Received: 20 February 2019 | Revised: 23 September 2019 | Accepted: 2 October 2019
DOI: 10.1002/asl.939

RESEARCH ARTICLE

Atmospheric Science Letters RMetS

Long-term trends in tropical cyclone tracks around Korea and Japan in late summer and early fall

Minkyu Lee[1] | **Dong-Hyun Cha**[1] | **Jihong Moon**[1] | **Jinyoung Park**[1] | **Chun-Sil Jin**[2] | **Johnny C. L. Chan**[3]

[1]School of Urban & Environmental Engineering, Ulsan National Institute of Science and Technology, Ulsan, Republic of Korea

[2]Department of Nuclear Emergency Preparedness Division of Emergency Preparedness, Korea Institute of Nuclear Safety, Daejeon, Republic of Korea

[3]Guy Carpenter Asia-Pacific Climate Impact Centre, School of Energy and Environment, City University of Hong Kong, Hong Kong, China

Correspondence
Dong-Hyun Cha, School of Urban and Environmental Engineering, Ulsan National Institute of Science & Technology (UNIST), 50 UNIST-gil, Ulju-gun, Ulsan 689-798, Republic of Korea.
Email: dhcha@unist.ac.kr

Funding information
Korea Meteorological Administration, Grant/Award Number: KMIPA 2017 7010; National Research Foundation of Korea, Grant/Award Number: NRF-2016M3C4A7952637

Abstract

This study investigates long-term trends in tropical cyclones (TCs) over the extratropical western North Pacific (WNP) over a period of 35 years (1982–2016). The area analyzed extended across 30–45°N and 120–150°E, including the regions of Korea and Japan that were seriously affected by TCs. The northward migration of TCs over the WNP to the mid-latitudes showed a sharp increase in early fall. In addition, the duration of TCs over the WNP that migrated northwards showed an increase, specifically in early to mid-September. Therefore, more recently, TC tracks have been observed to significantly extend into the mid-latitudes. The recent northward extension of TC tracks over the WNP in early fall was observed to be associated with changes in environmental conditions that were favorable for TC activities, including an increase in sea surface temperature (SST), decrease in vertical wind shear, expansion of subtropical highs, strong easterly steering winds, and an increase in relative vorticity. In contrast, northward migrations of TCs to Korea and Japan showed a decline in late August, because of the presence of unfavorable environmental conditions for TC activities. These changes in environmental conditions, such as SST and vertical wind shear, can be partially associated with the Pacific decadal oscillation.

KEYWORDS

long-term trends, power dissipation index, synoptic field analysis, tropical cyclones

1 | INTRODUCTION

Tropical cyclones (TCs) are considered to be the most destructive natural hazards in East Asia. Storm surges, floods, and strong winds that are associated with TCs cause significant casualties and damage to property. About 25 to 30 TCs occur annually over the western North Pacific (WNP) basin, among which at least four TCs have caused direct damage in Korea and Japan (Wu *et al.*, 2004). More recently, climate change has brought about a rapid increase in temperature in the lower troposphere and the sea surface temperatures (SST) in the WNP (Kim *et al.*, 2011; Liu and Zhang, 2013). Such environmental changes, along with changes in the associated synoptic fields, could affect the characteristics of TC, which can subsequently alter the damage caused by them in Korea and Japan. For example, Typhoon Rusa in 2002 caused 4.5 billion USD worth of damage in Korea due to record-breaking heavy rainfall, and Typhoon Songda in 2004 resulted in about 9 billion USD worth of damage in Japan due to flooding and strong winds (Lee and Choi, 2010; Re, 2014). These two typhoons caused severe damage in Korea and Japan in the early fall season. Since the damage caused by TCs in early fall appear to have increased in the recent years, research on the long-term variability of TCs and associated events is necessary. Therefore, the purpose of this study is to investigate the recent changes in the characteristics of the TCs (e.g., track, genesis, and destructiveness) affecting Korea and Japan and to analyze the potential reasons for these changes using synoptic field analysis techniques.

There have been a number of studies on the long-term variability of TCs over the WNP. Zhang *et al*. (2018) indicated that TC frequency over the WNP decreased between 1980 and 2014. However, the damage caused by the TCs increased when more TCs made landfall in Korea and Japan (Park *et al*., 2011). Several studies have also suggested that an increase in SST caused by climate change could lead to an increase in TC intensity (Emanuel, 2005; Webster *et al*., 2005). These findings imply that the possibility of significant damage caused by TCs on the Far East Asian countries could increase. Therefore, it is essential to understand the variability of the TCs passing through the mid-latitudes. Previous studies that have been conducted on TC variability focused on the entire period of TC occurrence, that is, from summer to autumn. In this study, the long-term trends in TCs over the WNP, migrating to the mid-latitudes and observed between late summer and early fall, were analyzed and the factors influencing TC variability were investigated based on an analysis of synoptic fields.

2 | DATA AND METHODS

2.1 | Data

In this study, the best track dataset from the Joint Typhoon Warning Center (available at https://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/wpindex.php) was used to analyze the trends in TCs over the WNP (Chu *et al*., 2002). To analyze track density, all categories of TCs (i.e., tropical depression, tropical storm, severe tropical storm, and typhoon) were included, and the genesis of a TC was defined from the moment that a TC changed from a tropical depression to a tropical storm. Additionally, the Optimum Interpolation 0.25° daily sea surface temperature analysis (Version 2) and the AVHRR-only (advanced very high resolution radiometer-only) data (Reynolds *et al*., 2007) were used to examine the effect of possible SST warming on TC variability. The ERA-interim reanalysis data with a horizontal resolution of T255 (0.70°) (Dee *et al*., 2011) was used to analyze large-scale fields, such as the vertical wind shear, subtropical highs, steering winds, and relative vorticity. Finally, the PDO (Pacific decadal oscillation) index dataset from the University of Washington's Joint Institute for the Study of the Atmosphere and Ocean was also incorporated into this study (http://research.jisao.washington.edu/pdo/PDO.latest.txt).

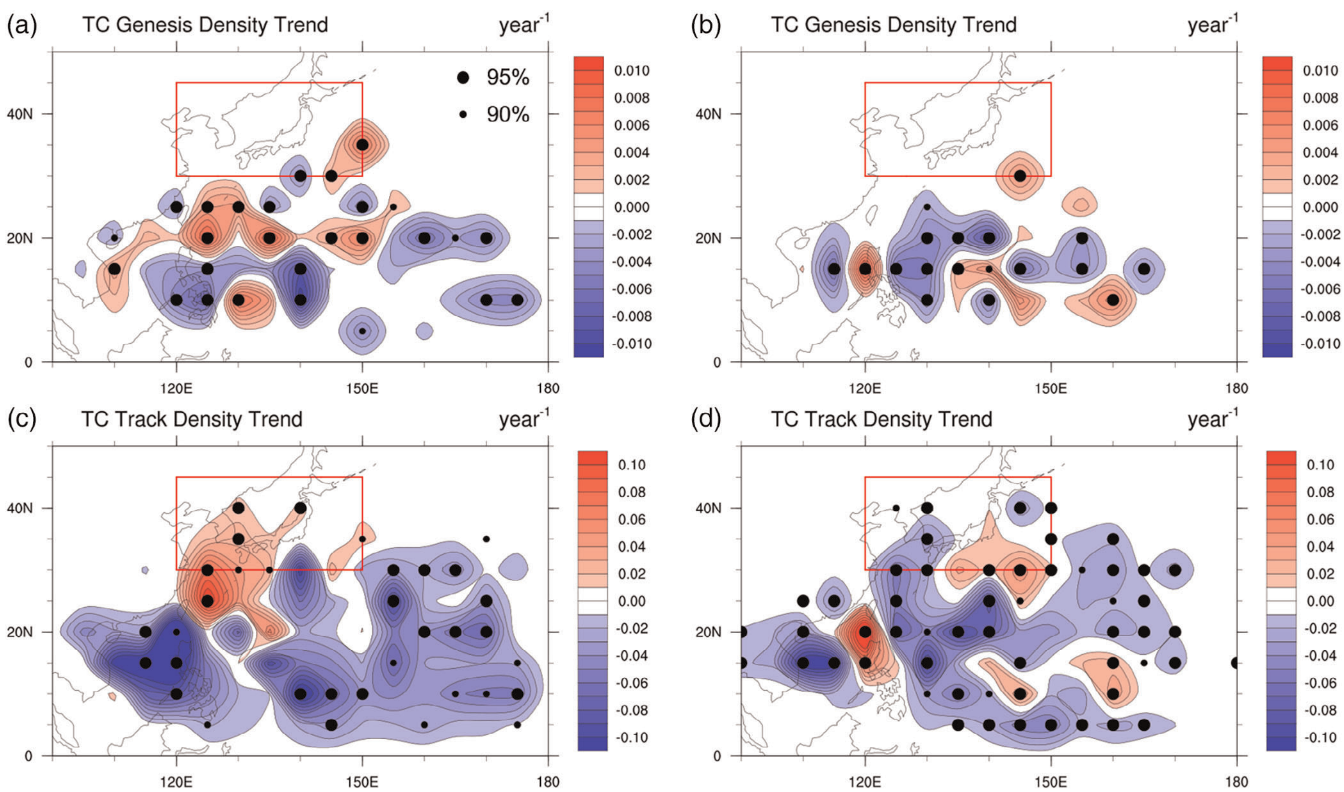

FIGURE 1 Linear trends maps of TC genesis density and track density from September 1 to September 20 (left panels) and from August 21 to August 31 (right panels). Dotted areas indicate *p*-value from the Mann-Kendall nonparametric test <.05

2.2 | Methods

The area analyzed (red box in Figure 1) extended across 30–45°N and 120–150°E, covering Korea and Japan. It was assumed that the TCs had direct or indirect impacts on both countries when they passed through the region. Hereafter, the TCs passing through the analyzed area are referred to as "TCs around Korea and Japan."

The data for the analysis was collected between June and November for 35 years, from 1982 to 2016, because approximately 95% of the total annual TCs approaching Korea and Japan occurred during this period (Kim *et al*., 2005). Each month was divided into three periods (each period consisting of 10 or 11 days), and the variability in the TCs occurring in each period around Korea and Japan was examined. The statistical significance of the linear trend was calculated using the Mann-Kendall nonparametric test (Mann, 1945; Kendall, 1948; Gilbert, 1987). The Mann-Kendall test was used to find the presence of linear or nonlinear trends in the time series based on the relative ranking of the input data. The linear trend map was obtained using the coefficients obtained from the simple linear regression of the time series for each grid.

Changes in the characteristics of TCs were investigated using genesis and track densities, which were displayed by binning the latitudinal and longitudinal positions into 5° × 5° grid boxes; this method has previously been applied for the binning of TC data (Jin *et al*., 2016). TC track density was computed by binning 6-hourly TC positions onto corresponding grid boxes. The same TC migrating in the same grid box was counted only once.

The 1-3-4-3-1 filtering method (Emanuel, 2007), which reduces the interannual variabilities of TC activities and synoptic fields over the WNP, was applied to the time series and linear trends map. The filtering method was defined using the following equation:

$$x_i' = \frac{\{4\times(x_i) + 3\times(x_{i-1} + x_{i-1}) + (x_{i-2} + x_{i-2})\}}{12},$$

where x_i' indicates the filtered value of the target year; x_i is the raw value of the target year; and $x_{i\pm1\ or\ 2}$ is the raw value of target year ±1 or 2.

In this study, vertical wind shear, which was significantly related to TC activity, was calculated using the following equation:

$$\text{Vertical wind shear} = \sqrt{(u_{200} - u_{850})^2 + (v_{200} - v_{850})^2},$$

where u is the zonal wind; v is the meridional wind; and 200 and 850 imply the 200 and 850 hPa levels, respectively.

The Power Dissipation Index (PDI) was calculated only for the reanalysis area. PDI was defined using the following equation (Emanuel, 2005):

$$\text{PDI} = \int_0^{\tau} V_{max}^3\, dt,$$

where $V_{\max}$ and τ indicate the maximum sustained wind speed and the lifetime of the TCs within the analyzed area, respectively.

Simple duration, which is defined as the total duration of occurrence of TCs during the period of interest for the analysis within a certain year, is not dependent on the number of TCs. Hence, to disentangle the impact of the TC number and intensity, a velocity-weighted duration was used, which defined TC i as (Emanuel, 2007):

$$D_i = \frac{\int_0^{\tau} V_{max}\, dt}{V_{smax}},$$

where V_{smax} is the maximum sustained wind speed during the lifetime of the TC. The average value for all TCs occurring in a given year was defined as (Emanuel, 2007):

$$D = \frac{1}{N}\sum_1^N D_i.$$

where N indicates the annual number of the TC events.

PDI is more sensitive to the occurrence of intense TCs since it is calculated as the cube of the maximum sustained winds. Thus, annually averaged intensity was used to understand the impact of changes in maximum sustained winds on PDI. The annually averaged intensity of TC i was defined using the following equation (Emanuel, 2007):

$$\text{I} = \frac{\sum_{i=1}^{N} \int_0^{\tau_i} V_{max}^3 dt}{\sum_{i=1}^{N} D_i}$$

3 | RESULTS

3.1 | Analysis of changes in TCs

To investigate the period during which a significant increasing trend in TC frequency is observed, the long-term (35 years) variability of TCs around Korea and Japan was analyzed. Table 1 shows the number of TCs around Korea and Japan during the analysis period. A total of 387 TCs, causing direct or indirect damage, passed through the area analyzed between 1982 and 2016. August and September witnessed a higher frequency of TCs around Korea and Japan; a frequency of 31 and 27%, respectively. The period during which there were more than 30 TCs around Korea and Japan was selected for further analysis (Table 2). The analysis period was divided into a first half (1982–1998) and a second half (2000–2016) to identify the relative changes that have occurred due to recent TCs and compare them to past events. The frequency of TCs around Korea and Japan tended to decrease in late August, late September, and early October, while they increased in early August and early to mid-September. In particular, the increasing trend in early to mid-September and the decreasing trend in late August was considerably large (more than 25%). Thus, we examined the significance of the increasing trend in early to mid-September and the decreasing trend in late August, and the factors influencing these trends.

Figure 2 shows the interannual time series of the frequency of TCs around Korea and Japan occurring in early to mid-September and in late August; this data was filtered using the 1-3-4-3-1 filtering method. Hereafter, late August and early to mid-September are considered as late summer and early fall, respectively. The recurring pattern of TC frequency was detected as a decadal oscillation in early fall (e.g., 1985–1994, 1995–2004, 2005–2015). There was a robust increasing trend of TC frequency in early fall, which was statistically significant at the 99% level (p-value <.01). Around Korea and Japan, a total of 29 TCs occurred in the first half, and 40 TCs in the second half, increasing the relative change by 38%. In contrast, TC frequency significantly decreased in late summer, and the relative change between the first half and the second half decreased by about 30%.

Figure 3 shows the time series of PDI, annually averaged intensity, and velocity-weighted duration of TC around Korea and Japan, which were filtered using the same method as Figure 2 (1-3-4-3-1 filtering method). PDI, intensity, and duration were calculated only when the center of the TC was located within the area analyzed. PDI, which indicated the potential destructiveness of TCs, was used to determine whether the damage caused by the TCs in Korea and Japan has changed in recent years. Changes in mean PDI in the second half (2000–2016) were marginal compared to those

TABLE 1 The number of TCs around Korea and Japan in each period for 35 years (1982–2016)

DATE	NUM_TEW
June 1–June 10	6
June 11–June 20	11
June 21–June 30	12
July 1–July 10	15
July 11–July 20	17
July 21–July 31	27
August 1–August 10	43
August 11–August 20	37
August 21–August 31	41
September 1–September 10	33
September 11–September 20	38
September 21–September 30	34
October 1–October 10	31
October 11–October 20	20
October 21–October 31	12
November 1–November 10	6
November 11–November 20	2
November 21–November 30	2

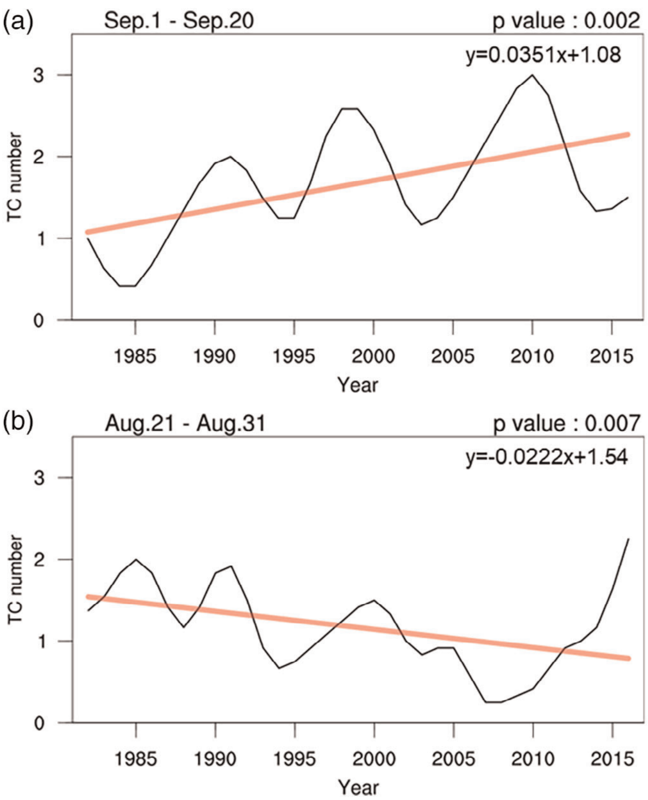

FIGURE 2 The time series of the frequency of TC around Korea and Japan with linear trend line and p-value from the Mann-Kendall nonparametric test

TABLE 2 The number of TCs around Korea and Japan in the first half (1982–1998) and the second half (2000–2016) and relative change for the periods with more than 30 TCs

	August			September			October
	Early	Middle	Late	Early	Middle	Late	Early
1982–1998	18	18	23	13	16	18	17
2000–2016	21	17	16	20	20	15	13
Relative change (%)	16.7	−5.6	−30.4	53.8	25.0	−16.7	−23.5

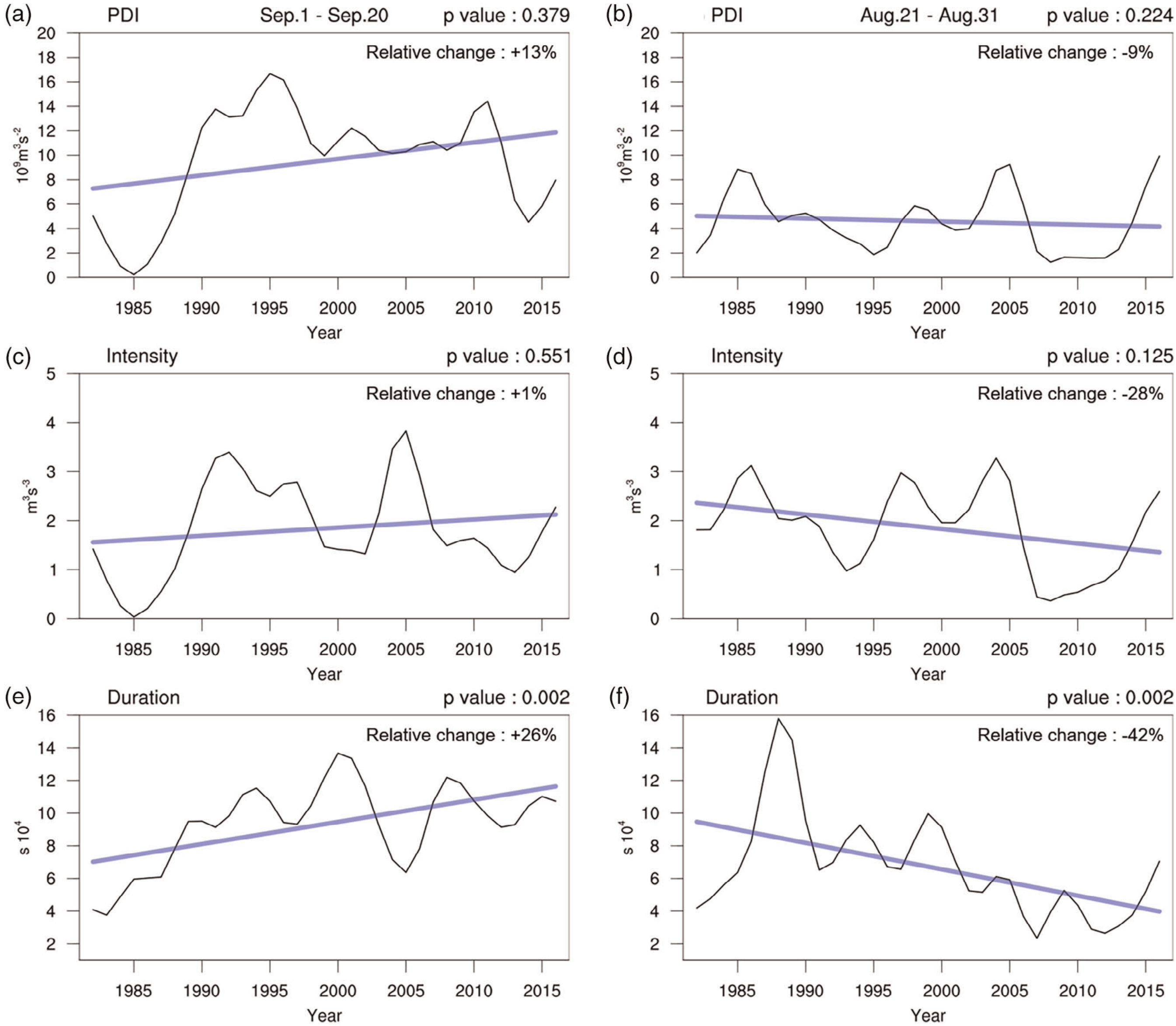

FIGURE 3 The time series of PDI, annually averaged intensity, and velocity-weighted duration of TC around Korea and Japan from September 1 to September 20 (left panels) and from August 21 to August 31 (right panels) with linear trend line and p-value from Mann-Kendall nonparametric test

in the first half (1982–1998) (Figure 3a). To investigate the contributions of intensity and duration to changing PDI, this study also analyzed changes in these two factors. The increase in the trend line for intensity was negligible (Figure 3c). Besides, the enhancement was not statistically significant across the analysis period. On the other hand, the duration of TCs around Korea and Japan notably increased with a high relative change between the first half and the second half (around +26%) (Figure 3e), because of a larger number of TCs moving from the subtropics to the mid-latitudes in the second half (Figure 2). Thus, changes in PDI and intensity were insignificant, but the frequency and duration of TCs around Korea and Japan increased considerably. In contrast, in late summer, the intensity and duration of TCs around Korea and Japan decreased by about 28 and 42%, respectively (Figure 3d, f).

Figure 1 shows the linear trends map of TC genesis and track density from September 1 to 20 and from August 21 to 31. In Figure 1a, the increasing trend of TC genesis density near the ocean northeast of the Philippines (20–25°N and 120–140°E) seemed to prevail, while a decreasing tendency was dominant near the ocean east of the Philippines (10–20°N and 125–145°E). This indicated that, more recently, the region of genesis of the TCs occurring in early fall around the ocean east of the Philippines shifted northwards. However, the change in genesis density was not prominent in the mid-latitudes above 30°N. In contrast, the TC track density significantly changed in broader regions compared with TC genesis density (Figure 1c). Overall, the increases in TC track density are primarily confined to the northwest part of the WNP. In particular, the track density of the TCs that make landfall around Korea and Japan showed a prominent increase.

There are two reasons for an increase in TC track density in the mid-latitudes. The first reason is related to the northward shift of TC genesis to the ocean northeast of the Philippines, as shown in Figure 1a. The second reason is associated with the increased longevity of TCs around Korea and Japan migrating from the lower latitudes. These results indicate that the impact of TCs on Korea and Japan has recently increased in the early fall period. In contrast, in late summer, the TC genesis density has decreased over a larger region as compared to its increase (Figure 1b). Overall, the TC track density has decreased in the area analyzed, except for the southeast boundary (Figure 1d). The increasing TC track density in the southeast boundary of the area analyzed was associated with a recent increase in the TC genesis.

3.2 | Synoptic field analysis

The results described in the previous section show a recent increase in the frequency of TCs around Korea and Japan in early fall, followed by a decrease in late summer. To investigate the specific factors that caused the recent changes in the characteristics of the TCs occurring over the WNP from September 1 to 20 and from August 21 to 31, this study analyzed the linear trends in synoptic conditions, such as SST, vertical wind shear, subtropical high, steering flow, and relative vorticity, all of which have significantly impacted the development and maintenance of TCs (Figure 4). Warm SST have had a positive effect on the strength of TCs, which may have led to an increase in their duration (Emanuel, 1986; Emanuel, 1988). In Figure 4a, the increase in SST observed across the entire domain is most likely due to global warming. Therefore, the oceanic conditions were more favorable for the maintenance of the TCs around Korea and Japan, especially because any further increase in the SST over the mid-latitudes only provided more energy to the TC (Park *et al*., 2011).

Strong vertical wind shear was an unfavorable condition for the development and maintenance of TCs owing to the generation of eddies in the inner core, which advected environmental mid-tropospheric dry air into the center of the TC, thereby weakening convection and raising the pressure of the TC (Tang and Emanuel, 2010, 2012). If TCs enter a weak vertical wind shear area, they could sustain their strength to migrate northwards without weakening. Figure 4c shows that the vertical wind shear substantially decreased between 30°N and 40°N, which may be associated with the meridional SST distribution over the WNP (Figure 4a). The linear trend of the SST was relatively weak in subtropical regions below 35°N, whereas it was strong in the mid-latitudes above 35°N. This SST distribution caused a weak meridional temperature gradient and a weak subtropical jet, based on the thermal wind relationship (Yang *et al*., 2002). When the subtropical jet became weak, vertical wind shear also decreased in the subtropical region. The decreasing trend of vertical wind shear in the subtropics helped sustain the TC vortex, implying that the weakened vertical wind shear in early fall was another favorable condition for the northward migration of TCs over the WNP. Thus, it is highly likely that a TC would maintain its intensity when it makes landfall on Korea and Japan.

Also, TC movements were considerably influenced by the WNP subtropical high (Ho *et al*., 2004). In general, TCs over the WNP migrated along the periphery of the subtropical high. Figure 4e depicts the 5,880 gpm contours of the geopotential height in the first half (1982–1998) and the second half (2000–2016), which were widely used as benchmarks to measure the subtropical high (Liu and Chan, 2013; He *et al*., 2015). In the first half, the subtropical high had a smaller areal extent and shifted eastwards, which allowed the TCs to move to the Pacific Ocean east of Japan. In contrast, the subtropical high expanded more northwestward in the second half period, allowing the northward migration of TCs to the ocean south of Korea and Japan.

Steering flow, defined in this paper as the mean wind from 850 to 300 hPa (Chan, 2005), was another important factor in the movement of the TCs. The trends observed in the steering flow data showed strong easterly winds between 30°N and 40°N (Figure 4e). This could lead to an increase in the number of TCs that make landfall in Korea and Japan, without passing through the Pacific Ocean east of Japan. Furthermore, the increasing trend in lower-tropospheric relative vorticity, which is a favorable condition for the formation and development of TCs, was significantly enhanced over the East China Sea and the Pacific Ocean south of Japan (20–30°N and 120–150°E) (Figure 4g). This substantial increase in relative vorticity in the area could be responsible for the northward shift of the genesis location of the TCs, as shown in Figure 1a.

In contrast, in late summer, vertical wind shear observed within 30–40°N and 120–150°E showed an increase trend (Figure 4d) and the southward steering wind was dominant around Korea and Japan (Figure 4f), which was relatively unfavorable for the development or migration of TCs in the area analyzed. Therefore, the frequency and duration of TCs around Korea and Japan during late summer showed a decrease, as shown in Figure 2b.

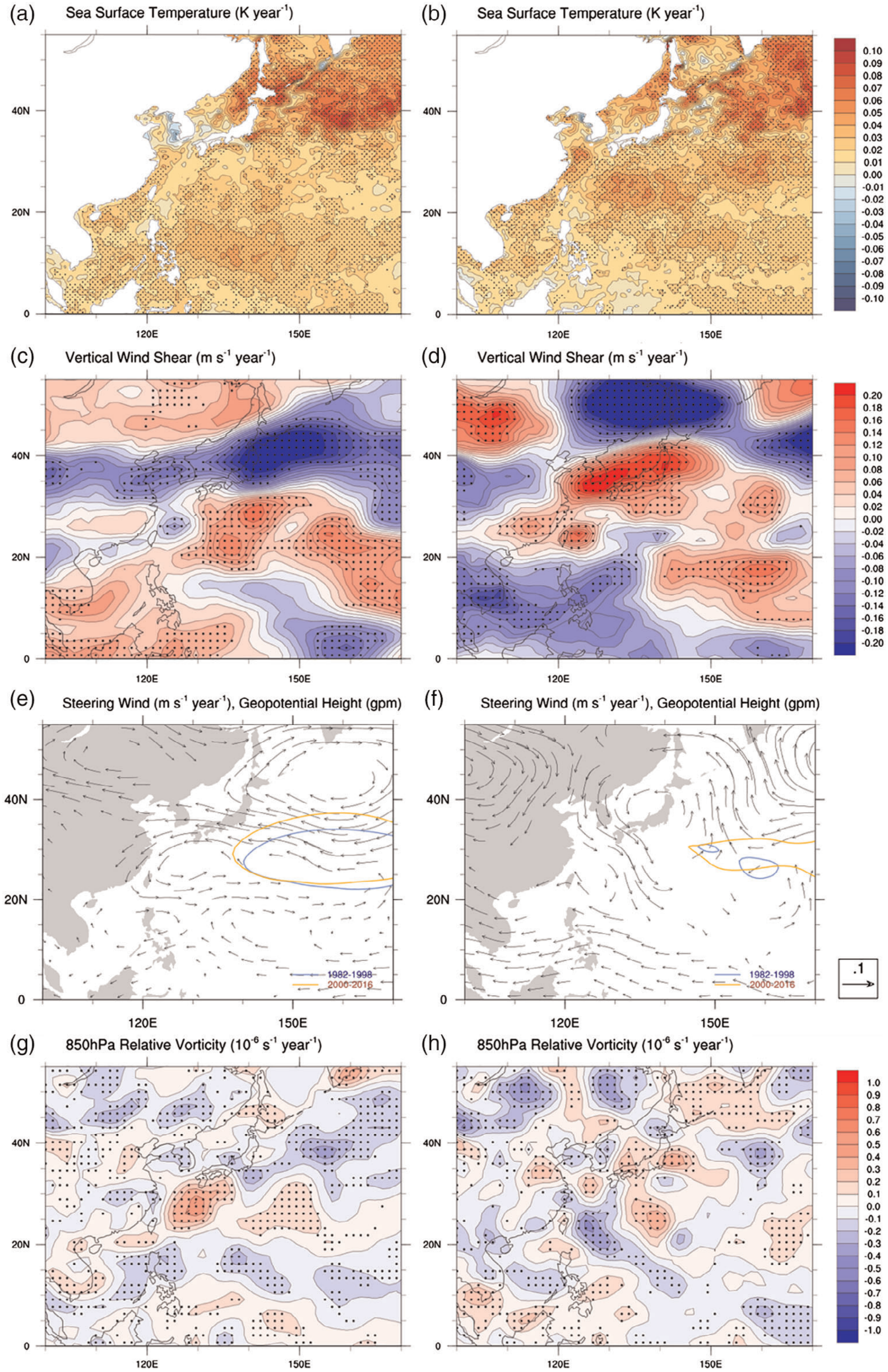

FIGURE 4 Linear trend maps of (a, b) SST (K·year^{-1}), (c, d) vertical wind shear (m·s^{-1}·year^{-1}), (e, f) steering wind (m·s^{-1}·year^{-1}), and (g, h) 850 hPa relative vorticity (10^{-6}·s^{-1}·year^{-1}) from September 1 to September 20 (left panels) and from august 21 to august 31 (right panels) during 35 years (1982–2016). Dotted areas and wind vectors indicate *p*-value from the Mann-Kendall nonparametric test <.05. Contour lines in e and f designate 5,880-gpm contour of 500 hPa geopotential height in the first half (1982–1998) and the second half (2000–2016)

4 | SUMMARY AND DISCUSSION

In this study, the long-term variability of TCs migrating from the subtropics of the WNP to the mid-latitudes, particularly near Korea and Japan, was investigated. The area analyzed extended across 30–45°N and 120–150°E, which includes Korea and Japan, since they have been significantly affected by TCs. The frequency of TCs around Korea and Japan that caused damage in the region was observed to be relatively high (more than 30 TCs) between August and early October. From 1982 to 2016, the frequency of TCs around Korea and Japan showed a significant increase in early to mid-September and a decrease in late August. Thus, the time period chosen for the analysis included early to mid-September and late August, taking into account the increasing and decreasing trends observed as well as the high relative change values. PDI directly associated with the TC damages was also calculated for the areas analyzed. The results confirmed that the changes in mean PDI in the second half (2000–2016) were negligible compared to those observed in the first half (1982–1998). On the other hand, the duration and frequency of TCs around Korea and Japan showed an increase in early to mid-September, and a decrease in late August. In particular, the increasing trend observed in the TC track density during early fall (early to mid-September) prevailed in the mid-latitudes due to the northward shift of the genesis of TCs and further migration of TCs from the lower latitudes. An analysis of the synoptic fields was conducted to explain the reasons behind the changes in the frequency of TCs around Korea and Japan. From early to mid-September, SST increased in the whole WNP, and vertical wind shear significantly decreased near the mid-latitudes (30–40 °N), thus creating favorable conditions to maintain the TC intensity. In addition, the WNP subtropical high expanded to the northwest, strong easterly steering winds in the mid-latitudes were prominent, and an increasing trend in relative vorticity was dominantly observed near the East China Sea and near the Pacific Ocean south of Japan, thus creating favorable conditions for TCs to migrate northwards to Korea and Japan. In contrast, the synoptic conditions showed a reversal in late August. However, further studies using detailed datasets are required to achieve reliable results, since there are limitations with respect to uncertainties present in the Best-Track data (Knapp *et al.*, 2010; Schreck III *et al.*, 2014) and due to the nonphysical trends of the ERA-Interim data associated with changes in the observing system (Dee *et al.*, 2011).

There are a number of factors that could have induced the recent changes in TCs around Korea and Japan. The PDO was considered to be one of the factors that could result in environmental conditions favorable for the increase in TCs around Korea and Japan between early and mid-September; PDO can contribute to changes in the vertical wind shear (Tang and Emanuel, 2010, 2012; Wang and Liu, 2016). More recently, the SST distribution over the WNP between early and mid-September was related to the negative PDO phase. Warmer SST in the mid-latitudes provided greater energy resources resulting in a longer duration of TCs occurring around Korea and Japan. In addition, the SST distribution of the negative PDO phase caused a reduction in the meridional temperature gradient and a weak upper-level jet, based on the thermal wind relationship (Yang *et al.*, 2002). When the upper-level jet became weak, vertical wind shear also tended to decrease in the extratropical region. The decreasing vertical wind shear provided favorable conditions for TCs to maintain their intensity and extend into the mid-latitudes. Thus, in September, the interannual variability of TCs around Korea and Japan significantly correlated with the PDO index; the temporal correlation coefficient was −0.51. Further studies using numerical models and observations are needed to investigate the relationship between the PDO and TCs around Korea and Japan.

The possibility of enormous economic loss and human casualties can increase tremendously if more TCs over the WNP extend to megacities, such as Seoul and Tokyo located in Far East Asia. According to the results of this study, TCs over the WNP, which moved to the mid-latitudes and affected Korea and Japan, significantly increased during the early fall period. For example, three of the top five TCs (i.e., Rusa in 2002, Maemi in 2003, Bolaven in 2012) that caused great economic loss in South Korea occurred in early fall. Fall TCs are often associated with severe heavy precipitation due to the strong atmospheric instability, which is caused by the large differences in the warm and moist low-level air mass and the cold and dry upper-level air mass (Kim *et al.*, 2006). Therefore, it is essential to understand the physical factors influencing the recent trend in TCs in the fall season based on historical data, as well as to estimate the future changes in the TC variability based on numerical experiments.

ACKNOWLEDGEMENTS

This work was funded by the Korea Meteorological Administration Research and Development Program under the Grant KMIPA 2017-7010, and the Next-Generation Information Computing Development Program through the National Research Foundation of Korea (NRF), funded by the Ministry of Science, ICT (NRF-2016M3C4A7952637).

ORCID

Dong-Hyun Cha https://orcid.org/0000-0001-5053-6741

REFERENCES

Chan, J.C.L. (2005) The physics of tropical cyclone motion. *Annual Review of Fluid Mechanics*, *37*, 99–128.

Chu, J.H., Sampson, C.R., Levine, A.S. and Fukada, E.. (2002) *The joint typhoon warning center tropical cyclone best-tracks, 1945–2000*. Ref. NRL/MR/7540–02, p. 16.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, D.P. and Bechtold, P. (2011) The ERA-interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *13*, 553–597.

Emanuel, K.A. (1986) An air-sea interaction theory for tropical cyclones. Part I: steady-state maintenance. *Journal of the Atmospheric Sciences*, *43*, 585–605.

Emanuel, K.A. (1988) The maximum intensity of hurricanes. *Journal of the Atmospheric Sciences*, *45*, 1143–1155.

Emanuel, K. (2005) Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, *436*, 686–688.

Emanuel, K. (2007) Environmental factors affecting tropical cyclone power dissipation. *Journal of Climate*, *20*, 5497–5509.

Gilbert, R.O. (1987) *Statistical Methods for Environmental Pollution Monitoring*. John Wiley & Sons, New York: Van Nostrand Reinhold.

He, C., Zhou, T., Lin, A., Wu, B., Gu, D., Li, C. and Zheng, B. (2015) Enhanced or weakened western North Pacific subtropical high under global warming? *Scientific Reports*, *5*, 16771.

Ho, C.H., Baik, J.J., Kim, J.H., Gong, D.Y. and Sui, C.H. (2004) Interdecadal changes in summertime typhoon tracks. *Journal of Climate*, *17*, 1767–1776.

Jin, C.S., Cha, D.H., Lee, D.K., Suh, M.S., Hong, S.Y., Kang, H.S. and Ho, C.H. (2016) Evaluation of climatological tropical cyclone activity over the western North Pacific in the CORDEX-East Asia multi-RCM simulations. *Climate Dynamics*, *47*, 765–778.

Kendall, M.G., 1948. *Rank Correlation Methods*. 4th ed. London: Griffin.

Kim, J.H., Ho, C.H., Sui, C.H. and Park, S.K. (2005) Dipole structure of interannual variations in summertime tropical cyclone activity over East Asia. *Journal of Climate*, *18*, 5344–5356.

Kim, N.W., Won, Y.S. and Chung, I.M. (2006) The scale of typhoon RUSA. *Hydrology and Earth System Sciences Discussions*, *3*(5), 3147–3182.

Kim, S.J., Woo, S.H., Kim, B.M. and Hur, S.D. (2011) Trends in sea surface temperature (SST) change near the Korean peninsula for the past 130 years. *Ocean and Polar Research*, *33*, 281–290.

Knapp, K.R., Kruk, M.C., Levinson, D.H., Diamond, H.J. and Neumann, C.J. (2010) The international best track archive for climate stewardship (IBTrACS) unifying tropical cyclone data. *Bulletin of the American Meteorological Society*, *91*, 363–376.

Lee, D.K. and Choi, S.J. (2010) Observation and numerical prediction of torrential rainfall over Korea caused by Typhoon Rusa (2002). *Journal of Geophysical Research-Atmospheres*, *115*(D12), 20.

Liu, K.S. and Chan, J.C. (2013) Inactive period of western North Pacific tropical cyclone activity in 1998–2011. *Journal of Climate*, *26*, 2614–2630.

Liu, Q. and Zhang, Q. (2013) Analysis on long-term change of sea surface temperature in the China seas. *Journal of Ocean University of China*, *12*, 295–300.

Mann, H.B. (1945) Nonparametric tests against trend. *Econometrica: Journal of the Econometric Society*, *13*, 245–259.

Park, D.S., Ho, C.H., Kim, J.H. and Kim, H.S. (2011) Strong landfall typhoons in Korea and Japan in a recent decade. *Journal of Geophysical Research-Atmospheres*, *116*(D7). https://doi.org/10.1029/2010jd014801.

Re, M. (2014) *NatCatSERVICE Database*. Munich: Munich RE.

Reynolds, R.W., Smith, T.M., Liu, C., Chelton, D.B., Casey, K.S. and Schlax, M.G. (2007) Daily high-resolution-blended analyses for sea surface temperature. *Journal of Climate*, 20(22), 5473–5496.

Schreck, C.J., III, Knapp, K.R. and Kossin, J.P. (2014) The impact of best track discrepancies on global tropical cyclone climatologies using IBTrACS. *Monthly Weather Review*, *142*, 3881–3899.

Tang, B. and Emanuel, K. (2010) Midlevel ventilation's constraint on tropical cyclone intensity. *Journal of the Atmospheric Sciences*, *67* (6), 1817–1830.

Tang, B. and Emanuel, K. (2012) A ventilation index for tropical cyclones. *Bulletin of the American Meteorological Society*, *93*(12), 1901–1912.

Wang, X. and Liu, H. (2016) PDO modulation of ENSO effect on tropical cyclone rapid intensification in the western North Pacific. *Climate Dynamics*, *46*(1–2), 15–28.

Webster, P.J., Holland, G.J., Curry, J.A. and Chang, H.R. (2005) Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science*, *309*, 1844–1846.

Wu, M.C., Chang, W.L. and Leung, W.M. (2004) Impacts of El Niño–Southern Oscillation events on tropical cyclone landfalling activity in the western North Pacific. *Journal of Climate*, *17*, 1419–1428.

Yang, S., Lau, K.M. and Kim, K.M. (2002) Variations of the East Asian jet stream and Asian–Pacific–American winter climate anomalies. *Journal of Climate*, *153*, 306–325.

Zhang, W., Vecchi, G.A., Murakami, H., Villarini, G., Delworth, T.L., Yang, X. and Jia, L. (2018) Dominant role of Atlantic Multidecadal Oscillation in the recent decadal changes in western North Pacific tropical cyclone activity. *Geophysical Research Letters*, *45*, 354–362.

How to cite this article: Lee M, Cha D-H, Moon J, Park J, Jin C-S, Chan JCL. Long-term trends in tropical cyclone tracks around Korea and Japan in late summer and early fall. *Atmos Sci Lett*. 2019;20:e939. https://doi.org/10.1002/asl.939