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LETTER

Autumn tropical cyclone slowdown in East Asia: a link to pacific decadal oscillation

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Abstract

In the mid-1990s, a phase shift in the Pacific Decadal Oscillation (PDO) altered atmospheric circulation over the western North Pacific (WNP). This study explores the relationship between seasonal changes in environmental flow associated with PDO phase shift and the translation speed of tropical cyclones (TCs) over East Asia during the 41-year period from 1982 to 2022. In summer, despite a negative phase in the PDO, changes in westerly winds (25–45 °N, 120–150 °E) are relatively small, resulting in no significant trend in TC translation speed or steering flow over East Asia. In contrast, autumn shows a notable weakening of westerly winds, accompanied by significant decreases in both TC translation speed and steering flow. In particular, TCs between 25 °N and 35 °N experience a marked slowdown in the translation speed during negative PDO phases in autumn. Although a northward migration of autumn TCs during negative PDO phases is generally associated with faster translation speeds in the mid-latitude, the observed slowdown in autumn suggests that the weakening of westerly flow during negative PDO phases has a stronger influence on TC motion than the acceleration effect of increased TC latitude. These findings highlight a strong seasonal dependence in the relationship between the PDO and TC translation, with the PDO playing a critical role in slowing TC movement over East Asia during autumn.

1. Introduction

Tropical cyclones (TCs) frequently cause severe disasters such as heavy rainfall, strong winds, and storm surges, particularly affecting coastal regions. From 1991 to 2020, South Korea, Japan, and China, located in the western North Pacific (WNP), experienced annual averages of 3.4, 11.7, and 13.0 TCs, respectively, resulting in significant human casualties and economic damage (Peak Re 2024, JMA 2025, KMA 2025). TC activity in the WNP is strongly influenced by climate phenomena, notably the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Zhang *et al* 1997, Huang *et al* 2022). ENSO, characterized by fluctuations in sea surface temperature (SST) across the tropical Pacific, significantly affects the expansion and contraction of the subtropical high. This variability influences TC genesis locations in the WNP and contributes to interannual variations in TC intensity (Carmago *et al* 2007, Wang and Wang 2013, Kim *et al* 2020a).

The PDO represents long-term variations in SST over the North Pacific, occurring on a longer time scale than ENSO (Zhang *et al* 1997, Mantua and Hare 2002). The PDO significantly alters the large-scale environmental conditions in the WNP, with its impacts varying seasonally (Lee *et al* 2021). During negative PDO phases, the SST in the North Pacific typically increases, the subtropical high changes, and the westerly winds weaken in the mid-latitude. These changes are especially pronounced in autumn, substantially influencing TC activity (Lee *et al* 2019b, Yamaguchi and Maeda 2020). Consequently, the number of autumn TCs affecting East Asia has increased since the PDO shifted to a negative phase in 1997 (Basconcillo and Moon 2022).

The movement of TCs is primarily influenced by large-scale environmental flow patterns, such as monsoons, anticyclonic circulations of subtropical highs, and jet streams in the mid-latitude. Generally, these large-scale flows have a stronger impact on TC motion than internal forces within the TC itself (Torn *et al* 2018, Ashcroft *et al* 2021). Internal forces, notably the beta effect, typically contribute about 1 to 3 ms^{-1} to the translation speed of TCs (Holland 1982, Chan and Williams 1987, Chan 2005).

Kossin (2018) reported a global decrease in TC translation speeds from 1949 to 2016, attributing this to weakened atmospheric circulation under global warming. However, Moon *et al* (2019) and Lanzante (2019) argued that the TC best track data before the 1970s, as used in Kossin (2018), are unreliable due to incomplete records, particularly for weaker TCs far from coastlines. Furthermore, several studies have shown that TC translation speeds since the satellite observation era do not exhibit significant slowing trends globally (Chan 2019, Kim *et al* 2020b). This lack of a clear global trend is explained by offsetting effects: a northward shift in TC activity and weakening atmospheric circulation, both driven by global warming. Nevertheless, numerical experiments under future warming scenarios indicate that TC translation speeds could decrease in mid-latitude regions (Yamaguchi *et al* 2020, Zhang *et al* 2020, Cao *et al* 2025).

In the WNP, analyses based solely on TC best track data do not reveal clear trends in TC translation speed (Wang *et al* 2020, Sun *et al* 2021). Only studies employing additional analytical methods—such as subdividing the WNP (Chang *et al* 2020), clustering TC tracks (Fu *et al* 2025), removing climate drivers' trends from TC data, and applying weighted averages based on relative track density (Feng 2024) —identified meaningful trends. Over the Korean Peninsula and Japan, recent northward shifts in TC activity combined with changes in large-scale climate patterns have increased TC frequency and track density (Choi and Kim 2019a, Choi and Kim 2020, Kim *et al* 2023). Several recent studies have examined TC tracks and intensities in East Asia, as well as the influence of large-scale climate variability on TC translation speed (Wang *et al* 2020, Guo *et al* 2023). However, seasonal variations in these relationships remain largely unexplored. Therefore, this study aims to investigate seasonal changes in TC translation speed over East Asia and examine their connection to natural climate variability, with particular focus on the PDO. The rest of the paper is organized as follows: section 2 describes the datasets and methods used in this study, section 3 examines the seasonal differences in TC translation speed and their relationship with the PDO, and section 4 provides the summary and discussion of the findings.

2. Data and methods

The PDO and Oceanic Niño Index (ONI) data used in this study were obtained from the Physical Science Laboratory (PSL) of the National Oceanic and Atmospheric Administration (NOAA). These indices cover the period from 1982 to 2022 and were calculated using the Extended Reconstructed Sea Surface Temperature (ERSST) dataset. To identify significant shifts in large-scale climate fields, the change-point detection method by Truong *et al* (2020) was applied to these climate indices.

Seasonal mean atmospheric variables (geopotential height and horizontal wind) were obtained from the fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data (ERA5, Hersbach *et al* 2020), which provide monthly mean data at a horizontal resolution of $0.25^\circ \times 0.25^\circ$. The mean flow was calculated using a vertical mass-weighted average from 850 hPa to 200 hPa (Moon *et al* 2021). Similarly, the steering flow was calculated from 6-hourly ERA5 data using the same vertical averaging method but was computed as an area average within a radius between 500 km and 800 km from the TC center, minimizing the influence of the TC itself.

We utilized 6-hourly TC best-track data from the Joint Typhoon Warning Center (JTWC) and the Japan Meteorological Agency (JMA). To ensure data homogeneity and reliability, we selected TC data over the WNP during the satellite observation era (1982–2022). TC data points were included only if their maximum wind speeds exceeded the threshold of tropical storm intensity (17.2 $\mathrm{m\,s}^{-1}$). We selected TC points within the range of 25–45 °N and 120–150 °E as the analysis area, and the records at the standard observational times: 00, 06, 12, and 18 Coordinated Universal Time (UTC). The translation speed of TCs was calculated using the centered difference method, except for initial and final points, which employed forward and backward difference methods, respectively. A 3-year running average was applied to clarify long-term trends. The trends of TC motion-related variables and environmental data, are implemented with the least-squares linear regression. Additionally, statistical significance of linear trends, correlation coefficients, and differences between means were tested using Student's t-test.

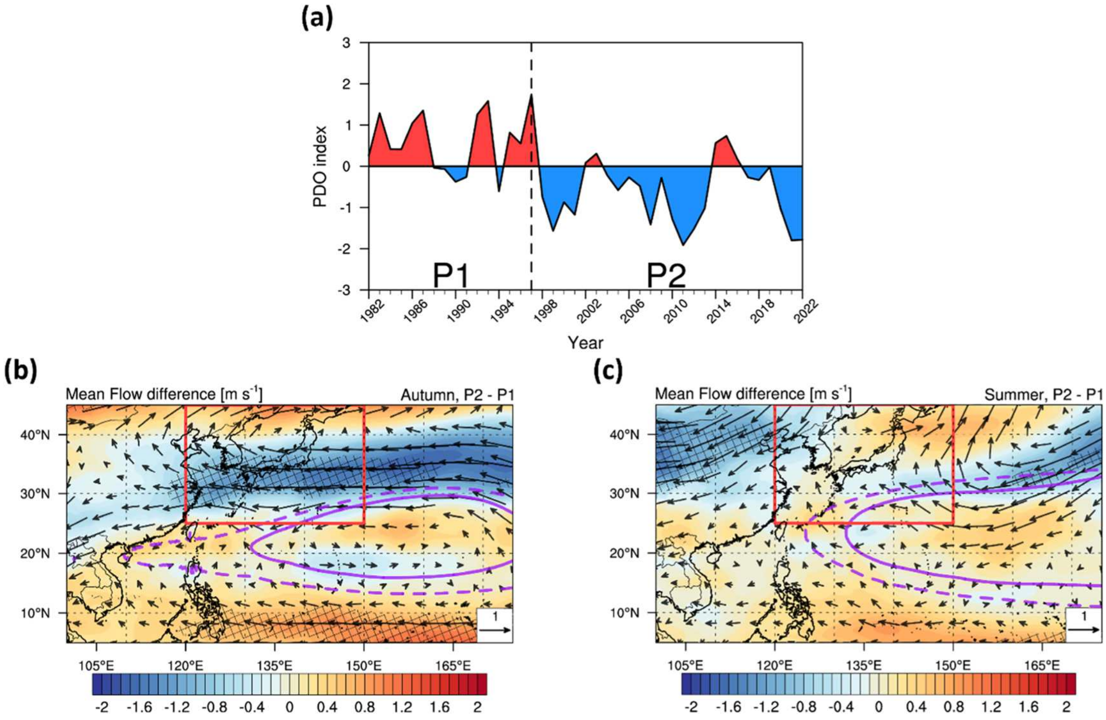

Figure 1. (a) Time series of annual PDO index in June-November, and (b), (c) the difference in the mean flow between P1 period and P2 period in the (b) autumn and (c) summer. The dashed line of (a) indicates a change point of PDO. Shading and vector in (b), (c) represent the magnitude and direction of mean flow differences. Solid red boxes in (b), (c) denote the analysis area (25–45 °N, 120–150 °E). Purple solid and dashed lines in (b), (c) are the edges of subtropical high (5870 gpm) in P1 and P2, respectively. The difference in the speed of mean flow at 0.05 confidence level in (b), (c) is indicated by the hatched lines.

3. Results

3.1. Phase shift of the PDO and changes in environmental flows over East Asia by season

We applied a change-point detection method to both the PDO and ONI indices; however, due to the relatively short and frequent phase shifts observed in the ONI (figure S1), a valid change point was identified only for the PDO. Figure 1(a) shows the annual PDO index during the TC active season (June–November) over the WNP, with the dashed line marking the identified PDO phase shift. Figures 1(b) and (c) illustrate differences in seasonal mean flow and subtropical high boundaries over the WNP for two distinct periods: until 1997 (P1) and after 1997 (P2). Generally, the large-scale flow over East Asia is governed by the subtropical high and westerly wind in the mid-latitude (Choi and Kim 2019b, Son *et al* 2021, Kukulies *et al* 2024). During period P2, the subtropical high expanded further westward compared to period P1 in both seasons. In summer, the westerlies weaken over the Inner Mongolia and North China region (30–45°N, 100–120°E) and the North Pacific (30–40° N, 155–175°E). However, the westerly wind significantly weakened only during autumn near the Korean Peninsula and Japan (25–45 °N, 120–150 °E). This seasonal difference aligns well with previous studies examining changes in atmospheric conditions associated with PDO phases (Lee *et al* 2021, Basconcillo and Moon 2022). Based on these findings, we defined the region experiencing significant mean flow changes (25–45°N, 120–150°E; red boxes in figures 1(b) and (c)) as the analysis area, selecting TC points entering this area for further analysis.

Within the analysis area (figures 1(b) and (c)), the difference in mean flow between the two periods is considerably larger in autumn (-0.472 m s^{-1}) than in summer (-0.047 m s^{-1}). Meridional wind differences between the periods are similar for both autumn (0.137 m s^{-1}) and summer (0.114 m s^{-1}). However, the zonal wind difference is notably greater in autumn (-0.596 m s^{-1}) compared to summer (-0.120 m s^{-1}). This marked reduction in zonal wind during period P2 is associated with a weakening meridional temperature gradient (figure 1(b) and figure S2), resulting the change of thermal wind balance. The thermal wind is defined as the vector difference in the geostrophic wind between two pressure levels p_1 and p_0, where p_0 is closer to the surface (and thus $p_0 > p_1$). It is not an actual wind, but it is a useful construct that allows us to link the geostrophic wind (a kinematic field) to temperature (a mass field). Equation (1) defines the thermal wind and states that the change in geostrophic wind between two isobaric levels is directly related to the horizontal layer-mean temperature gradient.

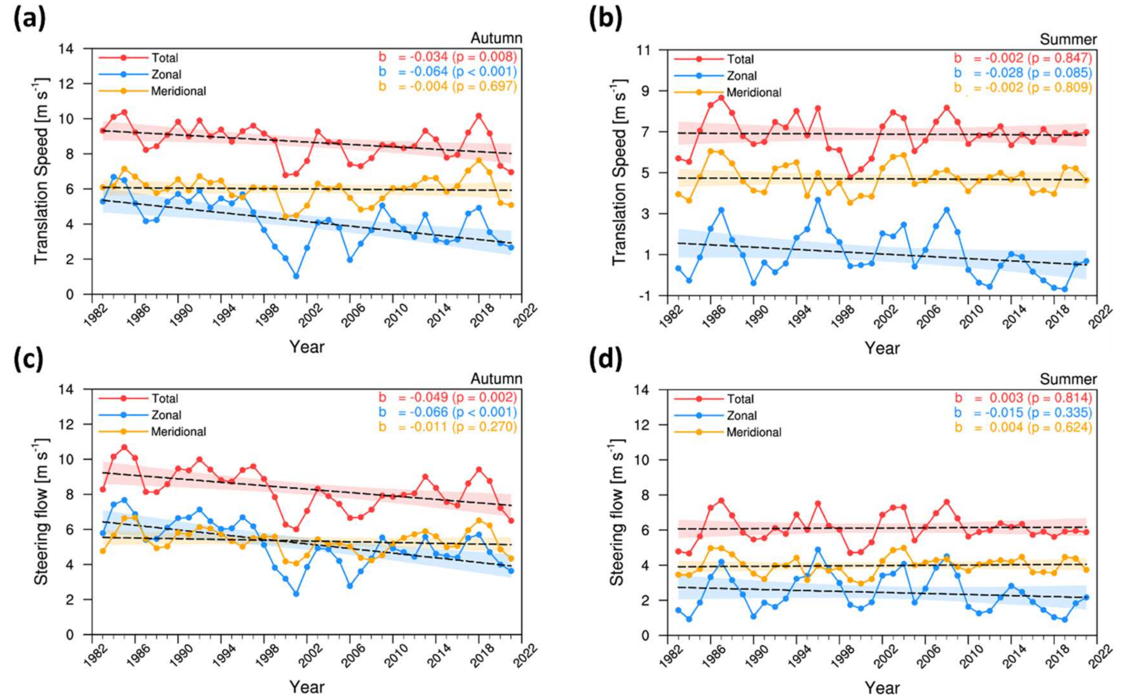

Figure 2. Time series of annual TC (a, b) translation speed and (c, d) steering flow for selected samples from JTWC best track data in the (a, c) autumn and (b, d) summer. Red, blue, and orange dotted solid lines indicate total, zonal, and meridional components, respectively. The time series are calculated by a 3-year running average using annual means of TC samples entering the analysis area (25–45 °N, 120–150 °E). **b** and **p** mean the slope and p-value for linear trends of both variables. The black dashed lines and color shading mean the linear fit of TC translation speed and steering flow in each component and 95% confidence interval for the linear fit.

$$u_T \equiv u_g(p_1) - u_g(p_0) = -\frac{R_d}{f}\frac{\partial \overline{T_v}}{\partial y}\ln\left(\frac{p_0}{p_1}\right) \tag{1a}$$

$$v_T \equiv v_g(p_1) - v_g(p_0) = \frac{R_d}{f}\frac{\partial \overline{T_v}}{\partial x}\ln\left(\frac{p_0}{p_1}\right) \tag{1b}$$

Therefore, a reduced meridional temperature gradient weakens the upper-level jet through thermal wind balance (Lee *et al* 2019a, Wu *et al* 2024, Park *et al* 2025). Since TC motion in the mid-latitude is primarily driven by the upper-level wind, weakening of the upper-level jet reduces TC translation speed. Alternatively, during negative PDO phases, the SST front shifts northward, causing a corresponding poleward displacement of the upper-level jet (Matsumura and Horinouchi 2016), potentially reducing its influence on TC motion.

3.2. Slowing trends in TC translation speed and steering flow in autumn

Figure 2 illustrates the annual mean translation speed and steering flow of TC samples that entered the analysis area during autumn and summer. Comparing periods P1 and P2, the differences in translation speed for total, zonal, and meridional components are -0.896 m s^{-1}, -1.905 m s^{-1}, and -0.253 m s^{-1} in autumn, and -0.466 m s^{-1}, -0.573 m s^{-1}, and -0.274 m s^{-1} in summer, respectively. The reduction in zonal translation speed during autumn is significantly greater, approximately three times larger than in summer. Similarly, the zonal component of steering flow also exhibits a more pronounced decrease in autumn compared to summer (table S1).

Linear trends of TC translation speed in autumn are significant for total (-0.034 m s^{-1} yr^{-1}, $p = 0.008$) and zonal (-0.064 m s^{-1} yr^{-1}, $p < 0.001$) components, but not for the meridional component (-0.004 m s^{-1} yr^{-1}, $p = 0.697$). In contrast, summer trends are insignificant and smaller (figures 2(a) and (b)). Similar to TC translation speed, trends of the steering flow in autumn also show significant decreases in total (-0.049 m s^{-1} yr^{-1}, $p = 0.002$) and zonal (-0.066 m s^{-1} yr^{-1}, $p < 0.001$) components, but an insignificant meridional trend (-0.011 m s^{-1} yr^{-1}, $p = 0.270$). The steering flow in summer displays no significant trends (figures 2(c) and (d)). TC translation speed and steering flow are highly correlated ($r > 0.88$) in both seasons. These seasonal differences and trends are consistent with results derived from the JMA best-track data (figure S3). These results emphasize the critical role of weakening environmental flow over East Asia during period P2, particularly in autumn.

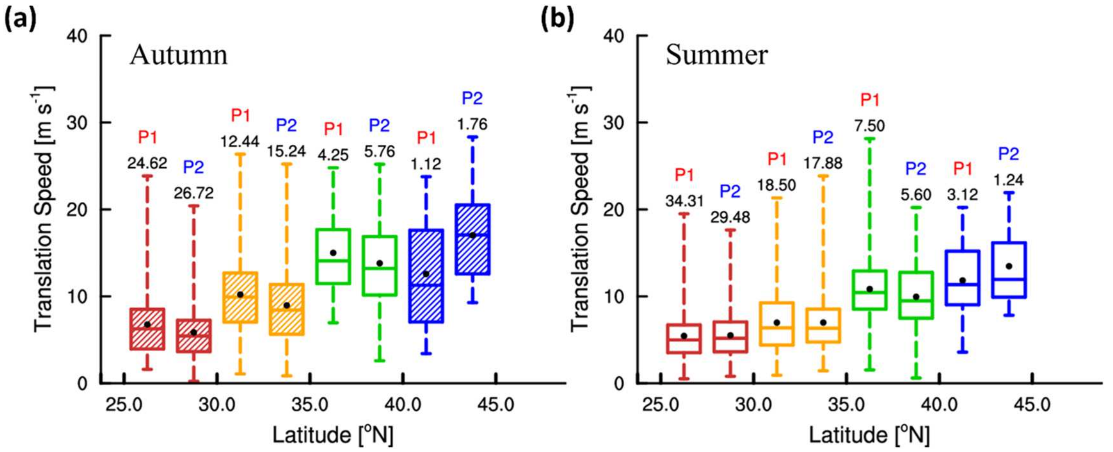

Figure 3. The boxplots of latitudinal translation speed with 5° interval during two periods (P1 and P2) for JTWC best track data in the (a) autumn and (b) summer. The boxplots are calculated using TC samples entering the analysis area (25–45 °N, 120–150 °E) during each period. The black dots indicate the mean translation speed for each range and the numbers above the boxplots are the annual mean sample sizes in each range. The hatched boxes indicate regions where the mean difference between the two periods is statistically significant at the 95% confidence level. The difference between the means (black dots) of two periods is shown in Table S3.

Table 1. Correlation coefficients between climate indices (PDO, ONI) and TC-related variables for JTWC best track data in autumn and summer. Annual values for each variable by season are used to calculate the correlation. The asterisk mark means the significance level (*: 0.05 level, **: 0.01 level).

	AUTUMN		SUMMER	
	PDO	ONI	PDO	ONI
Total Translation Speed	0.571^{**}	0.302	0.293	0.324^{*}
Zonal Translation Speed	0.612^{**}	0.199	0.358^{*}	0.144
Meridional Translation Speed	0.417^{*}	0.353^{*}	0.252	0.313^{*}
Total Steering Flow	0.666^{**}	0.316	0.237	0.301
Zonal Steering Flow	0.706^{**}	0.283	0.319^{*}	0.189
Meridional Steering Flow	0.430^{**}	0.288	0.210	0.280
Latitude	-0.394^{*}	−0.200	0.440^{**}	0.235

Although TC translation speed generally increases with latitude, there is an overall decreasing trend during autumn. To investigate this further, we analyzed latitudinal variations in TC translation speed over the analysis area. Figure 3 presents latitudinal boxplots of TC translation speed for both periods P1 and P2 in autumn and summer. The translation speed consistently rises with latitude in both seasons. In summer, differences in translation speed between the two periods are minor at latitudes below 35 °N. However, during autumn, the differences between P1 and P2 are notably greater and statistically significant, particularly in the latitude range of 25–35 °N (table S3). Although the translation speed between 40–45 °N increases in P2 for both seasons, small sample sizes make this finding unreliable. Similar trends and significant differences are also observed in autumn steering flow across the same latitude bands (figure S4 and table S3). In summary, a pronounced weakening of steering flow at lower latitudes (25–35 °N) during autumn leads to a significant reduction in TC translation speeds, whereas summer data shows minimal changes between periods P1 and P2.

3.3. Correlation between the PDO and translation speed of autumn TCs

Changes in steering flow over East Asia, which strongly influence TC translation speed, are closely linked to climate factors that modify environmental conditions in the region. Table 1 shows correlation coefficients between climate indices (PDO, ONI) and various TC-related variables for autumn and summer. Correlations were calculated using seasonal means of climate indices and TC-related variables derived from selected TC samples. Despite ENSO's known impacts on TC activity over East Asia, the ONI shows weak correlations with TC motion variables in both seasons. In contrast, TC translation speed exhibits a significant positive correlation with the PDO only in autumn, with no significant correlation observed in summer. Among the analyzed variables, the zonal steering flow demonstrates the strongest positive correlation with the PDO, particularly in

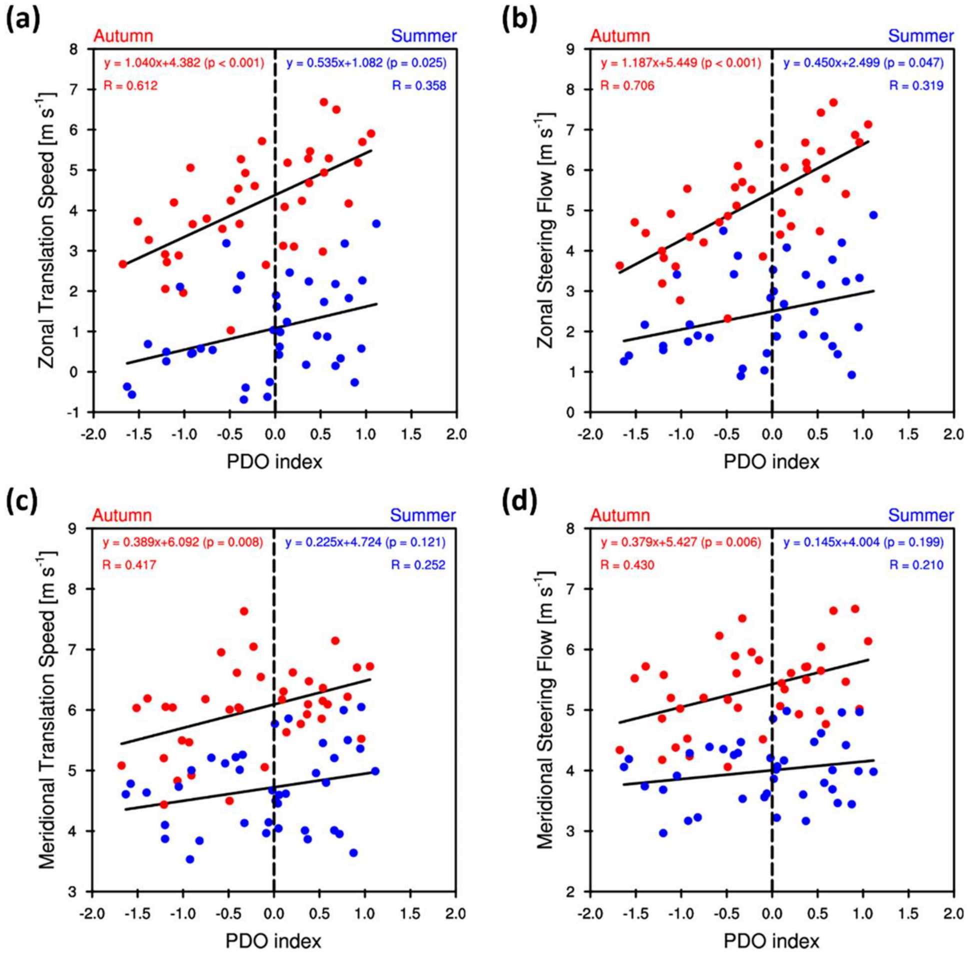

Figure 4. Scatter plots of annual (a), (c) translation speed and (b), (d) steering flow with PDO index in the (a), (b) zonal and (c), (d) meridional direction. Red (blue) dots and labels represent autumn (summer) TCs. Two black dashed lines in each panel mean linear fit for autumn and summer TCs. The linear relationship (**y**) and significance level (**p**) are shown at the top of each panel. **R** is the correlation coefficient between the PDO index and motion-related variable.

autumn, whereas the meridional steering flow shows a weaker correlation. In summer, correlations between PDO and TC-related variables are generally weaker or insignificant, except for TC latitude. TC latitude is positively correlated with the PDO in summer but negatively correlated in autumn. Although the northward migration of autumn TCs at the mid-latitude typically results in faster TC translation speed, the observed trend in autumn instead shows a slowdown (figure 2(a)). Furthermore, TC translation speed in autumn is positively correlated with the PDO. This indicates that the weakening of westerly in the mid-latitude during negative PDO phases has a more substantial impact on reducing TC translation speeds than the northward shift in latitude, which would otherwise accelerate TC motion.

Figure 4 presents scatter plots of TC motion-related variables against the PDO index, along with corresponding linear regressions, to examine the linear relationships between the strengthening of the negative PDO phase and TC motion-related variables. On average, all components of TC translation speed and steering flow are greater in autumn than in summer. When comparing the zonal and meridional components by season, autumn shows similar magnitudes between the two components, whereas in summer, the meridional component is larger than the zonal component. Both the zonal components of TC translation speed and steering flow exhibit statistically significant linear relationships with the PDO in both seasons, but the regression slopes are steeper in autumn than in summer. For the meridional components, only autumn shows significant linear associations with the PDO. These results suggest that the strengthening of the negative phase of the PDO is associated with a slowdown in TC translation speed over East Asia, with this influence being particularly pronounced in autumn.

3.4. Seasonal differences in the influence of the PDO on TC translation speed

In summer, weaker baroclinicity results in a slow westerly at the mid-latitude, whereas in autumn, stronger baroclinicity enhances the westerly flow (figure S5 and S6). The steering flow in summer shows no clear trend, while in autumn, the zonal component exhibits a significant decreasing trend. The seasonal structure of steering flow also differs: in autumn, the zonal and meridional components are relatively balanced, while in summer, the meridional component is dominant (figure 4). Since TCs tend to follow the western edge of the subtropical high, autumn TC tracks often show recurvature, while in summer, recurving typically occurs farther north or may not occur at all, with some TCs continuing their northward movement (figure S8). The larger meridional component observed in summer may reflect the seasonal northward expansion of the subtropical high. Although PDO-related weakening of westerlies is detected in both seasons (figures S4 and S5), its influence on TC motion appears limited during summer, when the zonal component is already weak. Consequently, it is inferred that TC translation speed and steering flow are positively correlated with the PDO only during autumn, with the linear relationships showing steeper slopes than those observed in summer.

4. Summary and discussion

This study investigated the influence of a major climate driver, the PDO, on TC translation speed over East Asia by season. The PDO shifted to a predominantly negative phase after 1997. During negative PDO phases, the mean flow over East Asia, especially in autumn, weakened significantly, with the zonal component showing the largest reduction. Correspondingly, TC translation speed and steering flow also declined, with statistically significant decreasing trends observed in their zonal components. In contrast, no clear trends were identified in summer for either translation speed or steering flow, although a slight reduction in interannual variability was noted in recent years. The latitude-based analysis further revealed that TCs in autumn moved more slowly after the PDO phase shift, particularly within the lower latitude range of 25–35 °N. This region where TC translation speed and steering flow showed significant decreases, corresponds to the pathway of TCs that made landfall in East China, the Korean Peninsula, and Japan (figure S9). Moreover, the northward migraion of TC tracks and overlap between major paths of landfalling autumn TCs and regions of increased TC track density after the phase shift of PDO support the importance of investigating TCs in this area (25–35 °N) over East Asia (figure S9-10 and table S4-5).

The correlations between TC motion-related variables and the PDO are generally stronger in autumn than in summer, with statistically significant positive correlations and linear relationships observed particularly in the zonal components during autumn. In contrast, during summer, the correlations between the PDO and TC translation variables are weaker, and the slopes of the linear relationships are more modest. In autumn, the zonal and meridional components of the steering flow are comparable magnitude, whereas in summer, the contribution of the zonal component is considerably smaller, and TCs tend to recurve later or move predominantly northward. As a result, the weakening of the westerly during the negative phase of the PDO has a limited impact on TC movement in summer.

The PDO was considered as a key mode of natural climate variability in this research. However, many studies have shown that various modes of long-term climate variability are linked to TC activity in the western North Pacific, one of which is the Atlantic Multidecadal Oscillation (AMO) (Chan and Liu 2022, Wang *et al* 2022, Wang *et al* 2023). Thereforeexploring the linkage between other climate variability modes such as the AMO and TC translation speed over East Asia could serve as a valuable topic for future research.

We know the analyzed 41-year period inevitably includes the influence of global warming. To assess whether global warming effects are significant, it is necessary to minimize the impact of long-term climate variability. Following previous studies (Kossin *et al* 2014, Kossin *et al* 2016, Feng *et al* 2021), we performed a linear regression using a least-squares method to estimate and remove the PDO-driven variability from TC-related variables. After removing PDO-related variations from the translation speed and steering flow, the meridional components showed minimal changes (figure 5). However, the declining trends in zonal translation speed and steering flow notably decreased by more than half. The changes in residual components of TC translation speed were not statistically significant, and no discernible trend attributable to global warming was identified. Since we removed the PDO-related signal using a simple method over the analysis period, we cannot conclusively rule out the influence of global warming. However, the substantial reduction in the declining trend underscores the significant role of the PDO in contributing to the recent slowdown of TC translation speed over East Asia in autumn.

Previous studies have shown that under global warming, TC activity is shifting poleward (Feng 2024, Cao *et al* 2025) and that weakened atmospheric circulation in the future can reduce the latitudinal translation speed of TCs. There is also broad consensus that TC intensity is strengthening and will continue to do so in warming scenarios (Elsner 2020, Kossin *et al* 2020). While the present study confirms that natural variability has played a dominant role in driving changes in TC translation speed over East Asia, it underlines the need for a detailed

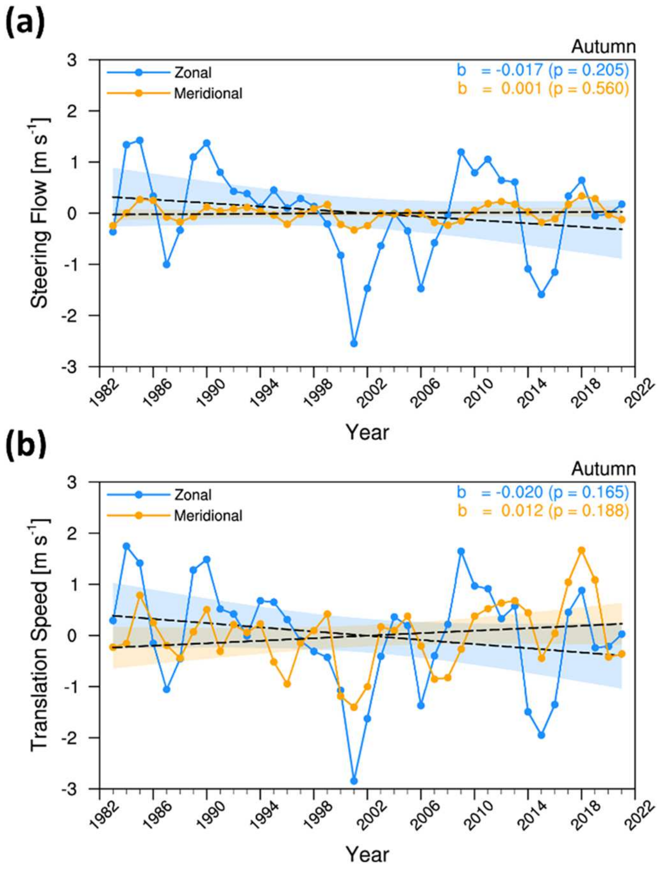

Figure 5. Time series of annual TC (a) translation speed and (b) steering flow for JTWC best track data with PDO-related value removed in the autumn. Blue and orange dotted solid lines indicate zonal and meridional components, respectively. The time series are calculated by a 3-year running average using annual means of TC samples entering the analysis area (25–45 °N, 120–150 °E). **b** and **p** mean the slope and p-value for linear trends of both variables. The black dashed lines and color shading mean the linear fit of TC translation speed and steering flow in each component and 95% confidence interval for the linear fit.

assessment of how future changes in the atmospheric environment under global warming may affect TC translation speed.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Author contributions

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