Anomalous variation in summer tropical cyclone activity by preceding winter Aleutian low oscillation

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Abstract

This research found a high-positive correlation between Aleutian low oscillation during the winter (November–March) and tropical cyclone (TC) genesis frequency during the following summer (July–September) over a 26-year period (1982–2007). In the years with high Aleutian low oscillation, a number of characteristics were analyzed. In the preceding winter, anomalous pressure patterns, such as south-low and north-high at the low level, formed as the center for the regions near 20°N in the western North Pacific. Sea ice concentration was less than the average around the Sea of Okhotsk and the Bering Sea, which weakened the Aleutian Low in this area. This anomalous pressure pattern continued until the following summer, and it reinforced the anomalous easterlies at the mid-latitudes (20°–40°N) in East Asia and contributed to the high TC passage frequency in the East Asian continent.

Keywords: tropical cyclone; Aleutian low oscillation; sea ice concentration

1. Introduction

Gray (1984) identified six physical parameters that influence tropical cyclone (TC) genesis: (1) low-level relative vorticity, (2) local or planetary vorticity (Coriolis parameter), (3) the inverse of the vertical shear of the horizontal wind between the lower and upper troposphere, (4) ocean thermal energy maintaining temperatures above 26.8°C at a depth of 60 m, (5) the vertical gradient of the equivalent potential temperature between the surface and 500 mb (hPa), and (6) the middle-troposphere relative humidity. Gray’s parameters have been used as common large-scale predictors in statistical models for predicting the seasonal genesis frequency of TCs because of their accuracy in reflecting the seasonal characteristics related to TC activity (Mcdonnell and Holbrook, 2004). In particular, it has been shown that these parameters, when combined, can broadly identify the geographical and seasonal distribution of tropical cyclogenesis in each of the major ocean basins. This combination of parameters is known as the seasonal genesis parameter (Royer et al., 1998).

As seen in the above studies, prediction of TC genesis using the atmosphere and ocean parameters in the main area of TC genesis was performed successfully. However, in addition to TC genesis resulting from the environmental factors in the tropical regions, TCs also often occurred due to interactions among many different teleconnection patterns that existed in areas outside the tropical regions. Therefore, it is important to search for the signals of teleconnection patterns in order to determine a clear relationship with TCs and to influence the genesis of TCs.

The Aleutian low is one of the semi-permanent atmospheric action centers in the Northern Hemisphere, and it plays a vital role in the sea–air interaction in the North Pacific. The variations in its intensity and location play an important role in Northern Hemispheric climate change (Trenberth and Hurrell, 1994). Sun and Wang (2005) showed that the key factor for the Arctic Oscillation (AO), coupled with the Pacific Decadal Oscillation, may lie in the Aleutian low. Park et al. (2012) emphasized the dual contributions from the atmosphere and ocean to the local sea surface temperature (SST) variability in explaining the recent unusual warming in the western North Pacific (WNP). Previous studies have also found that variability of the Aleutian low can influence climate anomalies in remote regions (Zhu and Wang, 2010; Ye and Duan, 2015).

The Arctic condition affects the climate in the high and mid-latitudes of the Northern Hemisphere. Such changes have, in turn, been accompanied by various environmental changes, including Eurasian snow, sea ice, and Northern Hemisphere atmospheric circulation (Budikova, 2009; Li et al., 2013).

Even though the WNP is the ocean basin in which TCs are most active, the seasonal prediction problem in this area is relatively unexplored. The two well-known typhoon centers in this basin – the Regional Specialized Meteorological Center (RSMC) Tokyo and the Joint Typhoon Warning Center – provide only track and intensity forecasts for an individual TC and do not issue seasonal predictions. Thus, the seasonal prediction of TCs is conducted separately by each country in the WNP, and the accurate seasonal prediction of TC genesis can be an important issue in these countries. Therefore, the ultimate aim of this research is to determine whether the teleconnection pattern in the preceding winter is a good predictor for summer TC genesis frequency (TCGF).
2. Data and methods

The information about TC activity was obtained from the best track archives of the RSMC Tokyo Typhoon Center. We used data from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) (Kistler et al., 2001) over a period of 26 years (1982–2007).

This study used the Student’s t-test to determine significance (Wilks, 1995).

3. Relationship between the winter ALI and TCGF during the following summer

Figure 1 shows the genesis frequency of TCs in the WNP in July, August, and September, and it shows these 3 months collectively as well as for a time series of the Aleutian low index (ALI) in the preceding winter. In each of the 3 months, and in the 3 months collectively, a positive correlation between two variables can be found. The positive correlation has been reinforced by the increase of the month, which indicates a correlation of 0.55 at the 95% confidence level in September. In particular, the TCGF and the 3-month ALI had a correlation coefficient of 0.58 (significant at the 95% confidence level), which is higher than the correlation coefficient in September. This means that TCGF in summer increases if the Aleutian low in the preceding winter is weak and decreases if it is strong.

4. Differences between high ALI years and low ALI years

In order to examine the characteristics of the Aleutian low in the winter that can influence the TCGF in the following summer, the 8 years with the highest ALI (1982, 1985, 1989, 1990, 1991, 1994, 2006, and 2007, hereafter called the high ALI years) and the 8 years with the lowest ALI (1983, 1984, 1986, 1987, 1992, 1998, 2001, and 2003, hereafter called the low ALI years) were defined from the time series, as shown in Figure 1(d). Then, the characteristics between the two phases were compared. Here, we selected a standard deviation of >0.7 and <−0.7 from the normalized ALI time series as high ALI years and low ALI years, respectively. In addition, these 16 years account for approximately 62% of all analysis periods (26 years).

4.1. Tropical cyclone genesis frequency

Figure 2(a) shows the monthly differences in TCGF between the two phases. There was a total of 25 differences between the two phases for the 3 months. These differences mean that approximately three more TCs occurred, on average, during the summers of high ALI years than during the summers of low ALI years. As the months progress, it can be seen that the difference between the two phases also increases: July = 4 TCs, August = 7 TCs, and September = 14 TCs. September, in particular, accounted for more than half of the differences over the 3 months. This had been determined previously because the correlation between the TCGF and the ALI was highest in September.

Figure 2(b) shows the characteristics of the spatial distribution of TCGF in the summer between the two phases. The largest difference between the two phases appears in the east sea (10°–20°N, 130°–155°E) of the Philippines. In this area, TCGF was higher during the high ALI years. The open ocean east of the Philippines is known as the Western Pacific Warm Pool (WPWP), and it has a dominant influence on the climate and the
interannual (interdecadal) variabilities of TCGF. The SST variability in the WPWP region moves the wave train of atmospheric circulation toward the northeast, and it eventually affects the variation of the Aleutian low (Zhao et al., 2003). Thus, the difference in the TCGF in this region between the two phases is shown in Figure 2(b) (bar graph). In the 3 months combined, the TCGF is approximately two times higher in the high ALI years than in the low ALI years (high ALI years: 51 TCs, low ALI years: 27 TCs). The largest difference is in September (July: 3 TCs, August: 5 TCs, September: 16 TCs). The difference between the two phases in September accounts for approximately two thirds of the total difference (24 TCs) over the 3 months in this area.

4.2. TC passage frequency (TCPF)

The TC genesis location has an effect on the TC track. Wang and Chan (2002) noted that when TCs occur in the southeast in the subtropical WNP, the TC passage tends to follow a curve along the western periphery of the WNP high. In addition, Ho et al. (2005) stressed that when TCs occurred near the Philippines (in other words, when they occurred in the west of the subtropical WNP), they showed a tendency to move to the west or northwest without turning. Therefore, this study analyzed the difference in the average TCPF between the two phases per grid box of 5° × 5° latitude-longitude (Figure 2(c)). The west side, based at about 150°E, showed a higher frequency of TCs in high ALI years, while the east side showed higher frequency for low ALI years. During high ALI years, in particular, it is apparent that the passage moved to Korea and Japan through the East China Sea from the east sea of the Philippines. In the areas of Vietnam and South China, the TCGF is not small. Therefore, we can determine that East Asian countries located on the coast should pay greater attention to the damage caused by TC occurrences during high ALI years.

4.3. Environmental conditions

The characteristics of the environmental conditions that influenced the differences in TCPF and TCGF between the two phases were analyzed with regard to the summer and the preceding winter.

The left panel of Figure 3 shows the differences between the two phases for 850hPa geopotential heights and horizontal winds during the preceding winter. In the high ALI years, in the north (about 25°N), the anomalous anticyclonic circulations, and in the south, the anomalous cyclonic circulations, are strengthened. This is a positive North Pacific Oscillation (NPO), and it is similar to the pattern analyzed by Walker and Bliss (1932). They discovered that there is a seesaw pattern in the sea level pressure (SLP) between high latitudes from eastern Siberia to western Canada during the winter and subtropical low latitudes below 40°N in the Pacific sector, which is like the North Atlantic Oscillation (NAO). This oscillation between the north and south regions in the North Pacific is the NPO. Wang et al. (2007) showed that the summer TCGF in the WNP is higher during a positive NPO phase than during a negative NPO phase in the preceding spring. Therefore, when an anomalous pressure pattern, such
as south-low and north-high, strengthens in the North Pacific during the preceding winter and spring, we know that in the following summer, TCGF will be high, while a strong north-low and south-high pattern in the preceding winter and spring would lead to a low TCGF in the following summer. These anomalous pressure patterns were also shown in the 500 hPa geopotential height field (not shown). In particular, the Aleutian low from the region near the Aleutian develops climatologically in the winter and spring. Thus, the anomalous anticyclonic circulations based on this region in high ALI years indicated a weak Aleutian low, while the anomalous cyclonic circulations in low ALI years indicated a strong Aleutian low. When the Aleutian low is weak during the preceding winter and spring, the TCGF increases in the following summer.

The Aleutian low can be associated with the sea ice condition in this region. Therefore, in the area near the Sea of Okhotsk and the Bering Sea, the difference in sea ice concentration between the two phases during the winter was analyzed, as shown in the right panel of Figure 3. In high ALI years, it appears that there was a negative anomaly in most of the areas, with the exception of the northern areas of the Aleutian, while the reverse pattern appears in low ALI years. This means that the TCGF increases in the summer when the sea ice concentration in the area is low in the preceding winter. Fang and Wallace (1994) showed that a higher than average concentration of sea ice in the North Pacific during the winter and spring can strengthen the Aleutian low. Fan (2007) also showed that a greater than average concentration of sea ice in the North Pacific reinforces the Aleutian Low in the North Pacific, which then forms an anomalous pressure pattern, such as south-high and north-low, which has a negative impact on TCGF in the following summer.

The difference that appears in the environmental conditions between these two phases during the winter continues through to the following summer (left panel of Figure 4). Although anomalous cyclonic circulations are located near the Sea of Okhotsk and the Bering Sea (based at 25°N in the south of 45°N) in high ALI years, the anomalous pressure pattern south-low and north-high was still maintained. The opposite pressure pattern appears in low ALI years. These anomalous pressure patterns in the two phases can be clearly seen through outgoing longwave radiation (OLR) analysis (right panel of Figure 4). In high ALI years, the OLR anomaly for each negative and positive is formed as the standard at about 25°N in the region of south and north, respectively. This means that convection is much more active in the subtropical WNP in high ALI years. In contrast, a positive OLR formed from the northeast to southeast, moving from the southeast region of the subtropical WNP to the south region in China, in low ALI years. In conclusion, it is shown that the anomalous south-low and north-high pressure pattern was reinforced, as the preceding winter in high ALI years provided a favorable environment for increased TCGF in the following summer.

We found that the anomalous pressure patterns during the high ALI years and low ALI years (Figure 2(c)) caused the difference in TCPF between the two phases. In the high ALI years, it can be seen that the anomalous easterlies are especially notable at the latitude of 20°–40°N from the winter to the following summer. The steering flows play a role in allowing TCs to move easily toward East Asia. However, when anomalous westerlies are reinforced near 20°N in the low ALI years, the steering flows can interfere with TC movement toward the East Asian region.

The effect of the atmospheric and oceanic environments on TC genesis was also analyzed (Figure 5). These figures show differences in (a) vertical wind shear (200–850 hPa), (b) 850 hPa specific humidity, (c) 850 hPa relative vorticity, (d) vertical meridional circulations (based on the average latitude-pressure cross-section between 100° and 180°E, which was the longitudinal range in which there was frequent TC genesis), and (e) SST between the two phases. The analyses of the vertical wind shear (200–850 hPa) and the 850 hPa specific humidity and relative vorticity show negative anomalies and positive anomalies in the subtropical WNP, respectively (Figures 5(a)–(c)). These results indicate that favorable environments for frequent genesis of TCs are formed in the high ALI years. As for vertical meridional circulations, there are intensified anomalous upward flows between 0° and 20°N (subtropical WNP) when there was frequent genesis of TCs (Figure 5(d)). This shows that there are favorable vertical structures that can increase TCGF in high ALI years. In SST analysis, warm SST anomalies are distinctive over the subtropical WNP, which is a good oceanic environment for TC genesis (Figure 5(e)).

### 4.4. Evaluation of the prediction performance of the TC statistical model using the preceding winter ALI

Choi et al. (2010) developed a multiple linear regression model (MLRM) for the prediction of summer TCGF in the WNP using the three teleconnection patterns. These patterns are representative of the Siberian High Oscillation (SHO) in the East Asian continent, the NPO, and the Antarctic Oscillation (AAO) during the preceding boreal spring (April–May). That is, the predictors in Choi et al.’s statistical model are the SHO index, the NPO index, and the AAO index in the preceding boreal spring. This statistical model for the seasonal prediction of TCGF is as follows:

$$\text{TCGF} = 1.07^\circ \text{SHO} - 0.71^\circ \text{AAO} + 0.28^\circ \text{NPO} + 10.22$$

In this study, the preceding winter ALI was added to Choi et al.’s MLRM as a fourth predictor as follows:

$$\text{TCGF} = 0.98^\circ \text{SHO} - 0.62^\circ \text{AAO} + 0.31^\circ \text{NPO} + 0.71^\circ \text{ALI} + 14.43$$
The prediction performance between Choi et al.’s MLRM (see Figure 3(d)) and the present study’s MLRM (Figure 5(f)) was compared. In Choi et al. (2010), the correlation coefficient between the observed TCGF and the hindcasted TCGF by MLRM was 0.73, while in this study, the correlation coefficient was 0.88 (significant at the 99% confidence level). In particular, the prediction performance in extreme years (e.g., 1967, 1994, and 1998) was significantly improved. Therefore, the preceding winter ALI can be used as an effective predictor for TCGF during the following summer.

5. Summary and conclusions

The relationship between the ALI in the winter and TCGF in the following summer was analyzed based on a period of 26 years (1982–2007). There was a high-positive correlation ($corr = 0.58$) between the two variables, and the highest correlation among the 3 months July, August, September (JAS) was for September (0.55).

In high ALI years, there was an increase in TCs from the eastern sea areas in the Philippines (WPWP region). These TCs mainly went to Korea and Japan through the East China Sea. Therefore, it was determined that countries located on the East Asian coast must pay more attention to TCs in high ALI years.

The anomalous south-high and north-low pressure pattern that formed in the WNP during the winter continued until the following summer, and the lower than average sea ice in the Sea of Okhotsk and the Bering
Sea during the winter reinforced this pressure pattern. Anomalous easterlies moving to the East Asian region as a result of the anomalous south-high and north-low pressure pattern led to more frequent movement of TCs to this area. Therefore, the anomalous pressure pattern formed in the WNP and the sea ice condition in the Sea of Okhotsk and the Bering Sea during the winter are good predictors of TCGF during the following summer.

We also analyzed the atmospheric and oceanic environments that affected TC genesis: the vertical wind shear (200–850 hPa), the 850 hPa specific humidity, the 850 hPa relative vorticity, and the vertical meridional circulations based on the average latitude-pressure cross-section between 100° and 180°E. The analyses of the vertical wind shear (200–850 hPa) and 850 hPa specific humidity and relative vorticity showed negative anomalies and positive anomalies in the subtropical WNP, respectively. With regard to the vertical meridional circulations, there were intensified anomalous upward flows between 0° and 20°N (subtropical WNP). In addition, warm SST anomalies were distinctive over the subtropical WNP. This indicates that there are favorable atmospheric and oceanic conditions that can increase TCGF in high ALI years.

The preceding winter ALI was added to Choi et al.’s (2010) MLRM as a predictor, and the prediction performance between the Choi et al. MLRM and the present study’s MLRM was compared. The correlation between the observed TCGF and hindcasted TCGF was stronger in the present study’s MLRM than in the Choi et al.
Figure 5. Differences in (a) vertical wind shear (200–850 hPa), (b) 850 hPa specific humidity, (c) 850 hPa relative vorticity (d) latitude-pressure cross-section of vertical velocity (contours) and vertical meridional circulations (vectors) averaged along 100°–180°E, and (e) sea surface temperature between high and low ALI years for JAS. Shaded areas are significant at the 95% confidence level. In (c), the values of vertical velocity are multiplied by $-100$. Contour intervals are 1 ms$^{-1}$ for VWS, 0.1 g kg$^{-1}$ for 850 hPa specific humidity, 10$^{-6}$ s$^{-1}$ for 850 hPa relative vorticity, 0.2 hPa s$^{-1}$ for vertical velocity, and 0.1°C for SST. (f) Time series of observed TCGF (blue line) and hindcasted TCGF by new multiple linear regression model that ALI predictor was added to model of Choi et al. (2010).

MLRM, and, in particular, the prediction performance was significantly improved in extreme years.

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