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Interdecadal variation of Korea affecting TC activity in early 1980s

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Abstract

By performing a statistical change-point analysis of activities of the tropical cyclones (TCs) that have affected Korea (K-TCs), it was found that there was a significant change between 1983 and 1984. During the period of 1984–2004 (P2), more TCs migrated toward the west, recurved in the southwest, and affected Korea, compared to the period of 1965–1983 (P1). These changes for P2 were related to the southwestward expansion of the subtropical western Pacific high (SWPH) and, simultaneously, elongation of its elliptical shape toward Korea. Because of these changes, the central pressure and lifetime of K-TC during P2 were deeper and longer, respectively, than figures for P1. This stronger K-TC intensity for P2 was related to the more southwestward genesis due to the southwestward expansion of the SWPH. The weaker vertical wind shear environment during P2 was more favorable for K-TC to maintain a strong intensity in the mid-latitudes of East Asia.

Keywords: Change-point analysis, Tropical cyclone, Korea, Shift, Vertical wind shear

Background

Many factors, including SST, vertical wind shear, thermodynamic instability/stability, upper-tropospheric momentum flux convergence, mid-tropospheric moisture, and so on have an influence on tropical cyclone (TC) activity (Gray 1968; Molinari and Vollaro 1989; Pfeffer and Challa 1992; DeMaria et al. 2001; Goldenberg et al. 2001; Baik and Paek 2001). In particular, TC movement and intensity in the subtropics or mid-latitudes are greatly influenced by environmental circulation systems, such as the location and strength of the subtropical western Pacific high (SWPH).

Chan and Shi (1996) fit the TC annual frequency in the Northwest Pacific into a second-order polynomial equation and observed that it has been increasing since 1994. Chu and Clark (1999) showed that the annual frequency of TCs was increasing in the central North Pacific. Kamahori et al. (2006) stressed that we must prepare against the effects of strong TCs because intense TC days have been increasing steadily for the last 30 years. Elsner et al. (2008) suggested similarly that the intensity of strong TCs is increasing in all TC basins except the South Pacific Ocean basin, and that this increase was particularly evident in the North Atlantic and north Indian Ocean basins. Tu et al. (2009) showed that TC frequency over the Taiwan-East China Sea region has been increasing since 2000 because of northward shift of TC track over western North Pacific (WNP)–East Asian region. Landsea et al. (1996) claimed that the frequency of intense hurricanes in the Atlantic had been decreasing for the previous 50 years. Ho et al. (2004) proved through a statistical change-point analysis that the annual frequency of TCs in the East China Sea had been decreasing since the mid-1970s and that the decreasing trend was more distinct around the Philippines. As an extension of the study by Chan and Shi (1996) after analyzing TC-frequency data for the Northwest Pacific that had been updated through the early 2000s, Chan (2005) showed that the frequency of TCs had actually decreased since the mid-1990s. Chan also observed this decreasing trend in the annual frequency of TCs in the South China Sea over the prior 40 years.

Gong and Ho (2002) demonstrated that the SWPH has enlarged, intensified, and shifted southwestward in recent years, which gives rise to an anticyclonic circulation anomaly over the region from the South China

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Sea to the western Pacific, and thus causes wet anomalies over the Yangtze River valley. Ho et al. (2004) also showed that this southwestward expansion of the SWPH from the late 1970s leads to a decrease in TC passage frequency in the East China Sea, but to an increase in the South China Sea. In addition, they suggested that this change in the SWPH resulted in the westward shift of the recent major TC tracks and therefore contributed to a larger elliptic pathway of TC migration. On the contrary, Choi and Kim (2007) demonstrated that both frequency and intensity of a TC at landfall in the Korean Peninsula have rapidly increased since the late 1980s. In particular, they showed that the frequency of TC with intensity greater than tropical storm (34 kts ≤ maximum sustained wind speed ≤ 47 kts) has increased remarkably and suggested that this result is because a SWPH tend to retreat eastward in recent years.

On the other hand, in relation to the interdecadal variations in the climate of the summer climate, Inoue and Matsumoto (2007) showed that in the early 1980s, there were shifts not only in TC activity around Japan, but also in the entire large-scale circulation pattern over East Asia and the western North Pacific (WNP). Therefore, it was known that except for variation of Korean Peninsula landfalling TC, most of the climate changes associated with the activity of the SWPH in the aforementioned studies occurred between late 1970s and early 1980s. In fact, climate regime shift in the later 1970s or the early 1980s occurred not only in East Asia but also in the seas and air over the Pacific, and thus related various studies were accumulated (e.g., Nitta and Hu 1996; Niebauer 1998; Chang et al. 2000; Stephens et al. 2001; Bond et al. 2003; Wu et al. 2005; Ye and Hsieh 2006).

In the South China Sea and Western Pacific region, previous study also identifies a decadal shift of the TC activity in the early 1990s (Yang et al. 2012). Yang et al. (2012) has found that the South China Sea has more TCs during 1994–2008. They also attributed it to the eastward migration of SWPH, lower wind shear, higher mid-level humidity as well as warmer upper ocean conditions (sea surface temperature and upper ocean heat content). Another relevant study suggested that the wind shear, humidity, and vorticity related to monsoon variation and Indian Ocean Basin mode might be the cause of the change of TC activity over the western Pacific (Du et al. 2011). Xie et al. (2016) summarized the relationship of the East Asia Climate and climate modes in the tropical Indo-Pacific and proposed that the Indo-western Pacific ocean capacitor (IPOC) mode dominates the interannual and decadal climate over the region.

This study also found that a climate shift related to TC activity affecting Korea exists in the early 1980s. Thus, we first analyzed the interdecadal changes on the activity of the TC affecting Korea and then their relation to atmospheric circulation patterns in East Asia and the WNP regions.

Data and methods

The present study used the TC best track dataset archived by the Regional Specialized Meteorological Center (RSMC)—Tokyo (http://www.jma.go.jp/en/typh/). This dataset includes TC measurements at 6-h intervals of latitude–longitude and intensity, including central pressure (hPa) and maximum sustained wind speed (MSWS; kt). A TC that affected Korea (hereafter, K-TC) was defined as one that passed through the area of 32°–40°N, 120°–138°E (Korea Meteorological Administration 1996; boxes in Fig. 2) for July–September. Based on this definition, 156 TCs were selected for the period of 1965–2004 (40 years). The reasons that the current study covered the period of 1965–2004 are as follows: Choi and Moon (2012) demonstrated that using K-TC frequency during summer (June–September), and significant regime shifts occurred in 2004, as well as in the mid-1960s and mid-1980s. Choi and Kim (2007) showed that K-TC frequency had increased rapidly since the early-2000s and that the increase in the frequency of intense K-TC was more obvious. Their analysis showed that the reason for the increase was that the SWPH shifted to the east, resulting in the TC track moving to the east and reducing the frequency of TCs passing through mainland China before making landfall on the Korean Peninsula.

The TC intensity was divided into 5 stages on the basis of the intensity of the MSWS: tropical depression (TD; MSWS < 34 kts), tropical storm (TS; 34 kts ≤ MSWS ≤ 47 kts), severe tropical storm (STS; 48 kts ≤ MSWS ≤ 63 kts), typhoon (TY; MSWS ≥ 64 kts), and extratropical cyclone (EC). Storms at the TD and EC stages were included in the K-TC activity, because these storms cause tremendous damage in the mid-latitude countries of East Asia, such as China, Korea, and Japan (Kitabatake 2002).

On the other hand, we defined a K-TC recurving location as the point where a TC's direction of movement changes from a westward to an eastward movement. Also, to define the K-TC passage frequency, TC position was binned into the corresponding 5° × 5° grid box and even if the same TC entered the same grid box multiple times, it was only counted once.

We also used the 6-h measurements of geopotential height (gpm), horizontal wind (m s^{-1}), air temperature (°C), and relative humidity (%) reanalyzed by the National Center for Environmental Prediction–the National Center for Atmospheric Research (NCEP–NCAR) to characterize the large-scale circulation patterns related to the decadal variation in the K-TC activity (Kalnay and

Coauthors 1996; Kistler and Coauthors 2001). These data are available on a 2.5° × 2.5° grid at standard pressure levels.

The NOAA Extended Reconstructed monthly Sea Surface Temperature (SST) (Reynolds et al. 2002), available from the same organization, was also used. The data have a horizontal resolution of 2.0° × 2.0° latitude–longitude and are available for the period of 1854 to the present day.

Meanwhile, while TC data are accessible for the period from 1951 to the present, the reliability of TC data in the 1950s and early 1960s prior to the weather satellite era could lead to problems (Ho et al. 2005). The NCEP–NCAR reanalysis data are also affected by two major changes in the observing system: upper air networks and satellite observations (Kistler and Coauthors 2001). To avoid any possible impact of unreliable data on the present results, all calculations are confined to the period from 1965 to 2004, during which weather satellites are used.

The interdecadal change in the K-TC activity was determined through a statistical change-point analysis (CPA). This type of statistical analysis can identify significant regime shifts in a time series in an objective manner. Because this variable does not follow a Poisson distribution, we use a different method to detect climate regime shifts in the temperature or passage frequency series: using a log-linear regression model in which a step function is expressed as an independent variable. If the estimated slope is at least twice as large as its standard error, one may reject the null hypothesis (i.e., the slope being zero) at the 5% significance level. The details of this analysis method are well described in Elsner et al. (2000) Chu (2002) and Ho et al. (2004) The vertical wind shear (VWS) analyzed to diagnose the large-scale condition related to the K-TC activity is calculated as follows:

$$VWS = \sqrt{(u_{200} - u_{850})^2 + (v_{200} - v_{850})^2}.$$

Here, u and v indicate the zonal and meridional flows, respectively. 200 and 850 represent 200 and 850-hPa levels, respectively.

The composite analysis is average for the months of the K-TC activity, and an anomalous map was obtained by subtracting the climatological summer (July, August, and September; JAS) mean during the period of 1965–2004 from the average for the months of K-TC activity. Here, JAS is defined as the seasons that the K-TC activity is the most active Park et al. (2006)

Shift between 1983 and 1984

TC Frequency and recurving location

As a result of applying the K-TC frequency to the CPA, a significant change point was found between 1983 and 1984 (Fig. 1a). While there were 61 K-TCs for the period of 1965–1983 (hereafter, P1), there were 95 for the period of 1984–2004 (hereafter, P2). That is, there were only about two-thirds as many K-TCs in P1 as in P2.

Ho et al. (2004) have already shown that the change in the TC passage frequency in the WNP is related to the southwestward shift of the SWPH in the late 1970s. Also, in the present study, an investigation was made of the change in the SWPH averaged for the months of the K-TC activity in each period, as shown in Fig. 2. As a result, the SWPH (5860 gpm contour) for P2 is shifted more southwestward than that for P1. At the same time, the shape of the SWPH becomes more elliptical toward Korea for P2. In addition, 5880 gpm contours for P2 were also stretched more toward Korea than those of P1 (not shown). This means that during P2, the SWPH provides a more favorable environment for TC to approach Korea. This feature can be confirmed in detail by examining the location of the SWPH for each K-TC during the two periods (right panel of Fig. 2).

Due to this southwestward expansion of the SWPH and its elliptical shape toward Korea, the K-TC track for P2

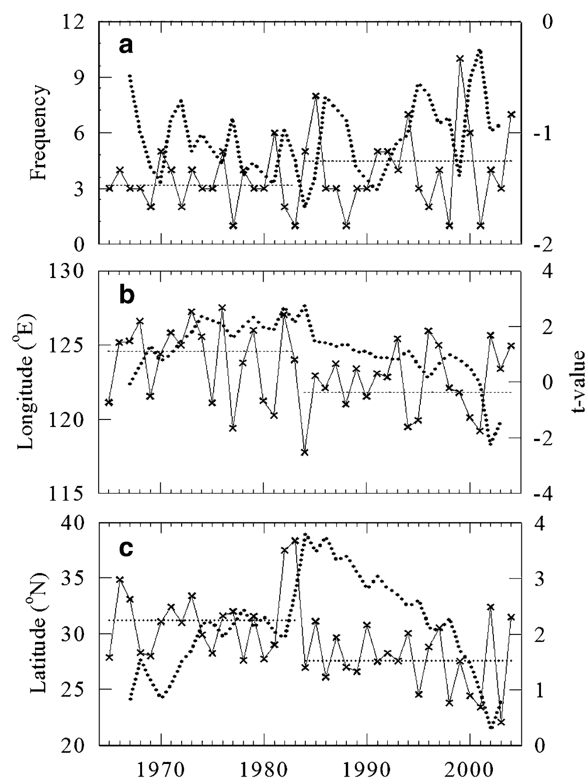

Fig. 1 Decadal variations in **a** frequency, **b** longitude, and **c** latitude for the recurving location of TCs affecting Korea (hereafter, K-TC). The *thick* and *thin dotted lines* denote t-values of change-point analysis and average values for three variables for the periods 1965–1983 (P1) and 1984–2004 (P2), respectively

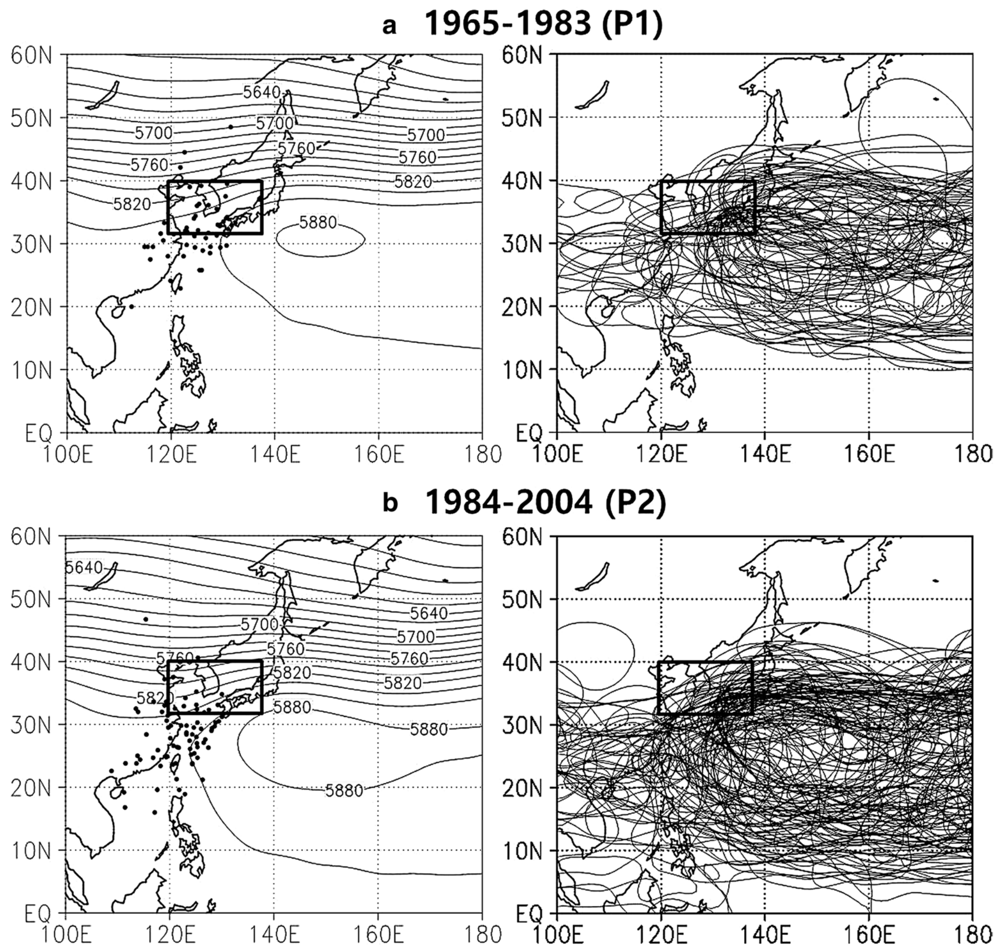

Fig. 2 500-hPa geopotential height composite averaged for the months of K-TC activity (*left*) and 5860 gpm contours in each of the months with K-TC activity (*right*) for **a** P1 and **b** P2. The *dots on the left* denote the recurving locations of the K-TCs. The *solid line box* represents the K-TC area (32°–40°N, 120°–138°E)

tends to migrate more westward than that for P1 (Fig. 3). That is, the higher K-TC passage frequency for P2 is distributed along the western periphery of the 5860 gpm contour (filled circle). Thus, East Asian coastal regions, such as the Philippines, the east coast of China, Korea, and Japan show a higher TC passage frequency for P2. This is well consistent with the results of Inoue and Matsumoto (2007) who analyzed the difference in the TC track frequencies in the late August between 1984 and 2000 and 1961–1983. On the other hand, the middle of China has the highest frequency in mainland China for P2. This may play an important role in the strengthening of wet anomalies over the Yangtze River valley in recent years, as analyzed by Gong and Ho (2002).

Generally, TCs tend to migrate along the western periphery of the SWPH. The recurving location of K-TCs may also change because of this recent shift in the SWPH. In relation to the change in the latitude of the recurving location, 34 of the 52 TCs (65.4%) that recurved in P1 recurved to the north of 30°N, while just 26 of the 77 TCs (33.7%) that recurved in P2 did so. In other words, about 70% of all the K-TCs that recurved during P2 recurved to the south of 30°N. Therefore, it can be concluded that K-TCs tended to recurve to the north of 30°N during P1 and to the south of 30°N during P2. On the other hand, in relation to the change in longitude, while only 7 of the 52 TCs for P1 recurved to the west of 120°E, 28 of the 77 TCs for P2 did so. Although the number of TCs that recurved to the west of 120°E is not very high for either period, the number of TCs that recurved to the west of 120°E for P2 is about four times that of P1. Also, in order to examine whether there was a significant change in the recurving location of K-TCs, we applied the time series of the latitude and longitude portions of the recurving locations to the CPA, respectively (Fig. 1b, c). Dramatically, this shows that there is clear change point between 1983 and 1984 for the two variables, just as with the TC frequency. The average recurving location for P1 is 31.2°N, 124.6°E and

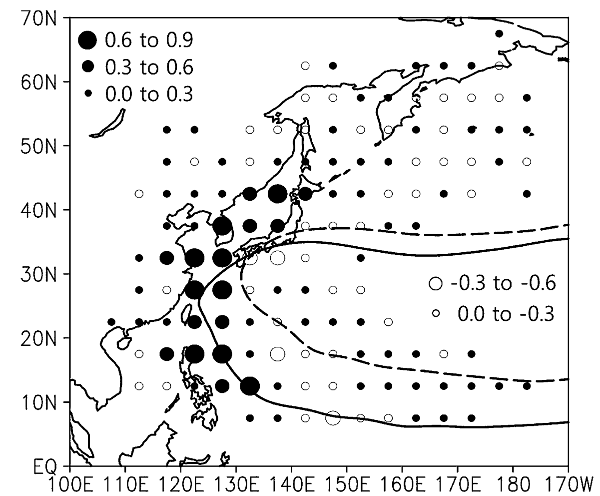

Fig. 3 Differences in mean K-TC passage frequencies (TPF) between P2 and P1 within each 5° × 5° latitude–longitude grid box. The *solid* and *dashed lines* denote 5860 gpm contours for P2 and P1, respectively

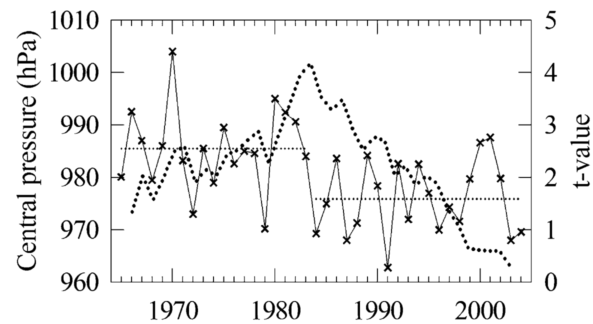

Fig. 4 As in Fig. 1, but for the annual variation in the central pressure averaged for the maximal approach to the boundary line of the K-TC area using the 6-h TC best track dataset

it is 27.6°N, 121.8°E for P2. Therefore, we can objectively confirm through the CPA that the recurving location of K-TCs has been shifted more southwestward since 1984.

TC intensity

The shifts in the track and recurving location of K-TCs, along with the recent southwestward expansion of the SWPH, may have had an effect on TC intensity. Thus, the CPA was also applied to the interannual variation in the average central pressure in the maximal approach to the boundary line of the K-TC area using the 6-h TC best track dataset (Fig. 4). As a result, a significant shift was also shown between 1983 and 1984, like the frequency and recurving location shifts. That is, this means that all the activities related to a K-TC experienced a significant change between 1983 and 1984. The average central pressure (975.9 hPa) for P2 is about 10 hPa deeper than the average (985.5 hPa) for P1.

Wang and Chan (2002) pointed out that the further southeastward in the western Pacific a TC is when it is formed, the stronger its intensity becomes and, therefore, the longer its lifetime becomes. Accordingly, the latitudes and longitudes of K-TC genesis locations and the K-TC lifetimes for the two periods were analyzed, as shown in Fig. 5. In relation to the longitude, the TCs during P2 occur further to the east (P1: 141.2°E, P2: 142.5°E), even though the difference between the two periods is not large. On the other hand, there is a difference of about 3°N for the latitude (P1: 15.8°N, P2: 13.1°N). This more southeastward TC genesis for P2 may be related, not only to the monsoon trough, but also to the southwestward expansion of the SWPH Chen et al. (1998). In addition,

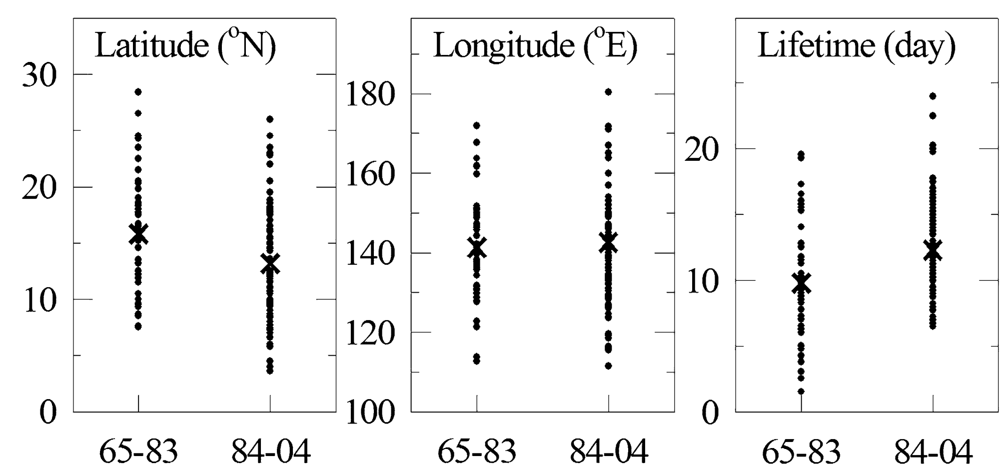

Fig. 5 Latitude (*left*) and longitude (*middle*) locations of K-TC genesis and TC lifetime (*right*) for P1 and P2. *Multiplication marks* indicate the mean value for each period

the closer to the equator a TC is during its formation, the longer its lifetime tends to become (P2:12.3 days, P1: 9.8 days), as indicated by Wang and Chan (2002).

Vertical wind shear difference between P1 and P2

In order to investigate the effect of large-scale conditions on the difference in the TC intensity between the two periods, we analyzed the vertical wind shear (VWS) anomalies for P1 (Fig. 6a) and P2 (Fig. 6b) and its difference between P2 and P1 (Fig. 6c). Associated with the VWS, Gray (1968, 1975) and McBride and Zehr (1981) have already emphasized that the patterns of the VWS have a critical role in an intensification of the TC. While the center of the positive anomalies for P1 is located around Korea and Japan and the region of negative anomalies is located to the south of 30°N (Fig. 6a), the negative anomalies for P2 is located not only to the south of 30°N, but also in Korea (Fig. 6b). In addition, the negative anomalies in the region south of 30°N for P1 are generally stronger for P2 (Fig. 6c). This indicates that during P2, K-TCs have a more favorable environment and thus could maintain stronger intensities than during P1, as analyzed in "TC intensity" section. In addition, in relation to the VWS difference between P2 and P1, the center of the negative anomalies is located in the mid-latitudes of East Asia, such as Korea, Japan, and some parts of northern China, and Japan. Also, most regions of the analysis area predominantly show negative anomalies. Consequently, this environment for P2 can also provide good conditions for maintaining a strong intensity in a K-TC, until it moves north into the mid-latitudes.

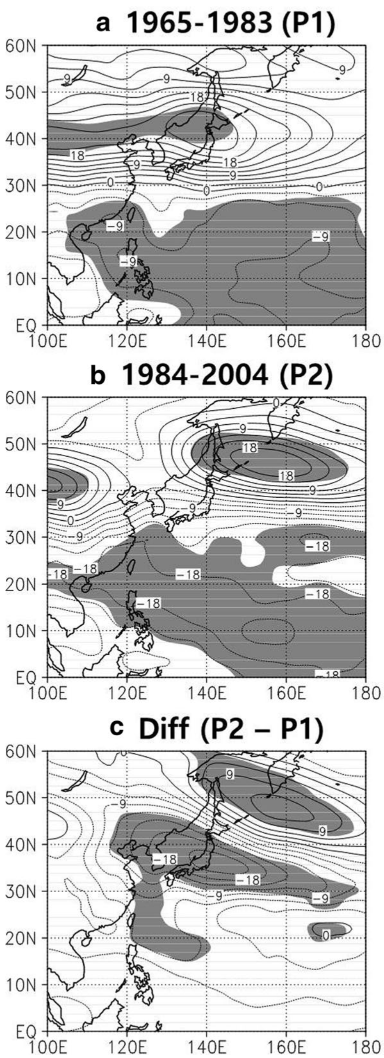

Fig. 6 Vertical wind shear (VWS) anomalies for **a** 1965–1983 (P1) and **b** 1984–2004 (P2) and **c** the VWS difference between P2 and P1. For anomalies, climatological average is the period from 1965 to 2004. The areas exceeding the 95% confidence level are shaded. The contour interval is 3 ms^{-1}

Eventually, it is concluded that the VWS in most regions of East Asia and the WNP is generally weaker for P2 than for P1. Thus, we can confirm that the period of P2 shows the potential for a TC to maintain a strong intensity in the mid-latitudes of East Asia.

After this study investigates other environmental fields, favorable conditions for TC intensification around Korea, such as anomalous warm sea surface temperature and warm air temperature, and anomalous high relative humidity are shown during P2 (not shown).

Summary and conclusions

The change-point analysis (CPA) was performed for tropical cyclone (TC) activities that affected Korea (K-TC) during the period of 1965–2004. As a result, we suggest that there is a clear shift in K-TC activities between 1983 and 1984 as follows: There were 95 TCs for the period of 1984–2004 (P2) and only 61 for the period of 1965–1983 (P1). The tracks and recurving locations of these TCs shifted more westward and southwestward in P2, respectively. This recent shift in K-TC activities was related to the southwestward expansion of the subtropical western Pacific high (SWPH) and, simultaneously, its elliptic shape toward Korea.

Associated with the K-TC intensity, the central pressure of the TCs near Korea also showed a difference between the 2 years. That is, the average central pressure for P2 was about 10 hPa deeper than that for P1. This was because the TCs during P2 occurred further to the southeast because of the recent southwestward expansion of the SWPH and, therefore, had a longer lifetime than those for P1. The cause of this difference in the TC intensity between the two periods was well confirmed through a vertical wind shear (VWS) analysis. The VWS for P2 was weaker over most regions of East Asia and the western North Pacific (WNP) than that for P1. Eventually, it could be determined that the period of P2 had a greater potential for a K-TC to maintain a strong intensity in the mid-latitudes of East Asia.

However, the increased typhoon activity that occurred in/around Korea starting in 1984 was not reflected basinwide (WNP). Yumoto and Matsuura (2001) and Matsuura et al. (2003) noted in common that the annual frequency of TCs in the WNP is high in the 1960s, low in the 1970s, and again high in the 1980s with a gradual increasing trend.

Authors' contributions

JWC designed and carried out the study and wrote the paper. YC provided detailed information on East Asian meteorological data. JYK acquired and processed the data of YC. JWC, YC, and JYK contributed extensively to the scientific discussion. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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