows an obvious northward shift which increases the likelihood that an RI-TC will make landfall and hence the percentage of RI-TCs that make landfall. These two changes lead to an increasing trend in the annual number of landfalling RI-TCs along the coast of East Asia. The annual PDI, a measure of the destruct-

ive potential of RI-TCs at landfall, also shows a significant increasing trend as a result of the increases in the annual frequency and mean landfall intensity of landfalling RI-TCs. The increase in mean landfall intensity is related to the higher LMI and the closer LMI location to the coast of the landfalling RI-TCs. The main contributors to the increase in the annual PDI of East Asia are the southern (the Philippines, South China, and Vietnam) and the northern (Japan and the Korean Peninsula) parts. The former is a result of the increases in both landfall frequency and landfall intensity in these regions. The latter is mainly related to the increase of landfall frequency, but the change of landfall intensity in the northern part of the domain is insignificant.

The long-term changes in VWS and TCHP are shown to be responsible for the increasing trend of the annual PDI along the coast of East Asia. The decreasing trend in VWS in the northwestern part of the WNP implies a northwestward shift in the favorable environment for TC genesis and intensification, which might explain the northwestward shift in the genesis, RI, and LMI locations of RI-TCs. The weakening of VWS over the northern part of the SCS is related to the increasing trend of the annual PDI associated with the RI-TCs making landfall in South China and Vietnam. Increasing trends in TCHP are found in most parts of the WNP. The higher TCHP provides more heat energy from the ocean for TC intensification and supports a TC undergoing RI, which partly explains the increasing frequency of RI-TCs over the entire WNP. Moreover, the increase of TCHP in the SCS and ocean south of Japan, where the climatological TCHP is generally lower and is less favorable for RI, leads to a higher frequency of RI-TCs affecting South China, Vietnam, Japan, and the Korean Peninsula. The LMI locations of the RI-TCs are generally closer to the coast, resulting in higher landfall intensity and hence the higher annual PDI in these regions.

5.2. Discussion

Compared with previous studies (Park et al., 2014; Mei and Xie, 2016; Guan et al., 2018) that investigated the long-term change in the threat of landfalling TC activity, this study focuses on the landfalling TCs that undergo RI prior to landfall. Among the TCs, the landfalling RI-TCs may be a particularly dangerous type because most of them could develop into intense TCs and the intensity at landfall may be high. Moreover, the migration of RI locations towards the coast of East Asia causes the LMI location to be closer to the coast so that the TC may make landfall shortly after the occurrence of LMI, leaving very little time for typhoon preparation and evacuation. The social and economic impacts could be tremendous due to the inadequate preparation and evacuation, which results from the short notice of an intense TC landfall. Thus, an accurate forecast of the RI events is very important. However, the forecasting of TC intensity change represents a forecast challenge, especially within the RI process. Our results, therefore, highlight the need for improving our understanding of RI and enhancing the skill in the forecast of RI events especially the ones that

occur just prior to landfall.

Previous studies have shown that the annual frequency (Song et al., 2020), the annual mean LMI (Song et al., 2021), and RI magnitude (Song et al., 2020) of RI-TCs have significant upward trends. Our study further shows a significant trend in the annual frequency of landfalling RI-TCs and the annual PDI along the coast of East Asia. Collectively, these results suggest an increasing threat of RI-TCs. Therefore, a need exists for a re-examination of contingency plans for RI-TCs, and the raising of public awareness of the risk of RI-TCs especially for the ones near the coast.

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