Interdecadal change in the genesis activity of the first tropical cyclone of each year over the western North Pacific

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Research Article

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Abstract

This study analyzed time series of the genesis latitude, longitude, and date of the first tropical cyclone (TC) each year over the 38 years between 1979 and 2016. Statistical change-point analysis applied to these three variables showed that a shift in climate regime occurred around 1998. More specifically, recent TCs have shown a strong tendency to occur more northwest in the western North Pacific (WNP), and day of TC genesis tend to be delayed. Also, we compared differences between the periods 1998 to 2016 (post-1998) and 1979–1997 (pre-1998) in terms of outgoing longwave radiation (OLR), total cloud cover, precipitable water, precipitation, vertical wind shear, 850 hPa relative vorticity, and sea surface temperature (SST). Our results showed that a favorable environment for TC genesis was formed near the South China Sea (SCS) and the Philippines and an unfavorable environment for TC genesis was formed in the southeastern part of the WNP. Analysis of stream flow showed that an anomalous cyclonic circulation at 850 hPa was formed in the SCS and an anomalous large anticyclonic circulation was formed in the North Pacific. From these circulations, a ridge extended to the east sea of the Philippines, and consequently, anomalous trade winds were strengthened in the equatorial Pacific. Such anomalous atmospheric circulation seems to be associated with the cold Pacific Decadal Oscillation (PDO) phase. At 200 hPa, the anomalous anticyclonic circulation was strengthened in the SCS, and an anomalous cyclonic circulation formed in the east sea of the Philippines, which strengthened anomalous westerlies in the equatorial Pacific. Furthermore, this circulation pattern is found to be related with a strengthening of Walker circulation. Therefore, during the post-1998, when trade winds were strengthened by the development of Walker circulation, the cold PDO phase was strengthened, the location of TC genesis moved toward the northwestern WNP, and TC genesis day tended to be delayed.

1. Introduction

Tropical cyclones (TCs) such as typhoons and hurricanes, one of the most devastating meteorological phenomena, influence the mid-latitude region as well as the tropical region and have enormous societal and economic damages. Moreover, the frequency of TCs impacting Korea has increased recently (Choi et al., 2012), and thus, it is very important to understand the recent characteristics of TCs to reduce damage to life and property and develop a new predictive disaster control system in line with the change.

The western North Pacific (WNP) is the region of the highest sea surface temperature (SST) in the world in which TC genesis is highly active. In fact, more than a third of all TCs occur in this region (McBride 1995; Elsberry 2004). Many studies have been conducted to model the characteristics of TCs by giving different atmospheric and marine environments over past decades. These studies can be classified into three categories. The first involves the prediction of TC development given various atmospheric conditions utilizing a low-resolution model (e.g., Ryan et al., 1992). The second method involves the use of a regional climate model (e.g., Knutson and Tuleya, 1999), which typically is approached using a high-resolution model. This meso-scale model uses oceanic boundary and atmospheric lateral conditions obtained from a global climate model. The third method simulates a tropical cyclone-like vortex using a global climate model, which offers a more direct means to identify the characteristics of TCs in terms of

large-scale atmospheric and oceanic conditions (e.g., Bengtsson et al., 1995). The characteristics of TCs simulated using this type of model are similar to the qualitatively observed characteristics of TCs, but the simulated intensities, sizes, and asymmetries are inaccurate since the horizontal resolutions of most global climate models are 100km or larger (e.g., Bengtsson et al., 1982; Camago and Sobel, 2004). By contrast, the characteristics of individual TCs simulated using a high-resolution climate model are similar to the observed characteristics of TCs, but the integrated period is relatively short and genesis frequencies exhibit some regionally dependent bias as compared with observations (Oouchi et al., 2006; Bengtsson et al., 2007).

TC genesis is considered to be highly dependent on SST, because higher SSTs supplies more energy and water vapor in the form of latent heat for TC formation. TC formation and development can be greatly influenced by an increase in SST, because the amount of water vapor produced increases exponentially according to the Clausius-Clapeyron relationship. However, many previous studies have suggested that the characteristics of TCs can also be changed by atmospheric conditions such as static stability, relative humidity, and upper and lower tropospheric wind shear (Gray,1979, Tang and Neelin, 2004; Thatcher and Pu 2013; Cecile and Timothy 2017; Wang et al. 2018; Zhang et al. 2019; Wang and Murakami 2020). In particular, Gray (1979) developed an index for estimating seasonal and spatial changes for a number of observed TC generation using environmental variables, and Emanuel and Nolan (2004) developed the Genesis Potential Index (GPI) by improving the index.

El Niño is a large-scale SST variation in the tropical Pacific, and atmosphere-ocean circulation changes induced by El Niño are known to influence TC activities in various regions. Gray (1984) demonstrated that El Niño influenced hurricane geneses in the North Atlantic, and Hastings (1990) showed that the frequency of TCs generated in the south western Pacific increased in the eastern region of Australia during La Niña years. Anthes (1982) reported that TC geneses and tracks in the WNP were influenced by El Niño. In 1997/1998, the El Niño phenomenon was of high intensity, but resolved quickly in May 1998, due to the development of a trade wind of exceptional intensity (Takayabu et al. 1999). As shown by these examples, many studies have been conducted on the correlation between El Niño Southern Oscillation (ENSO) and the climate system of the Indian Ocean, and various ENSO theories derived by the El Niño phenomenon in 1997/1998 (Saji et al. 1999; Webster et al. 1999; Yu and Rienecker 2000; Wang and McPhanden 2001; Tao et al. 2012; Chen et al. 2018; Liu et al. 2019; Ye et al. 2020). Furthermore, since the occurrence of the strongest El Niño phenomenon in 1997/1998, manifestations of climate change have become evident, such as significant increases in TC genesis frequencies being observed on the Pacific coast of the northwestern United States (Lander and Guard 2001; Allan and Komar 2002; Knutson et al. 2010; Sobel et al. 2016; Walsh et al.2016).

Many previous studies have investigated the correlations between TC development in the WNP and ENSO. In particular, it has been found that the number of typhoon occurrences and ENSO exhibit a nonlinear correlation, but were eventually affected by the ENSO (Chan 2000; Chen et al. 1998; Wang and Chan 2002; Chand and Walsh 2011; Li and Zhou 2012; Kang et al. 2019; Tan et al. 2019; Kim et al. 2020). Furthermore, it has been reported that the occurrence locations of TCs in strong El Niño years lean toward

the southeast WNP and that TC genesis frequency increases in the central Pacific region in El Niño years (Wang and Chan 2002; Clark and Chu 2002).

Many studies have also been conducted in South Korea to identify the characteristics of TCs. Sohn et al. (1999) analyzed a TC track cluster that occurred in the WNP, and Lee et al. (1998) researched TC structure and development. Lee and Lee (1998) examined the spatial distribution and causes of TC disasters in South Korea, and Kang et al. (1995) analyzed the correlation between interannual TC activity variation in the WNP and El Niño. Jang and Ha (2008) investigated the correlation between typhoon intensity and the locations of occurrences with respect to the development and extinction of ENSO. Choi et al. (2013) analyzed the correlation between North Atlantic Oscillation (NAO) in June and TC genesis in the western North Pacific in July and August.

However, studies on initial annual TC activity are very rare. Choi and Wang (2020) studied last annual TC activity by year and discovered that the longitude of the last TC genesis exhibited a strong negative correlation with the Antarctic Oscillation (AAO) and that the longitude locations of the last TC by year during the period 1998–2015 tended to be located more in the west WNP than during the 1983–1997 period.

In the present study, we examined the characteristics and mechanism of first TC activity by year. In Sect. 2, data and methodologies are introduced. Section 3 provides an overview of variations and mechanisms responsible for first annual TCs. Finally, Sect. 4 summarizes the findings of this study.

2. Data And Methodology

2.1 Data

We used best-track data produced by the Regional Specialized Meteorological Centre (RSMC)-Tokyo Typhoon Center. This data provides latitude, longitude, central pressure, and maximum sustained wind speed (MSWS) of TCs that occurred in the WNP since 1951 in 6-hour intervals. In this study, TC that occurred in the WNP was defined as a TC with an MSWS of $\geq 17 \text{ ms}^{-1}$, that is, one that developed to more than tropical storm (TS) strength. RSMC best-track data were compared with the one produced by Shanghai Typhoon Institute (STI) of the China Meteorological Administration (CMA) and the Joint Typhoon Warning Center (JTWC). The time series of first TC genesis latitude, longitude, and day for each year showed that RSMC and STI data were similar (a positive correlation of 0.99 was observed between the two time series) (Fig. 1). However, the JTWC has been providing TC intensities since 1999, and differs slightly from the other two time series.

To analyze large-scale environments with respect to the cause of TC activity, we used Reanalysis-2 (R-2) monthly average data issued by the National Center for Environmental Prediction (NCEP)-Department of Energy (DOE) since 1979 (Kanamitsu 2002). The data has a grid interval of $2.5^\circ \times 2.5^\circ$ in latitude-longitude and 17 vertical layers.

For SST data, we used Extended Reconstructed Sea Surface Temperature (ERSST) V3b data (Smith et al., 2008). The ERSST contains monthly average data from 1854 to the present and has a grid interval of $2^\circ \times 2^\circ$.

Outgoing longwave radiation (OLR) data were utilized for the analysis of convective activity (Liebmann and Smith, 1996).

Trade wind and 200 hPa zonal wind indice were obtained from the Climate Prediction Center (CPC) of the National Oceanic and Atmospheric Administration (NOAA) (<https://www.cpc.ncep.noaa.gov/data/indices/>).

The Walker circulation index is defined as the difference in 500 hPa omega velocities between the eastern equatorial Pacific (160°W – 80°W , 5°S – 5°N) and the western (80°E – 160°E , 5°S – 5°N) equatorial Pacific (Vecchi et al. 2006).

The Pacific Decadal Oscillation (PDO, Mantua et al., 1997) indices were obtained from the website of the University of Washington (<http://jisao.washington.edu/pdo>).

2.2 Methodology

Vertical wind shear (VWS), which was used to diagnose large-scale conditions, was calculated as follows:

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

where u and v indicate zonal and meridional flows, respectively, and 200 and 850 represent the 200 hPa and 850 hPa levels, respectively (Wingo and Cecil 2010).

Genesis potential indices (GPIs) were calculated using the equation derived by Camargo et al. (2007).

The occurrence date of the first TC in each year was defined as the first day when a TC reached TS strength. Figure 2 shows that months of the first TC in each year ranged from January to July and that the largest number of first TCs occurred in January. Months that had 10% or higher share of all occurrences were distributed from January to May.

To determine the significances of the results, we used the two-tailed Student's t test (Wilks 1995), and to examine the existence of a climate regime shift in the time series, we applied statistical change-point analysis to the time series (Elsner et al., 2000; Chu, 2002; Ho et al., 2004). Climate regime shift was defined as the time when the absolute t -value obtained from the result of this analysis was largest.

3. Results

3.1 Statistical change-point analysis

Figure 3 shows time series of TC genesis latitude, TC genesis longitude, and TC genesis day. First, in the time series of TC genesis latitude, a TC occurred at highest latitude (22.9°N) in 1998, and a distinct

interdecadal variation was observed (Fig. 3a). The overall linear trend showed a slightly increasing non-significant trend. This means that TCs have shown a tendency to move north recently. Statistical change-point analysis was applied to TC genesis latitude. The smallest t-value was observed in 1998, indicating the existence of a climate regime shift in TC genesis latitude. The average TC genesis latitude during 1979–1997 was 9.2°N , whereas the average TC genesis latitude during 1998–2016 was 11.9°N , that is, an increase of approximately 2.7° from 1998. This means that the genesis latitude of TCs has moved 2.7° north on average. This difference in TC genesis latitude between these two periods was significant at the 95% confidence level. In the time series of TC genesis longitude, it occurred easternmost in 1980 (177.7°E) and westernmost in 2012 (111.8°E) (Fig. 3b). Furthermore, the time series shows a distinct interdecadal variation. Hence, the time series of TC genesis longitude has exhibited a distinct decreasing linear trend, and this was significant at the 95% confidence level. Statistical change-point analysis was applied to this time series and showed the largest t-value occurred in 1998, which indicated the existence of a climate regime shift in TC genesis longitude. The average TC genesis longitude during 1979–1997 was 149.4°E , whereas the average TC genesis longitude during 1998–2016 was 131.4°E . This difference between the two periods was $\sim 18.0^{\circ}$, which was significant at the 95% confidence level. This means that the genesis longitude of TCs has moved 18.0° west on average. In the time series of TC genesis day, it occurred latest in 1998 on July the 9th, and earliest in 1979 on January the 2nd (Fig. 3c). Furthermore, a distinct interdecadal variation existed in the time series. Therefore, although the time series of TC genesis day showed an increasing linear trend, it was not statistically significant. Statistical change-point analysis was applied to this time series and showed the lowest t-value occurred in 1998, which indicated a climate regime shift in TC genesis day. The average TC genesis day during 1979–1997 was March 2, whereas the average TC genesis day during 1998–2016 was March 29, a difference of 27 days. Furthermore, this difference was significant at the 95% confidence level, which means that TC genesis days have occurred later recently. Summarizing, the first TC genesis location has been moving northwest in the WNP and TC genesis days have been delayed since 1998. Therefore, differences between averages during 1998–2016 (hereinafter referred to as post-1998) and averages during 1979–1997 (hereinafter referred to as pre-1998) were analyzed.

The spatial distribution of the first TC genesis location and the first TC full track were analyzed for each year during 1979–2016 (Figs. 4a and 4b). For spatial distributions of first TC geneses locations by year, TCs showed a tendency to occur at 0° – 20°N , which is considered to be due to lack of development of the monsoon trough to the north in winter and spring (Fig. 4a). Meanwhile, TCs in post-1998 tended to occur mainly in the South China Sea (SCS) and near the Philippines, whereas TCs in pre-1998 tended to occur in the southeast part of the WNP. Thus, recent TCs have occurred more in the northwest WNP.

TC full track analysis showed TCs in pre-1998 moved west toward the Indochina Peninsula, whereas TCs in post-1998 showed a strong tendency to move toward the mid-latitude region of East Asia (Fig. 4b). Therefore, we analyzed the time series of numbers of TS days (TS-day) that showed an intensity larger than the TS of the first TC in each year (Fig. 4c). The shortest TS-day appeared in 1979 and the longest in 1998. Furthermore, this time series showed a distinct interdecadal variation. Consequently, the time series

of TS-day showed an increasing linear trend, and this linear trend was significant at the 95% confidence level. This is believed to have occurred because TCs in post-1998 moved further toward the mid-latitude region of East Asia. When statistical change-point analysis was applied to this time series, the lowest t-value occurred in 1998, indicating the existence of a climate regime shift in TS-day in 1998. The average TS-day in pre-1998 was 4.3 days, whereas the average in post-1998 was 6.7 days. Hence, the difference between the two periods was 2.4 days, which was significant at the 95% confidence level. This result means that TCs have been stronger in post-1998 than in pre-1998.

3.2 Large-scale environments

To examine the cause of the recent shift in TC locations toward the northwest WNP, large-scale environments in these two periods were analyzed. (Fig. 5). The period from January to May was divided into winter (January-February) and spring (March-May). Initially, we analyzed thermodynamic factors that influence TC genesis. OLR analysis showed that in winter, convection is active in the northwestern WNP, including the SCS and the Philippines, but not active in the southeastern WNP (left panel Fig. 5a), and this trend appeared to be stronger in spring (right panel Fig. 5a). This result suggests environmental factors favored TC development in the northwestern WNP in post-1998. OLR analysis provided information on total cloud cover (Fig. 5b). In winter, there is a positive anomaly that extends from the SCS and the northeast region of the Philippines to the mid-latitude region of the WNP, whereas in the southeastern WNP, there is a negative anomaly (left panel of Fig. 5b). This spatial distribution becomes more distinct in spring (right panel of Fig. 5b). Differences between the spatial distributions of precipitable water in these two periods were similar to the spatial distributions of total cloud cover (Fig. 5c), that is, a positive anomaly existed from the SCS and near the Philippines to the mid-latitude region of the WNP, and a negative anomaly was present in the southeastern WNP. Thus, our analysis of differences in winter and spring precipitations between the two periods showed a positive anomaly in the SCS and near the Philippines and a negative anomaly in the southeastern WNP (Fig. 5d).

Dynamic factors that influence TC genesis were also analyzed. In spring, VWS showed a negative anomaly in the SCS and the northern Philippines and a positive anomaly in the southeastern WNP (left panel of Fig. 5e). A smaller VWS value stabilizes the upper and lower layers of the troposphere, which provides a more favorable environment for TC genesis. The different spatial distributions of VWS in the northwestern and southeastern WNP became more distinct in spring (right panel Fig. 5e). Analysis of 850 hPa relative vorticity showed a positive anomaly in the SCS and near the Philippines and a negative anomaly in the southeast part of the WNP in both winter and spring (Fig. 5f).

In spring and winter, SST showed a warm anomaly from the southwest to the northeast of the warm pool region of the WNP to the mid-latitude region of the central Pacific, and a cold anomaly from the southeastern WNP to the tropical central Pacific and eastern coast of the US (Fig. 5g). This spatial distribution provided a marine environment in post-1998 that favored TC development in the northwestern WNP associated with the cold phase of PDO.

GPI analysis, which included all thermodynamic and dynamic factors that influence TC genesis, showed that in winter, a positive anomaly exists from the east sea of the Philippines to the southern sea of the SCS, and that a negative anomaly exists in the southeastern WNP (left panel of Fig. 5h). These results show that the GPI spatial contrast between the northwestern and southeastern WNP in winter becomes more evident in spring (right panel of Fig. 5h).

In addition, horizontal divergences between lower and upper levels in winter and spring were analyzed (Fig. 6). At 850 hPa, in both winter and spring, there was a negative anomaly in the western WNP and a positive anomaly in the eastern WNP (Fig. 6a). In contrast, at 200 hPa, there was a positive anomaly in the SCS and northern Philippines and a negative anomaly in the eastern WNP (Fig. 6b). This result suggests that anomalous upward flows were strengthened in the western WNP and anomalous downward flows occurred in the eastern WNP post-1998.

Time series of factors influencing TC genesis averaged for the SCS and the sea area near the Philippines (10° - 20° N, 110° - 130° E) and the southeastern WNP (5° - 15° N, 140° - 180° E) were also analyzed (Fig. 7). These factors were averaged for the period of January to May. The OLR and VWS showed a decreasing linear trend in the SCS and the sea area near the Philippines, whereas the SST and GPI show an increasing linear trend, and these trend changes for all four factors were significant at the 95% confidence level. In contrast, in the southeastern WNP, OLR and VWS showed an increasing linear trend, and SST and GPI showed a strong linear decreasing trend, and these trend changes were also significant at the 95% confidence level. The above results indicate that a favorable environment for TC genesis recently formed in the SCS and near the Philippines and that an unfavorable environment for TC genesis recently formed in the southeastern WNP. Because the time series of these four factors in these two regions exhibited a distinct interdecadal variation, we applied statistical change-point analysis to each time series. Notably, all t-values had largest or smallest values in 1998, thus indicating the existence of a climate regime shift in the time series of the four factors in 1998 associated with the movement of first TC genesis location to the northwestern WNP.

3.3 Atmospheric circulations

We also analyzed differences in lower- and upper-level stream flows in winter and summer between pre- and post-1998 (Fig. 8). At 850 hPa in winter, an anomalous cyclonic circulation formed in the SCS (left panel Fig. 8a). In contrast, an anomalous huge anticyclonic circulation formed in the North Pacific with a ridge extending to the east sea of the Philippines, which resulted in the strengthening of anomalous trade winds in the equatorial Pacific, and this anomalous atmospheric circulation pattern was associated with the cold PDO phase. In spring, the spatial distribution of atmospheric circulation was similar to that observed in winter (right panel of Fig. 8a). Anomalous cyclonic circulation was strengthened from the SCS to the East China Sea (ECS), and anomalous anticyclonic circulation was formed from northeast to southwest from the North Pacific to the east sea of the Philippines. As a result, anomalous trade winds were strengthened in the equatorial Pacific. At 200 hPa in winter and spring, an anomalous anticyclonic circulation was strengthened in the SCS, whereas an anomalous cyclonic circulation was formed in the east sea of the Philippines (Fig. 8b), and as a result, anomalous westerlies were strengthened in the

equatorial Pacific. Thus, it can be seen that an anomalous cyclone and an anomalous anticyclone were formed in the lower- and upper-levels, respectively, in the SCS and near the Philippines, whereas opposite anomalous pressure systems were formed in the lower- and upper-levels of the southeastern WNP.

The above results regarding SST differences during the two periods show that the spatial pattern observed was associated with the PDO. In addition, analysis results of atmospheric circulation differences also showed that the anomalous circulation was associated with the PDO, and thus, we analyzed correlations between PDO averaged from January to May and TC genesis latitude, TC genesis longitude, and TC genesis day (Fig. 9). A negative correlation of -0.54 was observed between PDO and TC genesis latitude, which was significant at the 99% confidence level (Fig. 9a). Since PDO shows a strong linear trend with the cold phase, the correlation was reanalyzed after removing the linear trend from the two variables, and the correlation found did not differ significantly from the first correlation (Corr = -0.53; significant at the 99% confidence level). This means that the stronger (weaker) the cold PDO phase, the greater the tendency for TC genesis locations to move north (south). Furthermore, a positive correlation of 0.57 was observed between PDO and TC genesis longitude, which was significant at the 99% confidence level (Fig. 9b). The correlation was analyzed again after removing the linear trend from the two variables, and the correlation did not significantly differ from the first correlation (Corr = 0.54; significant at the 99% confidence level). This means that the stronger (weaker) the cold PDO phase, the greater the tendency for TC genesis locations to move west (east). A negative correlation of -0.48 was observed between PDO and TC genesis day, and this correlation was significant at the 99% confidence level (Fig. 9c). The correlation was reanalyzed after removing the linear trend from the two variables, and again was not significantly different from the first correlation (Corr = -0.46; significant at the 99% confidence level). This means that the stronger (weaker) the cold PDO phase, the later (sooner) TC genesis occurs. In other words, the above result shows that in the cold (warm) PDO phase, TCs have a strong tendency to occur in the northwestern (southeastern) region of the WNP, and that TC genesis tends to occur later (sooner). Statistical change-point analysis was applied to the PDO time series. The highest t-value occurred in 1998, and a climate regime shift in the PDO time series also occurred during 1998. Furthermore, PDO showed a high correlation with interdecadal and interannual variation on the TC genesis location and TC genesis day.

Post-1998 in the equatorial Pacific, anomalous trade winds strengthened at 850 hPa, and the anomalous westerlies strengthened at 200 hPa (Fig. 8), which suggests Walker circulation strengthened post-1998. Thus, we analyzed vertical zonal circulation averages for 0°-20°N (Fig. 10a). In both winter and spring, anomalous upward flows developed at 130°-150°E, whereas anomalous downward flows developed at 170°E-160°W, and these anomalous upward flows and anomalous downward flows were significant at the 95% confidence level. This result means that anomalous Walker circulation caused air to rise in the tropical western Pacific and descend in the tropical equatorial Pacific in post-1998. Such strengthening of anomalous Walker circulation in post-1998 was also observed by the analysis of different 850 hPa velocity potentials during the two periods (Fig. 10b). In winter and spring, anomalous convergence developed in the tropical western Pacific, whereas anomalous divergence strengthened in the tropical central and eastern Pacific. This means that anomalous Walker circulation, whereby air rises in the tropical western Pacific and descends in the tropical equatorial Pacific, developed in post-1998.

Therefore, we study analyzed correlations between trade wind index (200 hPa zonal wind index) averaged for January to May and TC genesis latitude, TC genesis longitude, and TC genesis day (Figs. 11a-11c). The time series of trade wind index and TC genesis latitude showed distinct interannual and interdecadal variations (left panel of Fig. 11a). Trade wind index showed a linear weakening trend, and this linear trend was significant at the 90% confidence level. Since there was a distinct out-of-phase tendency between the two time series, we examined the correlation between the two and found a negative correlation of -0.48, which was significant at the 99% confidence level. This negative correlation did not change significantly when the linear trend was removed from the two time series (Corr = -0.47; significant at the 99% confidence level). This result means that as the trade wind was strengthened (weakened), TC genesis occurred more in the south (north). The time series of trade wind index and TC genesis longitudes also show distinct interannual and interdecadal variations, and these two time series exhibited an in-phase trend (left panel of Fig. 11b). Therefore, the correlation between the two variables was analyzed and it showed a positive correlation of 0.46, which was significant at the 99% confidence level. Since these two variables showed a large linear trend, the correlation was analyzed again after the linear trend was removed from the linear trend, and this resulted in a positive correlation of 0.51, which was greater than the first correlation and significant at the 99% confidence level. This result means that as the trade wind strengthened (weakened), TC genesis occurred more in the east (west). The time series of trade wind index and TC genesis day also showed distinct interannual and interdecadal variations, and a distinct out-of-phase trend between the two (left panel of Fig. 11c). Therefore, the correlation between the two variables was analyzed and it showed a high negative correlation of -0.51, which was significant at the 99% confidence level. Removal of the linear trend had little effect on the correlation (Corr = -0.52; significant at the 99% confidence level). This result means that as the trade wind strengthened (weakened), TC genesis becomes was delayed (occurred sooner). Thus, statistical change-point analysis was applied to the trade wind index time series (left panel of Fig. 11d). Trade wind index also had largest t-value in 1998, indicating the existence of a climate regime shift in 1998. Correlations between 200 hPa zonal wind index and TC genesis latitude, TC genesis longitude, and TC genesis day showed the opposite of that observed for trade wind index. 200 hPa zonal wind index and TC genesis latitude showed a positive correlation of 0.49 (right panel of Fig. 11a), 200 hPa zonal wind index and TC genesis longitude showed a high negative correlation of -0.56 (right panel of Fig. 11b), and 200 hPa zonal wind index and TC genesis day showed a high positive correlation of 0.55 (right panel Fig. 11c). All three correlation results were significant at the 99% confidence level. When correlations were reanalyzed after removing linear trends from the time series, results did not differ appreciably, and all three correlations were significant at the 99% confidence level. This result means that when the 200 hPa zonal wind strengthened, TC genesis showed a strong trend to occur in the northwest WNP and TC genesis days were delayed. The 200 hPa zonal wind index has continued to show a significant increasing linear trend (and the increasing linear trend is significant at the 90% confidence level). Because it showed a distinct interdecadal variation, the statistical change-point analysis was applied (right panel of Fig. 11d). This analysis showed the t-value was lowest in 1998, indicating the existence of a climate regime shift in the 200 hPa zonal wind index time series in 1998.

To examine the strengthening of Walker circulation in post-1998, we analyzed 500 hPa omega differences between the two periods (Fig. 12a). The negative anomaly strengthened in the equatorial western Pacific, the SCS, and near the Philippines, whereas a positive anomaly was formed in the subtropical and tropical central Pacific. This means that the Walker circulation, whereby air rises in the tropical western Pacific and air descends in the tropical central Pacific, was strengthened. We analyzed correlations between Walker circulation index and TC genesis latitude, TC genesis longitude, and TC genesis day (Figs. 12b-12d). The time series of Walker circulation index and TC genesis latitude showed distinct interannual and interdecadal variations (Fig. 12b). The Walker circulation index continued to show an increasing linear trend, and this trend was significant at the 90% confidence level. A distinct in-phase trend was observed between these two time series. Correlation analysis showed a high positive correlation of 0.59 between the two variables, which was significant at the 99% confidence level, and this correlation was unaffected by removing the linear trend from the two variables (Corr = 0.57; significant at the 99% confidence level). This result means that when the Walker circulation is strengthened (weakened), TC genesis shows a strong tendency to move north (south).

Walker circulation index and TC genesis longitudes showed a high negative correlation of -0.65 (Fig. 12c), which was significant at the 99% confidence level. Since the linear trend of these two variables had large variations, their correlation was analyzed again after removing the linear trend from the two time series, which resulted in a higher negative correlation (Corr = -0.68; significant at the 99% confidence level). This result means that when the Walker circulation was strengthened (weakened), TC genesis occurred more in the west (east). Walker circulation index and TC genesis day showed a positive correlation of 0.45, which was significant at the 99% confidence level (Fig. 12d). Furthermore, when the linear trend was removed from the two time series, this correlation was unaffected (Corr = 0.46; significant at the 99% confidence level). This result means that when the Walker circulation strengthens, TC genesis is delayed. Since the Walker circulation index also shows considerable interdecadal variations, we applied statistical change-point analysis to the Walker circulation index time series (Fig. 12e). The t-value was lowest in 1998, indicating the existence of a climate regime shift in Walker circulation index in 1998.

3.4 Monthly variations of OLR and WNPSH

To examine why TCs in post-1998 occurred more in the northwestern WNP in more detail, differences in OLR between post-1998 and climatology (1979–2016) and differences in OLR between pre-1998 and climatology were analyzed monthly from January to May (Fig. 13). Overall, the analysis results show opposite monthly spatial patterns. Regarding differences between post-1998 and climatology, a strong negative anomaly was observed in the northwestern WNP and a strong positive anomaly in the southeastern WNP (left panel of Fig. 13). By contrast, the difference between pre-1998 and climatology revealed a strong positive anomaly in the northwestern WNP and a strong negative anomaly in the southeastern WNP (right panel Fig. 13). These characteristics of spatial distribution were more distinct for January to May monthly averages. Pattern correlation analysis was applied to the spatial distribution of differences between post-1998 and climatology and the spatial distribution of the difference between pre-1998 and climatology for each month and January to May monthly averages. The results showed a high negative correlation of ≥ -0.75 . Furthermore, pattern correlation analysis of the two spatial

distributions for January to May averages showed a high negative correlation of -0.92. Therefore, these results show TCs pre-1998 tended to form in the southeastern WNP and TCs post-1998 tended to form in the northwestern WNP.

To determine the reason for the recent delays in TC genesis, we examined the characteristics of the spatial distributions of average western North Pacific subtropical highs (WNPSHs) monthly from January to May pre- and post-1998 (Fig. 14). Here, WNPSH was defined as a region larger than 5,870 gpm. Monthly WNPSHs in post-1998 developed in more east-west and south-north directions than those pre-1998. This characteristic was also more distinct for January to May averages. The development of WNPSHs in the WNP makes it more difficult to generate TCs because convection is weakened. Hence, the genesis of TCs in post-1998 was reduced in the WNP when WNPSHs were more developed, and this delayed TC genesis and reduced TC genesis frequency (TCGF) (Fig. 14g). In fact, the TC genesis frequency (TCGF) in January to May continued to follow a linear decreasing trend throughout the study period, and this trend was significant at the 90% confidence level. Furthermore, average TCGF in pre1998 was 3.4 TCs, whereas average TCGF in post-1998 was 1.9 TCs, and this difference of 1.5 TCs was significant at the 95% confidence level.

4. Summary And Conclusions

This study analyzed time series of genesis latitude, genesis longitude, and genesis day of first TCs in each year over the period 1979–2016. Statistical change-point analysis indicated the existence of a climate regime shift in 1998 for all three variables. In other words, recent TCs have shown a stronger tendency to occur more frequently in the northwestern WNP. Therefore, we analyzed differences between the periods of pre- and post-1998 in terms of thermodynamic and dynamic factors.

To examine the cause of the occurrence of more TCs recently in the northwestern WNP, large-scale environments were analyzed in pre- and post-1998. The period January to May was divided into winter (January-February) and spring (March-May). Initially, we analyzed thermodynamic factors that influence TC genesis. OLR analysis showed that convection was active in the northwestern WNP, including the SCS and the Philippines, whereas convection was not active in the southeastern WNP. Analysis of total cloud cover revealed a positive anomaly from the SCS and the northeastern Philippines to the mid-latitude region of the WNP, but a negative anomaly in the southeastern WNP. The spatial distributions of precipitable water were similar to the spatial distributions of total cloud cover. Based on the above results, differences between precipitations in winter and spring showed a distinct positive anomaly in the SCS and near the Philippines and a distinct negative anomaly in the southeastern WNP.

Next, we analyzed dynamic factors that influence TC genesis. VWS showed a negative anomaly in the northern region of the Philippines and SCS and a positive anomaly in the southeastern WNP. However, 850 hPa relative vorticity results showed a positive anomaly in the SCS and near the Philippines and a negative anomaly in the southeastern WNP.

SSTs showed a warm anomaly from southwest to northeast direction and from the warm WNP pool region to the mid-latitude region of the central Pacific, and a cold anomaly from the southeastern WNP to the tropical central Pacific and the east coast of the US. Furthermore, this spatial distribution was associated with the cold phase of the PDO.

Time series of factors that influence TC genesis averaged for the SCS, the sea area near the Philippines, and the southeastern WNP were also analyzed. OLR and VWS in the SCS and the sea area near the Philippines showed a decreasing trend whereas SST and GPI showed an increasing trend. In contrast, in the southeastern WNP, OLR and VWS showed increasing trends, whereas SST and GPI showed strong decreasing trends. These results suggest that a favorable environment for TC genesis exists in the SCS and near the Philippines, whereas an unfavorable environment for TC generation is present in the southeastern WNP. Statistical change-point analysis applied to each time series showed absolute t-values were either at a maximum or minimum in 1998, which indicated a climate regime shift in 1998.

We also analyzed differences between lower- and upper-level stream flows in winter and spring in pre- and post-1998. At 850 hPa, an anomalous cyclonic circulation was observed in the SCS and an anomalous huge anticyclonic circulation in the North Pacific. From this circulation, a ridge extended to the east sea of the Philippines (Fig. 15). Consequently, anomalous trade winds were strengthened in the equatorial Pacific. This anomalous atmospheric circulation was associated with the cold PDO phase. At 200 hPa, an anomalous anticyclonic circulation strengthened in the SCS and an anomalous cyclonic circulation was formed in the east sea of the Philippines. As a result, anomalous westerlies were strengthened in the equatorial Pacific.

The correlations between average PDO index for the period from January to May and TC genesis latitudes, TC genesis longitudes, and TC genesis days were also analyzed. PDO index and TC genesis latitude were negatively correlated, meaning that as the cold PDO phase strengthened (weakened), TC genesis location tended to move north (south). PDO index and TC genesis longitude were positively correlated, implying that as the cold PDO phase strengthened (weakened), TC genesis location tended to move west (east). PDO index and TC genesis day were negatively correlated, indicating that as the cold PDO phase strengthened (weakened), TC genesis was delayed (occurred sooner). These results show that in the cold (warm) PDO phase, TCs show a strong tendency to occur in the northwestern (southeastern) WNP and TC genesis days tended to be delayed (occur sooner). Furthermore, the results of statistical change-point analysis applied to PDO time series showed that the PDO time series exhibited a climate regime shift in 1998.

We also analyzed vertical zonal circulation averaged over 0°-20°N. In both winter and spring, anomalous upward flows developed at 130°-150°E, whereas anomalous downward flows developed at 170°E-160°W. This result suggests the development of an anomalous Walker circulation involving rising air in the tropical western Pacific and descending air in the tropical equatorial Pacific post-1998. This strengthening of anomalous Walker circulation in post-1998 was also observed during the analysis of 850 hPa velocity potential differences between the two periods.

Therefore, we analyzed correlations between trade wind index (200 hPa zonal wind index) averaged for January to May and TC genesis latitude, TC genesis longitude, and TC genesis day. Trade wind index and TC genesis latitude showed a negative correlation, meaning as the trade wind strengthened (weakened), TC genesis occurred more in the south (north). However, trade wind index and TC genesis longitude were positively correlated, meaning that as the trade wind strengthened (weakened), TC genesis occurred more in the east (west). Trade wind index and TC genesis day were highly and negatively correlated, indicating that when the trade wind strengthened (weakened), TC genesis was delayed (occurred sooner). Statistical change-point analysis applied to the trade wind index time series also indicated the existence of a climate regime shift in 1998. Correlations between 200 hPa zonal wind index and TC genesis latitude, TC genesis longitude, and TC genesis days showed patterns contrary to those observed for trade wind index. This result suggests that when 200 hPa zonal wind is strengthened, TC genesis tended to occur in the northwestern WNP and TC genesis day was delayed. Statistical change-point analysis applied to 200 hPa zonal wind index also indicated a climate regime shift in 1998.

Correlations between Walker circulation index and these three variables were also analyzed. Walker circulation index and TC genesis latitudes exhibited a high positive correlation, meaning when Walker circulation strengthened (weakened), TC genesis showed a strong tendency to occur in the northern (southern) WNP. Walker circulation index and TC genesis longitude showed a strong negative correlation, showing that when Walker circulation strengthened (weakened), TC genesis occurred more in the western (eastern) WNP. Walker circulation index and TC genesis day were positively correlated, showing that when Walker circulation was strengthened, TC genesis was delayed. Statistical change-point analysis applied to the Walker circulation index time series, also demonstrated a climate regime shift in 1998.

To examine the reason that the TCs during post-1998 occurred more in the northwest region of the WNP in more detail, the difference in OLR between the post-1998 and climatology and the difference in OLR between the pre-1998 and climatology in each month from January and May were analyzed. The difference between post-1998 and climatology revealed a strong negative anomaly in the northwestern WNP and a strong positive anomaly in the southeastern WNP, and interestingly, the difference between pre-1998 and climatology showed the opposite pattern. Therefore, TCs during pre-1998 tended to form in the southeastern WNP, whereas TCs during post-1998 tended to form in the northwestern WNP.

Finally, to examine the reason for the delay of the recent TC genesis, the characteristics of the spatial distribution of average WNPSHs for each month from January to May during pre-1998 and post-1998 were examined. We found that in every month, WNPSHs in post-1998 tended to develop in east-west and south-north directions, whereas WNPSHs in pre-1998 tended to be weakened. Therefore, TC genesis was delayed and TCGF was smaller in post-1998 when WNPSHs were more developed in the WNP because WNPSH makes TC genesis more difficult.

Declarations

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Figures

Figure 1

Time series of (a) genesis latitude, (b) genesis longitude, and (c) genesis day (Julian day) of the yearly earliest tropical cyclone (TC) in the western North Pacific (WNP).

Figure 2

Monthly distribution on the genesis of the yearly earliest TC in the WNP.

Figure 3

The results of statistical change-point analysis on (a) normalized genesis latitude, (b) normalized genesis longitude, and (c) normalized genesis day of the yearly earliest TC in the WNP.

Figure 4

(a) TC genesis location, (b) TC full track, (c) time series of tropical storm (TS) day from the period of 1979-1997 (pre-1998; blue dots and blue tracks in (a) and (b)) and 1998-2016 (post-1998; red dots and red tracks in (a) and (b)). In (a) red and blue crosses denote mean TC genesis location of post-1998 (11.9°E, 131.4°E) and pre-1998 (9.2°N, 149.4°E).

Figure 5

Composite differences in (a) OLR, (b) total cloud cover, (c) precipitable water, (d) precipitation, (e) vertical wind shear (VWS), (f) 850 hPa relative vorticity, (g) SST, and (h) genesis potential index (GPI) between post-1998 and pre-1998 in January-February (left panel) and March-May (right panel). Hatched lines are significant at the 95% confidence level.

Figure 6

Composite differences in (a) 850 hPa and (b) 200 hPa horizontal divergence (unit: $s^{-1} \times 10^7$) between post-1998 and pre-1998 in January-February (left panel) and March-May (right panel). Hatched lines are significant at the 95% confidence level.

Figure 7

The results of statistical change-point analysis on normalized (a) OLR, (b) VWS, (c) SST, and (d) GPI in South China Sea (SCS) and Philippines (left panel) and southeastern part of WNP (right panel).

Figure 8

Composite differences in (a) 850 hPa and (b) 200 hPa stream flows between post-1998 and pre-1998 in January-February (left panel) and March-May (right panel). Shaded areas are significant at the 95% confidence level.

Figure 9

Relationships (a) between TC genesis latitude and Pacific Decadal Oscillation (PDO), (b) between TC genesis longitude and PDO, and (c) between TC genesis day (Julian day) and PDO. (d) The results of statistical change-point analysis on PDO.

Figure 10

Composite differences of longitude–pressure cross section of (a) vertical velocity (contours) and zonal circulations (vectors) averaged along 0°–20°N and (b) 850 hPa velocity potential between post-1998 and pre-1998 in January-February (left panel) and March-May (right panel). In (a), the values of vertical velocity are multiplied by -100 , dashed lines are significant at the 95% confidence level, and Contour intervals are 2–2hPa s⁻¹. In (b), shaded areas denote negative anomalies and contour interval is 3 m²s⁻¹.

Figure 11

Relationships (a) between TC genesis latitude and 850 hPa trade wind index (left panel) and 200 hPa zonal wind index (right panel), (b) between TC genesis longitude and 850 hPa trade wind index (left panel) and 200 hPa zonal wind index (right panel), and (c) TC genesis day (Julian day) 850 hPa trade wind index (left panel) and 200 hPa zonal wind index (right panel). (d) Results of statistical change-point analysis on 850 hPa trade wind index (left panel) and 200 hPa zonal wind index (right panel).

Figure 12

Composite difference in (a) 500 hPa omega between post-1998 and pre-1998 in January-May. Relationships (b) between TC genesis latitude and Walker circulation index, (c) between TC genesis longitude and Walker circulation index, and (d) between TC genesis day (Julian day) and Walker circulation index. (e) result of statistical change-point analysis on Walker circulation index.

Figure 13

Composite differences in OLR between post-1998 and climatology (1979-2016) (left panel) and between pre-1998 and climatology in (a) January, (b) February, (c) March, (d) April, (e) May, and (f) January-May. Contour interval is 2Wm⁻². Shaded areas denote negative values.

Figure 14

Monthly variation of WNP5H (5,870gpm contour) from (a) to (f). Red and blue lines denote WNP5Hs of post-1998 and pre-1998, respectively. Time series of TCGF in January-May.

Figure 15

Schematic diagram of 850 hPa anomalous atmospheric circulation in cold PDO phase in post-1994. "AA" and "AC" indicate anomalous anticyclone and anomalous cyclone, respectively.