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Possible connection between summer tropical cyclone frequency and spring Arctic Oscillation over East Asia

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Abstract This study shows that the frequency of summer tropical cyclones (TCs) in the areas of Japan, Korea, and Taiwan (JKT), which are located in the middle latitudes of East Asia, has a positive correlation with the Arctic Oscillation (AO) occurring during the preceding spring, while summer TC frequency in the Philippines (PH), located in the low latitudes, has a negative correlation with the AO of the preceding spring. During a positive AO phase, when the anomalous anticyclone forms over the mid-latitudes of East Asia, other anomalous cyclones develop not only in the high latitudes but also in the low latitudes from the preceding spring to the summer months. With this change, while southeasterlies in the JKT area derived from the mid-latitude anticyclone plays a role in steering TCs toward this area, northwesterlies strengthened in the PH area by the low-latitude cyclone plays a role in preventing TC movement toward this area. In addition, because of this pressure systems developed during this AO phase, TCs occur, move, and recurve in further northeastern part of the western North Pacific than they do during a negative AO phase.

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1 Introduction

Recently, TC activity in East Asia has led to several record-breaking events. In Japan, ten TCs made landfall in 2004 (Kim et al. 2005). In Korea, typhoon Rusa, which landed in 2002, created the highest accumulated rainfall (870.5 mm) ever recorded in Gangneung during a 24-h period (Park and Lee 2007). In Taiwan, typhoon Morakot, which landed in 2009, also created the highest one-day precipitation ever recorded in the southern region, which was the equivalent of a 1-year rainfall accumulation (Pan et al. 2010). And in the Philippines, about ten TCs are being documented annually, which is the highest TC frequency in East Asia (Lyon and Camargo 2008).

Therefore, there are ongoing efforts to determine the causes of the TC activities in each region of East Asia. Climate factors have been used for a correlation analysis using data from western North Pacific (WNP) TC activities. These factors include El Niño-southern oscillation (ENSO) (Chan 1985, 1995; Lander 1994; Saunders et al. 2000; Wang and Chan 2002; Camargo and Sobel 2005), Antarctic Oscillation (AAO) (Ho et al. 2005; Wang and Fan 2007), North Atlantic Oscillation (NAO) (Elsner and Kocher 2000), North Pacific Oscillation (NPO) (Wang et al. 2007), Pacific-Japan teleconnection pattern (PJ pattern) (Choi et al. 2010), quasi-biennial oscillation (QBO) (Ho et al. 2009), and Arctic Oscillation (AO) (Larson et al. 2005; Xie et al. 2005; Choi and Byun 2010).

Lander (1994) has suggested that while a statistically significant correlation has not been shown between the frequency of TC genesis and ENSO in the SWNP, a clear difference in the location of TC genesis based on changes of ENSO dose exist. Wang and Chan (2002) and Camargo and Sobel (2005) later showed that TCs mainly occur in the region southeast of the SWNP during ENSO warm episodes and tend to have a longer lifetime. Ho et al. (2005) attempted to relate the causes of changing TC activities in the WNP to large-scale atmospheric circulation in the Southern Hemisphere (SH). The authors showed that TC passage frequency in the middle latitude region of East Asia increases due to the anomalous anticyclone developing in this region during a positive AAO phase, but decreases due to the anomalous cyclone developing around the South China Sea. In addition, Wang and Fan (2007) found that a negative correlation exists between AAO and TC genesis frequency in the SWNP during June–September (JJAS). They showed in their study that unfavorable environments for TC genesis, such as a high vertical wind shear, low sea surface temperature, and a vertical structure of lower level-high pressure/upper level-low pressure are established during a positive AAO phase. On the other hand, Elsner and Kocher (2000) suggested that the global TC activity index from the main TC genesis basins extracted using a factor analysis model is closely related to changes in NAO. Wang et al. (2007) investigated a relationship between NPO and TC genesis frequency in both the SWNP and subtropical Atlantic during JJAS. As a result, they suggested that TC genesis frequency in the former and the latter ocean basins has a positive and negative correlation with NPO, respectively. In a recent study, Choi et al. (2010) analyzed changes in WNP TC activity based on Pacific-Japan teleconnection patterns (PJ patterns). They showed that in a positive PJ pattern phase, southerlies reinforced in the middle latitudes of East Asia play a role in steering TCs into this region.

Studies on the relationship between TC activity in the WNP and AO (Thompson and Wallace 1998), which is one of the clearest annular modes during the winter season in the Northern Hemisphere (NH), are scarce. Choi and Byun (2010) analyzed changes in TC activity in the WNP based on AO phase occurring during July–September (JAS). However, they did not treat the predictability of TC activity considering AO. Further, studies on the relationship between TC activity in the Atlantic and AO are also scarce (Larson et al. 2005; Xie et al. 2005). However, they suggested in common that AO has a positive correlation with TC genesis frequency in the Atlantic.

In general, AO is characterized as an opposite fluctuations in the surface pressure between the polar cap and mid-latitude regions along with an opposite fluctuation in the tropospheric westerlies between the sub-polar (60°N) and subtropical latitudes (30°N) (Thompson and Wallace 2000). Since Thompson and Wallace (1998) first introduced AO as an annular mode of atmospheric circulation, the impacts of AO on climate change have been analyzed in many studies (Gong and Wang 1999; Thompson et al. 2000; Thompson and Wallace 2001; Overland and Wang 2005). However, these studies focus on the winter season, and there are not many studies on the impacts on climate change during warm season. This is because AO is a teleconnection pattern that is clearly seen during the winter season. Nevertheless, Gong and Ho (2003) suggested that the preceding spring AO significantly affects changes of rainfall in the East Asia region during the summer season. They showed that East Asian summer rainfall has a positive relationship with May AO, and during a positive AO phase, anomalous low and high pressure systems are strengthened at the low and middle latitudes of East Asia, respectively. In addition, the authors pointed out that many climate systems influenced by cold season teleconnection patterns have a long memory to warm season and can cause a feed back to atmospheric circulations with time lags.

Therefore, this study attempts to analyze a correlation between AO during the preceding winter and spring seasons and summer TC activities occurring in the WNP; it also examines changes in TC activity based on AO phases and their relation to changes in large-scale atmospheric circulation.

2 Data and methodology

2.1 Data

In this study, information on TC activity was obtained from the best track archives of the Regional Specialized Meteorological Center (RSMC), Tokyo Typhoon Center. The data sets consist of TC names, longitude and latitude positions, minimum surface central pressures, and maximum sustained wind speeds (10-min average maximum winds to the nearest 5 kts) measured every 6 h from 1979 to 2008 (30 years). Additionally, this study focuses on extratropical cyclones (ETs) transformed from TCs. ETs are included in this analysis because they cause damages in the mid-latitude regions of East Asia.

For this analysis, we used the Global Reanalysis (R-2) dataset reanalyzed by the National Centers for Environmental Prediction/Department of Energy (NCEP/DOE) (Kanamitsu et al. 2002). The variables used are geopotential height (gpm), horizontal wind speed (m s^{-1}), air temperature (°C), and vertical velocity (hPa s^{-1}); these variables have a horizontal resolution of 2.5° × 2.5° latitude-longitude and are available for the period of 1979 to the present.

We also used NOAA interpolated Outgoing Longwave Radiation (OLR) data, which was retrieved from the NOAA satellite series for June 1974 to the present, located at NOAA's Climate Diagnosis Center (CDC). More detailed information regarding OLR data can be found on the CDC's website (http://www.cdc.noaa.gov) or in a paper by Liebmann and Smith (1996). The NOAA Extended Reconstructured 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.

Theoretically, the reanalysis dataset (R-1) from the National Centers for Environmental Prediction–National Center of Atmospheric Research (NCEP–NCAR) were also of use in this study, but the quality of the R-1 dataset for years in the late 1970s, which was prior to the common availability of satellite wind information, is unclear. This lack of satellite information is particularly harmful to analyses in data-sparse regions such as the ocean, which can be regarded as a frequent region of TC activity (Lawrence and Webster 2001).

2.2 Methodology and definition

AO is generally defined as the first leading mode from the empirical orthogonal function (EOF) analysis using the NCEP-NCAR monthly mean 1,000-hPa (or 700-hPa) height anomalies poleward of 20°N in the NH (Thompson and Wallace 1998). In this study, the AO index provided by the NOAA/Climate Prediction Center (CPC) was used (http://www.cpc.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml).

The El Niño (SSTA ≥ 0.5°C) and La Niña (SSTA ≤ −0.5°C) years were defined using SST anomalies (SSTA) in the Niño-3.4 region (5°S–5°N, 120°W–170°W). The climotological SST for SSTA is averaged over 30 years.

To calculate the TC passage frequency (TCPF), each TC position is binned into a corresponding 5° × 5° grid box, and a TC is only counted once even if it enters the same grid box several times (Ho et al. 2005). The TC genesis frequency (TCGF) is calculated using the same method as TCPF. The lifetime of a TC is defined as the period from the occurrence to the disappearance of a TC in an RSMC best-track dataset using 6-h intervals. The minimum central pressure of a TC is also defined as the lowest central pressure recorded for the TC lifetime in the same data.

To discover changes in TC activity in the East Asia region based on AO phase, this study divides the East Asia region into four areas (Fig. 13): Japan (30°–45°N, 130°–145°E), Korea (30°–45°N, 120°–130°E), Taiwan (20°–30°N, 120°–130°E) and Philippines (5°–20°N, 120°–130°E). These areas are located along the East Asia coast. Here, if a single TC passes through several of the areas, its frequency is counted independently for each area.

The statistical Student's *t* test is used as a significance test in this study (e.g., Wilks 1995). More details can be found in studies of Ho et al. (2004) and Choi et al. (2010).

3 Monthly variation of TC frequency in East Asia

The monthly variation in TC frequency was investigated for the four area defined above (Fig. 1). A total of 247 TCs occurring for the past 30 years had an influence in the Japan area, which indicates that an average of about 8 TCs pass through this area every year. Based on the monthly distribution, the largest frequency is shown to be during August and September, with high frequencies also occurring during July and October. Therefore, the TC frequency in the Japan area during July–October accounts for over 80% of the total TC frequency. The Korea area was influenced by a total of 120 TCs, which indicates that about 4 TCs pass through this area each year on average. The monthly distribution shows that the largest frequency occurs during August, with high frequencies also occurring during July and September. The TC frequency in the Korea area during JAS accounts for over 80% of the total TC frequency. A total of 242 TCs influenced the Taiwan area, which means that an average of around 8 TCs pass through this area each year. This average frequency is a similar to that in the Japan area. However, the monthly distribution of TC frequency shows a shape similar to the monthly distribution in the Korea area. That is, the TC frequency in the Taiwan area is the highest during JAS, which accounts for about 70% of the total TC frequency. The area of the Philippines was influenced by a total of 335 TCs, which indicates that an average of around 11 TCs pass through this region each year, which is an average TC influence of around one TC per month. The monthly distribution in this area shows its highest frequency from July to November. However, the TC frequency for June and December is also not low. Therefore, unlike the other three areas, the area of the Philippines is continuously influenced by TC activities during the second half of the year.

4 Lag-correlation between the preceding season AO and summer TC frequency

As analyzed above, TC frequency in East Asia is mainly distributed between June to November. Therefore, this study divides the TC season in the East Asian region into early (June–July; JJ), peak (August–September; AS), and late (October–November; ON) periods. Next, to determine the influences of AO on TC activity, the lag correlation between AO indices during the preceding winter (December-February) and spring (March–May) seasons,

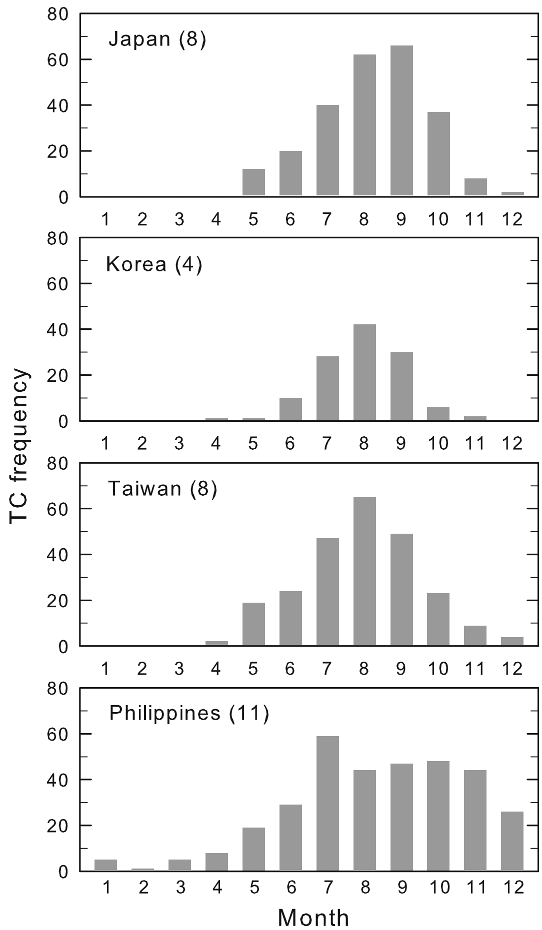

Fig. 1 Monthly distribution of tropical cyclones (*TCs*) affecting Japan (30°–45°N, 130°–145°E), Korea (30°–45°N, 120°–130°E), Taiwan (20°–30°N, 120°–130°E), and the Philippines (5°–20°N, 120°–130°E) during 1979–2008 (30 years). The *numbers* in the parentheses are the annual mean frequency of the TCs affecting these regions

and the TC frequency during the three TC seasons in the four areas of East Asia, were analyzed (Table 1). In the Japan area, the months indicating a high correlation at the 99% confidence level are not shown as a whole. The March AO index shows a positive correlation of over 0.4 with TC frequency during JJAS. A somewhat high correlation of $r = 0.35$ at the 95% confidence level with the TC frequency is indicated during ASON; however, this seems to be due to the effect of a slightly high correlation of $r = 0.38$ also at the 95% confidence level formed between the TC frequency and AO index during AS. The AO index during the spring season (MAM) also has the highest correlation with a TC frequency of $r = 0.4$ at the 95% confidence level during JJAS. On the other hand, in the Korea area, the April–May (AM) averaged AO and MAM AO indices all show a high correlation with TC frequency during JJAS at the 99% confidence level. The AO index in December also shows somewhat high correlation with TC frequency during AS and ASON at the 95% confidence level. The relationship between the two variables will be investigated in a future study. In the Taiwan area, just as in the Japan area, the March AO index shows a high correlation with TC frequency during AS, JJAS, and ASON. In particular, the correlation with TC frequency is the highest during the peak TC season. However, in the relationship with MAM AO index, the highest correlation with TC frequency is formed during JJAS. After all, the MAM AO index has its highest correlation with TC frequency in the above three areas during JJAS. Unlike in the above three areas, a negative correlation exists between AO index and TC frequency in the area of the Philippines. The March AO index and March–April (MA) averaged AO index show the highest negative correlation with TC frequency during AS at the 99% confidence level. The TC frequency during AS also forms somewhat highly negative correlation with the MAM AO index at the 95% confidence level.

On the other hand, in most cluster analyses of TC track in the WNP, a TC track is largely divided into two types; a pattern that moves westward from the Philippines toward the Indochina peninsula (or southern China) without recurvature, and a pattern that moves the north toward the mid-latitudes of East Asia after a recurvature (Elsner and Liu 2003; Camargo et al. 2007). Therefore, this study also analyzes the correlation between AO index and total TC frequency in the Taiwan, Korea, and Japan areas which are positioned along the latter TC track pattern. As a result, the TC frequency during JJAS shows a high positive correlation at a confidence level of over 95%, not only during each month of spring but also for the MA, AM, and MAM AO indices. In particular, the MAM AO index shows the highest positive correlation of 0.57 at the 99% confidence level. This indicates that TC frequency increases during JJAS in the above three areas, which are located in the middle latitude regions of East Asia, if AO is reinforced during the preceding spring. On the contrary, the TC frequency is reduced during the same season in the area of the Philippines, which is located in the low latitude regions of East Asia. Therefore, the relationship between MAM AO and TC activity during early (JJ) and peak (AS) TC seasons is analyzed as follows.

However, if the tendencies are removed from the two time series, the correlations between the two variables may be changed. Therefore, tendencies are removed from the two variables and correlations between them are analyzed again (Table 2). Correlation coefficients in Japan, Korea, Taiwan, and Japan–Korea–Taiwan areas are almost similar to correlation coefficients that are analyzed using original time series. However, in the area of the Philippines, negative correlations during AS are somewhat weakened, but their correlation coefficients are significant at the 90% confidence level.

Table 1 Correlation coefficients between TC frequency in each region over East Asia, and the AO index for the period of 1979–2008

	TC region	Season	AO								
			Dec	Jan	Feb	Mar	Apr	May	MA	AM	MAM
TC frequency	Japan (JP)	JJ	−0.25	0.18	0.13	0.22	0.11	0.00	0.17	0.07	0.14
		AS	−0.02	0.09	0.04	*0.38*	0.12	0.22	0.34	0.21	*0.37*
		ON	0.19	−0.01	0.00	0.15	0.06	0.28	0.20	0.21	0.27
		JJAS	−0.26	0.18	0.16	*0.41*	0.20	0.17	*0.40*	0.22	*0.40*
		ASON	0.11	0.07	−0.01	*0.35*	0.09	0.29	0.31	0.23	*0.37*
	Korea (KO)	JJ	−0.09	0.17	0.17	0.10	*0.44*	0.26	0.26	*0.42*	0.32
		AS	*0.41*	0.05	0.09	0.16	0.22	0.29	0.22	0.30	0.29
		ON	0.12	−0.14	0.07	0.27	0.23	*0.36*	0.30	*0.36*	*0.40*
		JJAS	0.31	0.19	0.22	0.21	*0.43*	*0.38*	*0.35*	**0.49**	**0.45**
		ASON	*0.39*	0.03	0.10	0.23	0.26	*0.35*	0.29	*0.37*	*0.38*
	Taiwan (TW)	JJ	−0.31	−0.17	−0.13	0.09	0.18	0.21	0.00	0.24	0.08
		AS	0.16	0.00	0.08	**0.48**	0.10	0.21	*0.42*	0.19	*0.43*
		ON	0.23	−0.16	−0.17	−0.03	0.14	0.21	0.04	0.21	0.11
		JJAS	−0.04	−0.09	−0.06	*0.40*	0.27	0.29	*0.43*	*0.35*	**0.48**
		ASON	0.22	−0.07	0.00	*0.38*	0.14	0.28	*0.36*	0.26	*0.41*
	Philippines	JJ	−0.19	−0.02	0.10	−0.01	0.06	0.27	0.02	0.20	0.11
		AS	0.19	0.06	−0.02	**−0.45**	−0.28	−0.03	**−0.49**	−0.18	*−0.35*
		ON	0.07	0.09	0.29	0.08	−0.06	−0.21	0.04	−0.16	−0.04
		JJAS	−0.02	0.02	0.06	−0.26	−0.16	0.17	−0.26	0.04	−0.16
		ASON	0.17	0.09	0.19	−0.23	−0.22	−0.16	−0.29	−0.23	−0.29
	JP + KO + TW	JJ	−0.26	0.09	0.08	0.07	0.29	0.18	0.18	0.29	0.22
		AS	0.26	0.06	0.09	*0.37*	0.19	0.32	*0.36*	0.31	*0.42*
		ON	0.26	−0.13	−0.07	0.18	0.19	*0.37*	0.22	*0.35*	0.32
		JJAS	0.02	0.12	0.14	*0.39*	*0.38*	*0.37*	**0.46**	**0.46**	**0.57**
		ASON	0.30	0.01	0.04	0.34	0.21	*0.38*	*0.36*	*0.36*	*0.44*

The bold and italic values are significant at the 99 and 95% confidence levels, respectively

The time series for the frequency of TCs passing through each area during the JJAS are presented in Fig. 2 along with MAM AO index. However, these high correlations between the two variables may change if the trends of the two variables are removed from each time series. Therefore, the correlation was reanalyzed again after removal. Here, as analyzed above, since the TC frequency during AS shows a relatively high correlation with the MAM AO index in the Philippine area, the time series for the TC frequency during AS is presented. With the exception of the TC frequency trend in Philippine area during AS, the majority of trends are nearly constant. Therefore, after removing the trend in the two variables in the Philippine area, the correlation shows a value of −0.31 (at the 90% confidence level), which is highly reduced compared with the previous value; however, the correlation between the two variables shows little change in the remaining areas.

5 Characteristics corresponding to the AO phase

While a high correlation was found to exist between TC frequency and the MAM AO index in the three areas during JJAS (AS in Philippine area), the results in this study may become meaningless if an AO pattern is not shown for this period. Therefore, in this study, we conducted an EOF analysis using 700-hPa geopotential height anomalies occurring during MAM, JJ, AS, and JJAS before examining changes in TC activity based on AO phase and the characteristics of the large-scale environments related to these changes (Fig. 3). Here, an anomaly is calculated from the climatological average for a 700-hPa geopotential height during 30 years period. In a regression occurring during MAM, a negative eigenvector is shown in the polar region, while a positive eigenvector occurs in the middle latitude regions and another negative eigenvector is found in low latitude regions. As mentioned above, a seesaw

Table 2 Correlation coefficients between detrended TC frequency in each region over East Asia, and the detrended AO index for the period of 1979–2008

	TC region	Season	AO								
			Dec	Jan	Feb	Mar	Apr	May	MA	AM	MAM
TC frequency	Japan (JP)	JJ	−0.25	0.12	0.11	0.20	0.11	−0.04	0.15	0.05	0.12
		AS	−0.02	0.12	0.06	*0.39*	0.12	0.24	*0.36*	0.22	*0.39*
		ON	0.19	0.02	0.02	0.23	0.06	0.30	0.21	0.22	0.29
		JJAS	−0.26	0.16	0.14	*0.40*	0.20	0.16	*0.40*	0.22	*0.40*
		ASON	0.11	0.10	−0.01	*0.36*	0.09	0.30	0.32	0.25	*0.38*
	Korea (KO)	JJ	−0.09	0.17	0.17	0.08	*0.43*	0.25	0.26	*0.42*	0.30
		AS	*0.41*	0.05	0.09	0.11	0.20	0.29	0.22	0.30	0.21
		ON	0.13	−0.20	0.04	0.24	0.26	*0.35*	0.30	*0.38*	*0.38*
		JJAS	0.31	0.18	0.21	0.11	*0.39*	*0.38*	*0.35*	**0.47**	*0.44*
		ASON	*0.39*	0.01	0.09	0.15	0.25	0.34	0.28	*0.37*	0.32
	Taiwan (TW)	JJ	−0.32	−0.15	−0.12	−0.08	0.18	0.22	0.06	0.25	0.09
		AS	0.17	−0.05	0.05	**0.47**	0.10	0.19	**0.45**	0.18	*0.42*
		ON	0.23	−0.12	−0.15	−0.02	0.14	0.23	0.06	0.23	0.12
		JJAS	−0.04	−0.14	−0.08	*0.39*	0.27	0.28	**0.48**	*0.34*	**0.46**
		ASON	0.22	−0.10	−0.01	*0.38*	0.14	0.27	*0.40*	0.26	*0.40*
	Philippines	JJ	−0.19	−0.02	0.10	−0.01	0.06	0.27	0.02	0.20	0.11
		AS	0.19	0.13	−0.08	*−0.43*	−0.21	−0.02	*−0.36*	−0.15	−0.31
		ON	0.07	0.09	0.29	0.08	−0.06	−0.21	0.04	−0.16	−0.04
		JJAS	−0.02	0.02	0.06	−0.26	−0.14	0.17	−0.24	0.04	−0.14
		ASON	0.12	0.09	0.19	−0.23	−0.15	−0.16	−0.27	−0.20	−0.23
	JP + KO + TW	JJ	−0.26	0.07	0.07	0.06	0.29	0.16	**0.53**	0.28	0.21
		AS	0.26	0.04	0.08	*0.36*	0.18	0.31	0.23	0.31	*0.42*
		ON	0.26	−0.12	−0.06	0.19	0.19	*0.39*	**0.45**	*0.35*	0.33
		JJAS	0.02	0.09	0.12	*0.38*	*0.38*	*0.36*	*0.41*	**0.45**	**0.52**
		ASON	0.31	0.00	0.03	0.34	0.21	*0.38*	*0.43*	*0.36*	*0.44*

The bold and italic values are significant at the 99 and 95% confidence levels, respectively

pattern for the atmospheric pressure and mass formed between the polar region and middle latitude region is similar to the typical spatial distribution during a positive AO phase (Wallace 2000). It was shown that this spatial distribution exists during all three TC seasons, although it is somewhat weakened during JJ.

Next, in order to examine changes in TC activity and the characteristics of large-scale environments based on the AO phase, the highest 8 AO years (hereafter, positive AO phase) and lowest 8 AO years (hereafter, negative AO phase) among the MAM AO indices were selected, and the average differences between the two phases were analyzed. Here, to reduce the effect of ENSO on TC activity and large-scale environments occurring during JJAS, 8-year periods in two AO phases were selected among the remaining years (that is, neutral ENSO years) excluding El Niño (1982, 1987, 1991, 1997, 2002, 2004) and La Niña years (1988, 1998–1999). In addition, the preceding MAM AO index shows low correlations of 0.03 and 0.12 with Niño-3.4 indices during the preceding MAM and JJAS, respectively. Each 8-year period selected is presented in Table 3. Differences in TC frequency between the two AO phases in the three areas excluding the Philippine area are larger during AS than during JJ. These differences are significant at a confidence level of over 95%. In addition, the difference in TC frequency between the two AO phases during JJAS increases as we move further toward the Japan, Korea, and Taiwan areas (that is, as we move counterclockwise on a map). As analyzed above, this result may be due to an increase in the correlation between the preceding MAM AO index and TC frequency during JJAS as we move counterclockwise. After all, there is a difference of 50 TCs between the two AO phases for total TC frequency of these three areas during JJAS, which indicates that an average of around 6 TCs (significant at the 99% confidence level) each year influences these regions more during a JJAS period of a positive AO phase than of a negative AO phase. On the other hand, negative value is shown for the difference between the two AO phases in the Philippine area. This is due to a negative correlation that

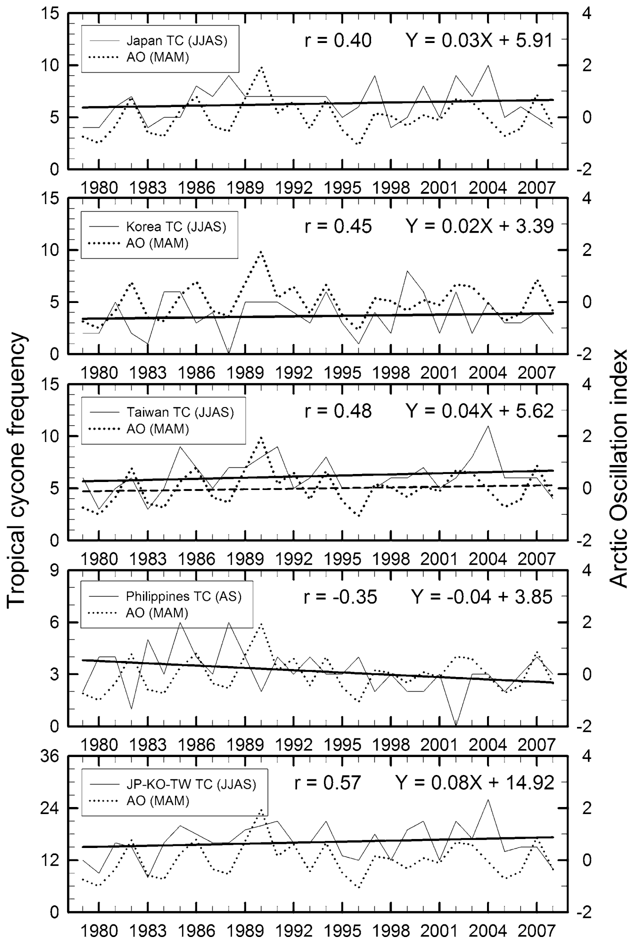

Fig. 2 Lag-correlation coefficients between the seasonal (JJAS in Japan, Korea, and Taiwan and AS in the Philippines) TC frequency in each region and AO index in MAM. The *thick solid* and *dashed lines* denote trends in the seasonal TC frequency in each region and the AO index in MAM, respectively

exists between the two variables during AS, as analyzed above, but it is not statistically significant.

5.1 TC genesis frequency (TCGF)

Figure 4 shows climatological average TCGF during JJAS and the difference in TCGF between the two AO phases during JJAS in the SWNP. Many TCs occur around the Philippine Sea, which is usually referred to as a warm pool region in the tropical western Pacific with high sea surface temperature (Fig. 4a). The center of TC genesis is located in the SCS and in the sea east of the Philippines.

In difference between the two AO phases, differing from the negative AO phase, TCs during the positive AO phase in the SWNP tend to occur a little toward the northeastern direction (Fig. 4b). This difference can be confirmed based on the average TC genesis location in each AO phase. Here, the differences in latitude and longitude of TC genesis locations between the two AO phases are significant at the 99 and 95% confidence levels, respectively. Moreover, a total of 137 TCs occur during JJAS in a positive AO phase, which is 24 TCs more than the 113 TCs that occur during JJAS in a negative AO phase. This indicates that on average, about 3 more TCs (significant at the 95% confidence level) occur during JJAS in each year of a positive AO phase.

5.2 TC passage frequency (TCPF)

Figure 5 shows the climatological average TCPF during JJ, AS, and JJAS as well as the difference in TCPF between the two AO phases during the three TC seasons in the WNP. Since TCs tend to migrate along the western periphery of the WNP subtropical high (WNPSH), the TCPF is higher over the SCS and East China Sea (left panel in Fig. 5) for all three TC seasons. Over the two regions, more than 1.5 TCs for each month and more than 2.5 TCs for the entire TC season are shown in each 5° × 5° grid box. The TCPF also indicates an elongated passage track (individual areas with more than 0.5 TCs per TC season and more than 1.5 TCs during all TC seasons) extending toward Korea and Japan.

In the difference between the two AO phases, TCs during a the positive AO phase mainly move toward Korea and Japan via Taiwan from the sea northeast of the Philippines, while those during a negative AO phase tend to move to the west toward southern China and the Indochina Peninsula from the Philippines (right panel in Fig. 5). Due to these TC track characteristics during the two AO phases, there is a large difference in TCPF between the two AO phases at 20°N in East Asia. That is, a spatial-like dipole distribution pattern is formed between Southeast and Northeast Asia.

5.3 TC recurvature

The difference in the main TC track between the two AO phases can influences the location of a TC recurvature. Therefore, this study investigates TC recurvature location during the two AO phases (Fig. 6). As a whole, TCs occurring during a positive AO phase recurve a little further toward the northeastern direction over the WNP than those occurring during a negative AO phase. The difference in the meridional direction of the TC recurvature location between the two AO phases shows a greater frequency of TCs occurring during a positive AO phase north of 30°N, and during a negative AO phase south of 30°N. The difference in the zonal direction of a TC recurvature location can be shown through a comparison of TC recurvature frequency between the two AO phases in mainland China (west of 120°E) and in the region east of 150°E. This characteristic is clearly indicated in the

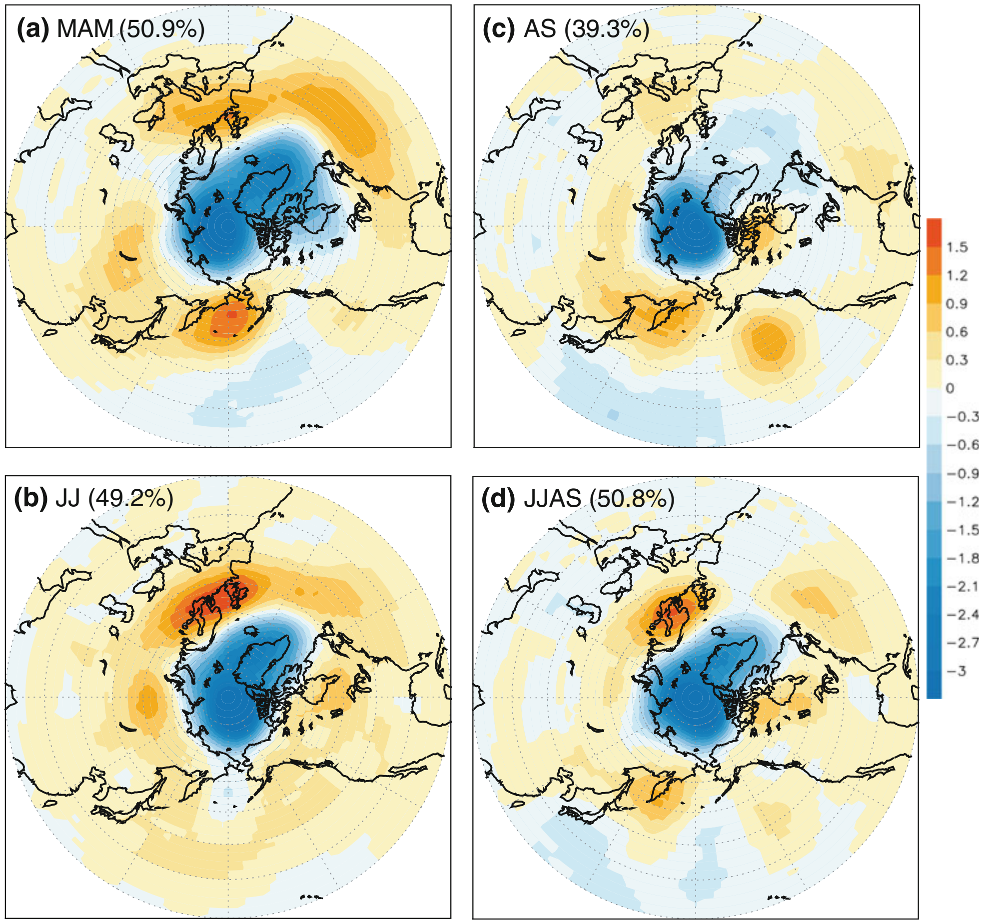

Fig. 3 Regression maps for 700-hPa geopotential height based upon the leading principal component during **a** MAM, **b** JJ, **c** AS, and **d** JJAS during a 30-year period. The *number* in the parentheses indicates the variance in the leading principal component

difference in the mean TC recurvature location between the two AO phases. Here, differences in the latitude and longitude locations of the TC recurvature location are significant at the 99% and 90% confidence level, respectively.

On the other hand, while 77 TCs (56%) out of the total 137 TCs that occur during JJAS in a positive AO phase recurve, only 49 TCs (43%) out of the total 113 TCs do so during the same season in a negative AO phase. Based on our detailed investigation, the reason for the lower frequency of TC recurvature during a negative AO phase is due to the dissipation of several TCs right after landing on the Indochina Peninsula (or southern China), or dissipation due to the effect of terrain during the course of movement through the mainland China.

5.4 TC intensity

Differences in TCPF and TC recurvature location between the two AO phases may have an impact on the differences in TC intensity. Therefore, this study investigates the TC intensity for the two AO phases (Fig. 7). In this study, TC intensity is defined as TC lifetime and lowest central pressure. TCs occurring during a positive AO phase show a stronger intensity during all three TC seasons. This difference in TC intensity is greater during AS than during JJ. As a result, the difference in TC intensity between the two AO phases is higher in terms of statistical confidence level during AS than during JJ. However, the difference in TC intensity between the two AO phases during JJAS is significant at the 99% confidence level. A weaker TC intensity in the negative AO phase occurs, as discussed above, because many TCs in this AO phase occur around the Philippines and then dissipate right after landing on the Indochina Peninsula (or southern China) or are weakened due to the terrain effect while moving through mainland China when they are not dissipated immediately.

5.5 Large-scale atmospheric circulation

To examine the characteristics of large-scale atmospheric circulation that affect the TC activity between the two AO phases, the difference in average value between a positive

Table 3 TC frequency in each region for the highest (positive phase) and lowest 8 (negative phase) years selected during the period of 1979–2008

AO phase	Year	TC region														
		Japan (JP)			Korea (KO)			Taiwan (TW)			Philippines			JP–KO–TW		
		JJ	AS	JJAS	JJ	AS	JJAS	JJ	AS	JJAS	JJ	AS	JJAS	JJ	AS	JJAS
Positive (P) phase	1985	1	4	5	2	5	7	3	6	9	2	4	6	6	15	21
	1986	3	5	8	1	2	3	3	4	7	3	2	5	7	11	18
	1989	2	5	7	2	3	5	3	5	8	5	5	10	7	13	20
	1990	1	6	7	2	3	5	2	6	8	5	3	8	5	15	20
	1992	1	6	7	0	4	4	1	4	5	4	4	8	2	14	16
	1994	2	5	7	3	4	7	4	4	8	5	2	7	9	13	22
	2003	3	4	7	1	1	2	2	6	8	4	2	6	6	11	17
	2007	1	4	5	1	3	4	1	5	6	1	3	4	3	12	15
	Sum	14	39	53	12	25	37	19	40	59	29	25	54	45	104	149
	AVG	1.8	4.9	6.6	1.5	3.1	4.6	2.4	5.0	7.4	3.6	3.1	6.8	5.6	13.0	18.6
Negative (N) phase	1979	0	4	4	0	2	2	2	4	6	4	4	8	2	10	12
	1980	1	3	4	1	1	2	1	2	3	5	6	11	3	6	9
	1983	0	4	4	0	1	1	1	2	3	3	4	7	1	7	8
	1984	2	3	5	2	4	6	3	2	5	2	2	4	7	9	16
	1995	2	3	5	1	2	3	2	3	5	2	3	5	5	8	13
	1996	2	4	6	0	1	1	1	4	5	2	3	5	3	9	12
	2005	2	3	5	0	3	3	1	5	6	0	3	3	3	11	14
	2006	1	5	6	1	2	3	3	3	6	5	4	9	5	10	15
	Sum	10	29	39	5	16	21	14	25	39	23	29	52	29	70	99
	AVG	1.3	3.6	4.9	0.6	2.0	2.6	1.8	3.1	4.9	2.9	3.6	6.5	3.6	8.8	12.4
P–N	Sum	4	10	14	7	9	16	5	15	20	6	−4	2	16	34	50
	AVG	0.5	*1.3*	*1.8*	*0.9*	*1.1*	*2.0*	0.6	*1.9*	*2.5*	0.7	−0.5	0.3	*2.0*	**4.2**	**6.2**

These years are selected excluding El Niño and La Niña years in JJAS. The bold and italic values are significant at the 99 and 95% confidence levels in the difference of the TC frequency between positive and negative years, respectively

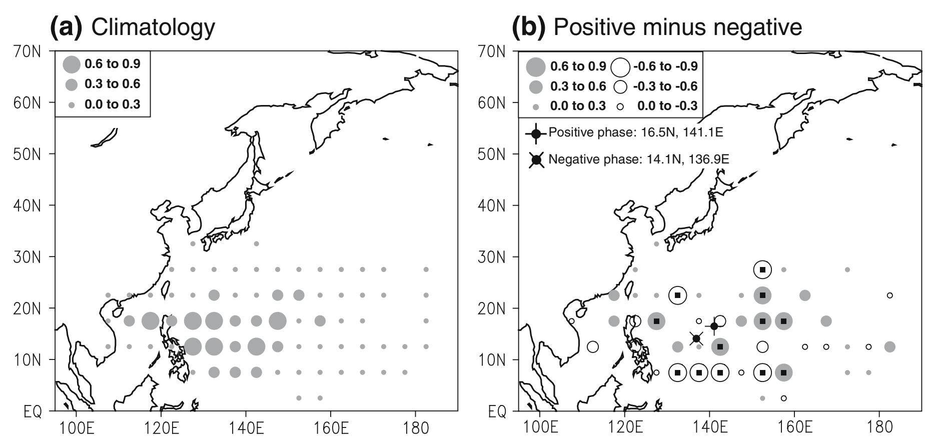

Fig. 4 **a** Climatology for TC genesis frequency (*TCGF*) in JJAS, and **b** difference in the TCGF between the highest (positive AO phase) and lowest 8-year period (negative AO phase) on the number of TCs occurring in East Asia (Japan, Korea, and Taiwan) in JJAS during a 30-year period. Closed circles with a cross and multiplication sign denote the mean genesis locations of the positive and negative AO phases, respectively. Small squares inside the circles on the right are significant at the 95% confidence level

and negative AO phase is analyzed for a 700-hPa geopotential height and 700-hPa streamline (Fig. 8). A difference in the 700-hPa geopotential height between the two AO phases shows a spatial distribution similar to a positive AO phase in all seasons, as described in the regression maps of Fig. 3 (left panel in Fig. 8). In particular, the spatial

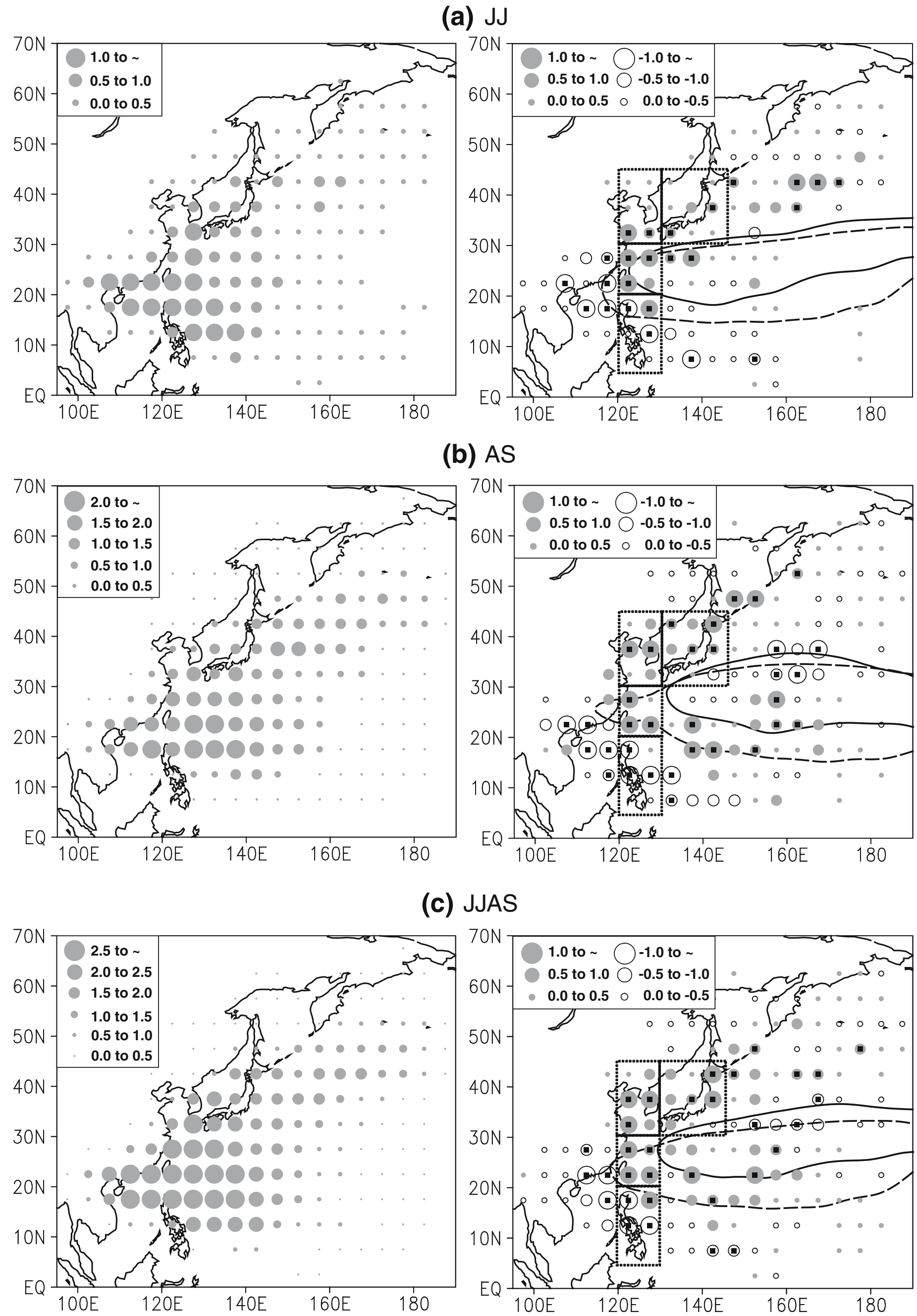

Fig. 5 Climatological distributions of TC passage frequency (*left*) and the difference between positive AO and negative AO phases (*right*) in **a** JJ, **b** AS, and **c** JJAS. *Small squares* inside the circles on the right are significant at the 95% confidence level

distribution of the difference between the two AO phases, which is shown during MAM, is very similar to the spatial distribution (Fig. 3a) of the regression during the same season (Fig. 8a).

In the difference in the 700-hPa streamline between the two AO phases in East Asia, the characteristics of the atmospheric circulation during MAM are continued up to JJAS (right panel in Fig. 8). During MAM, a huge anomalous cyclone is positioned to the south of 30°N and anomalous anticyclones are positioned to the north of this latitude in the WNP (Fig. 8a). Due to this spatial distribution in the anomalous pressure system, an easterly is being strengthened in the Japan, Korea and Taiwan areas, which indicates that steering flow, which can move a TC into these areas, is already being reinforced in these areas from the preceding MAM of the positive AO phase. On the contrary, a northwesterly is being reinforced in the sea east of Philippine area, which can play a role in preventing the TC from moving into this region. Therefore, as analyzed above, the TC frequency in the Philippine area has a negative correlation with the AO index.

During JJ, a huge anomalous cyclone is additionally located to the south of 30°N in the WNP (Fig. 8b). On the contrary, anomalous anticyclones that are positioned to the

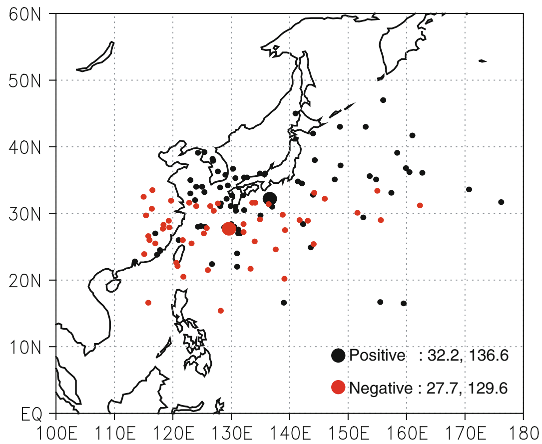

Fig. 6 TC recurvature locations in JJAS. *Black* and *red dots* denote TC recurvature locations during positive AO and negative AO phases, respectively. The *large dots* are the mean recurvature locations for the two phases. The values for the *black* and *red dots*, located in the lower-right corner denote the mean recurvature locations during positive and negative AO phases, respectively

north of 30°N during MAM are a little weakened during JJ. However, the easterly is still being reinforced in the three areas. In the Philippine area, the northwesterly is being reinforced even during JJ, compared to MAM.

During AS, the Japan and Korea areas are under the influence of a southerly (Fig. 8c). This southerly can play a role in steering TCs more easily into these regions than during the previous two seasons. The Taiwan area, which was under the influence of a northeasterly during the previous season, is already under the influence of a southeasterly. Due to a change in the favorable wind direction of this steering flow compared to previous seasons, as stated above, it is likely that the difference in TC frequency between the two AO phases in these three areas is larger during AS than during JJ. In the Philippine area, the westerly is still strengthening.

During the total TC season (JJAS), an easterly is being reinforced in the Japan, Korea and Taiwan areas, and the westerly is being reinforced in the Philippine area (Fig. 8d). As a result, the TC can easily move into these three areas due to the steering flow of a comparatively warm westerly, which moves northward from the south during JJAS in a positive AO phase. On the contrary, a TC in the Philippine area cannot easily approach to these region due to the steering flow of a comparatively cold westerly, which came southward from the north. The characteristics of air temperature related to this steering flow are shown in the differences in the average 700-hPa

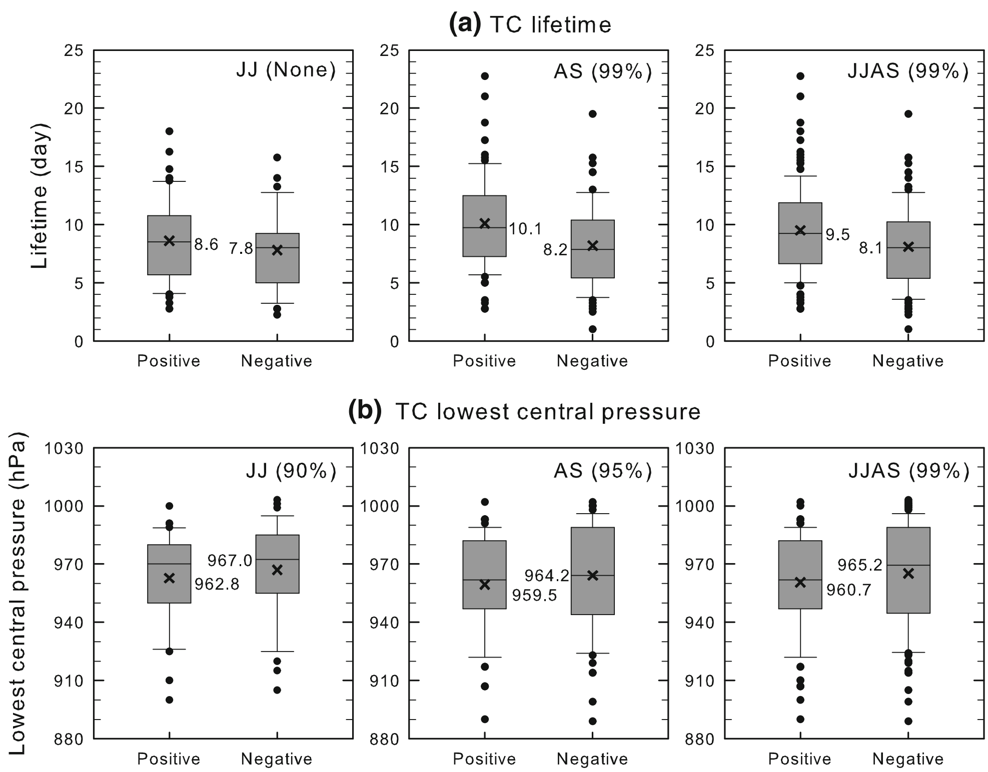

Fig. 7 TC (**a**) lifetime and **b** lowest central pressure. The *boxes* show the 25th and 75th percentiles, the *lines* in the boxes mark the median and the *circles* are values below (above) the 25th (75th) percentiles of distribution. The *numbers* to the left and right sides of the figure represent average values (*cross marks*) for the positive AO and negative AO phases, respectively. The *numbers* in the parentheses denote the statistical significance in the difference in TC intensity between the two AO phases

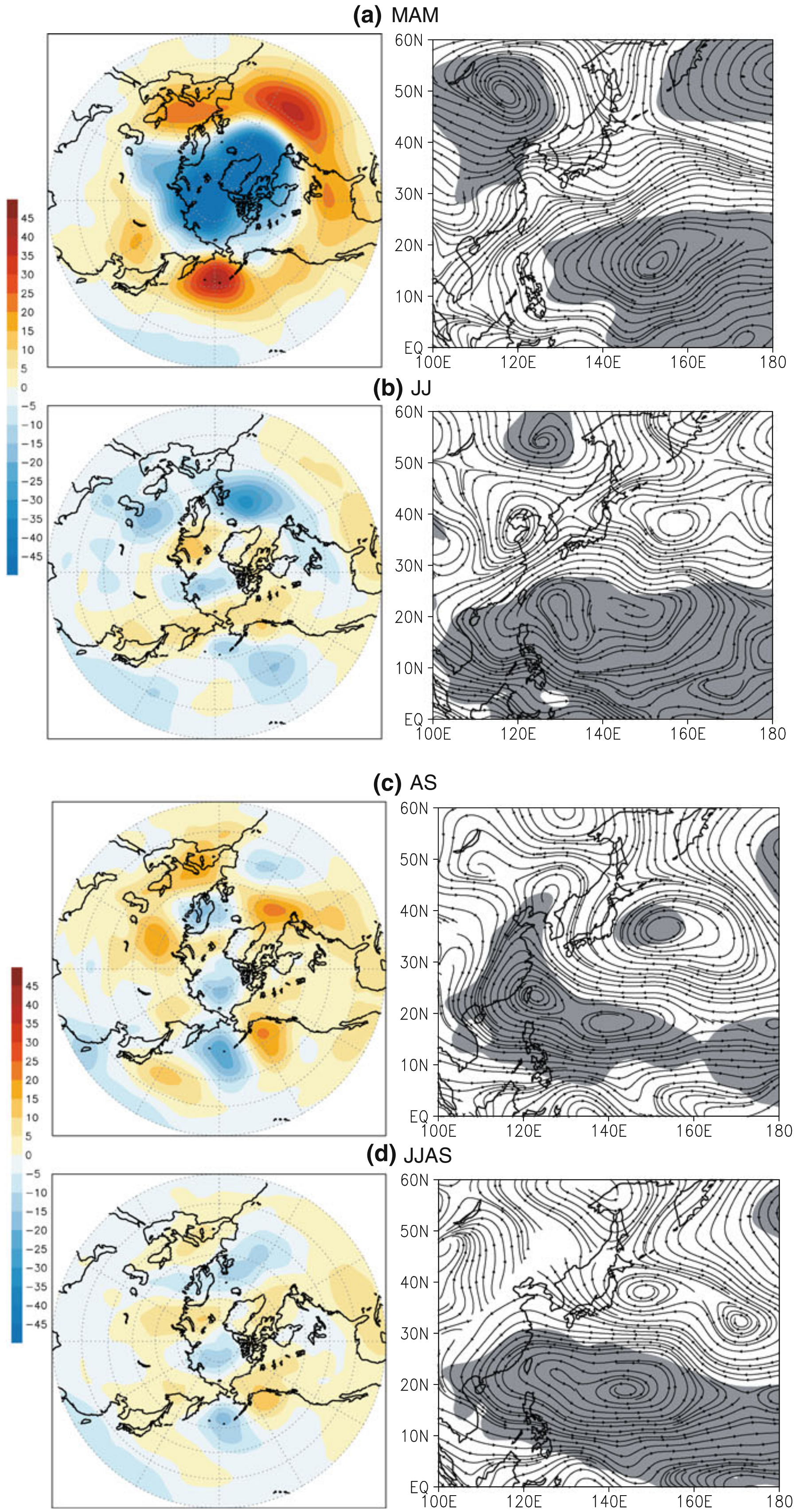

Fig. 8 Differences in 700-hPa geopotential height (*left*) and horizontal wind (*right*) between positive and negative AO phases in **a** MAM, **b** JJ, **c** AS, and **d** JJAS. The *shaded areas* on the right are significant at the 95% confidence level

air temperature between each AO phase and the climatological average during JJAS (Fig. 9). For a positive AO phase, an anomalous warm air temperature is located in the Japan, Korea, and Taiwan areas, while an anomalous cold air temperature is shown in the Philippine area (Fig. 9a), and vice versa for a negative AO phase (Fig. 9b).

On the other hand, a huge anomalous cyclone strengthened in the SWNP during the summer season of a positive AO phase implies that convection or monsoon troughs are more active in this region than during a negative AO phase. To understand this characteristic, the difference in OLR between the two AO phases during the period from the preceding MAM to JJAS is analyzed (Fig. 10). A negative OLR anomaly is shown to the south of 25°N in the SWNP during all four seasons. This indicates that convection or a monsoon trough is being reinforced in this region. TCs generally have a strong tendency to occur along monsoon troughs or in their

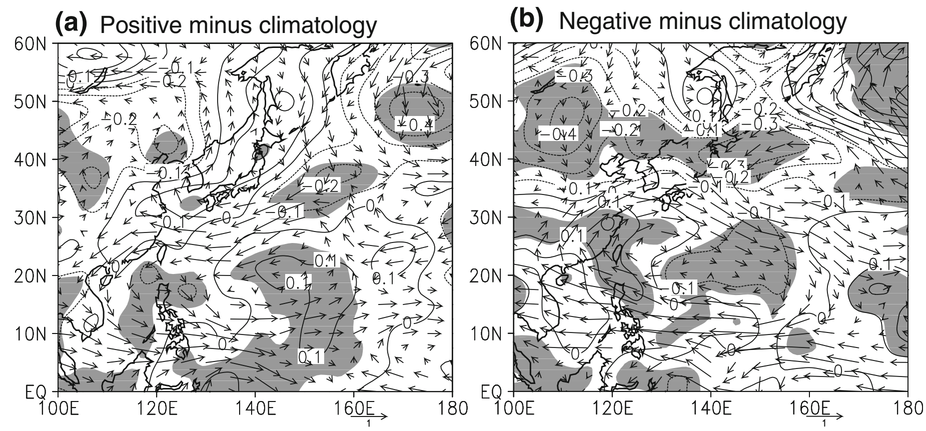

Fig. 9 Anomalies in air temperature and horizontal wind at the 700 hPa level for **a** positive and **b** negative years. The air temperatures in the *shaded areas* are significant at the 95% confidence level. The contour inter is 0.1°C

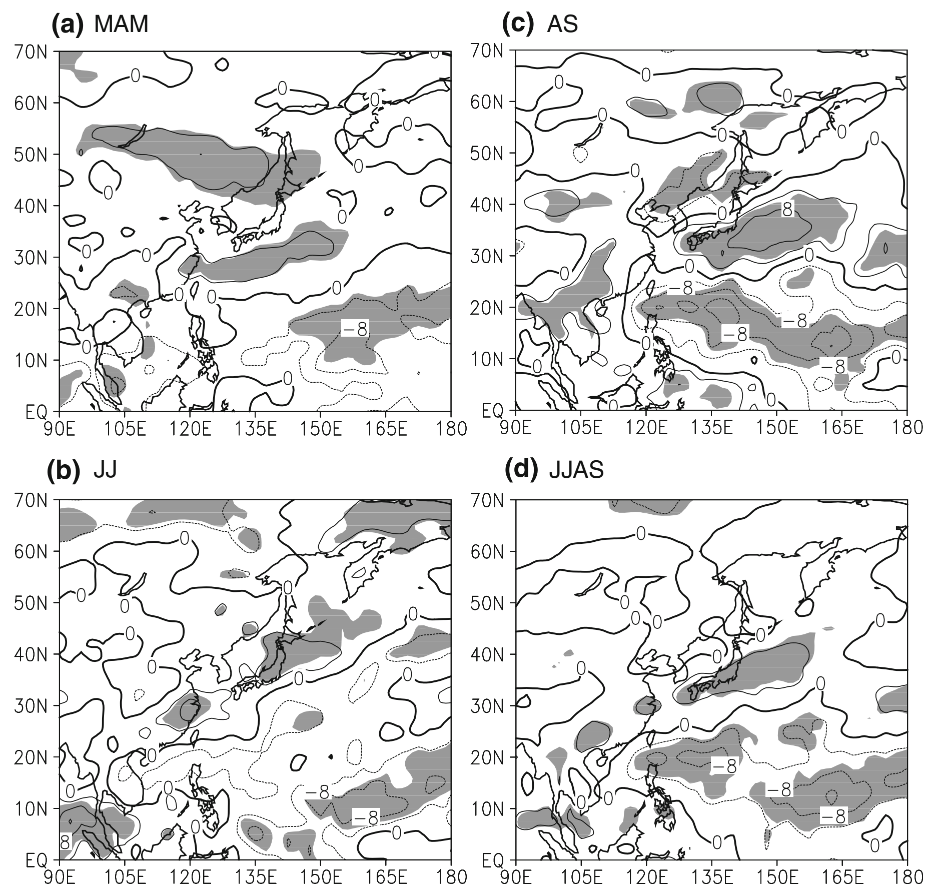

Fig. 10 Same as in Fig. 8, but for OLR. The contour interval is 4 W m^{-2}

surrounding region. Because of this TC genesis feature, a few more TCs occur during JJAS in a positive AO phase, as stated above. On the other hand, a positive OLR anomaly is shown in the middle latitude region north of 25°N, and a negative OLR anomaly is shown again in a high latitude region. The difference in the spatial distribution of OLR anomalies in this meridional direction over the East Asian region is shown through the difference in meridional vertical atmospheric circulation between the two AO phases averaged along the longitude band of 120°–145°E, which includes the four areas studied in this research (Fig. 11). During all three TC seasons, upward flow is reinforced in the region south of 25°N, while a downward flow is reinforced in the middle latitude region (30°–40°N), and another upward flow is reinforced in the high latitude region (40°–50°N). The huge anomalous cyclone reinforced in the SWNP during the summer season of the positive AO phase, along with the downward flow reinforced in the middle latitude region of East Asia, imply that WNPSH is slightly more developed toward the north than during the negative AO phase. This can be shown through the 5,870 gpm contour, which is averaged during each AO phase (right panel in Fig. 5). During all three TC seasons, the WNPSH of the positive AO phase is positioned a little further to the north than that of the negative AO phase. In contrast, the WNPSH of the negative AO phase is developed a little further to the west. TCs generally move along the western periphery of the WNPSH (Lander 1994; Chan 2000). Therefore, it is shown that the main TC track during each AO phase is in general agreement with the degree of expansion into the meridional or zonal direction of the WNPSH. In particular, due to the expansion of the WNPSH into the west during a negative AO phase, many TCs recurve further toward the west than during a positive AO phase and have a weaker intensity due to a terrain effect generated while passing through the mainland China.

5.6 Sea surface temperature

The role of SST also cannot be overlooked in TC genesis and development. Therefore, this study analyzes the difference in SST between the two AO phases (Fig. 12). Despite our selection of neutral ENSO years for the two AO phases during JJAS, the spatial pattern of SST, which is similar to a weak La Niña, is shown during all four seasons of a positive AO phase. However, an anomalous warm SST is shown in most of the regions except some in the WNP. These SST characteristics analyzed above can provide a favorable environment in which generate more TCs are generated and can maintain stronger intensity during the summer season of the positive AO phase.

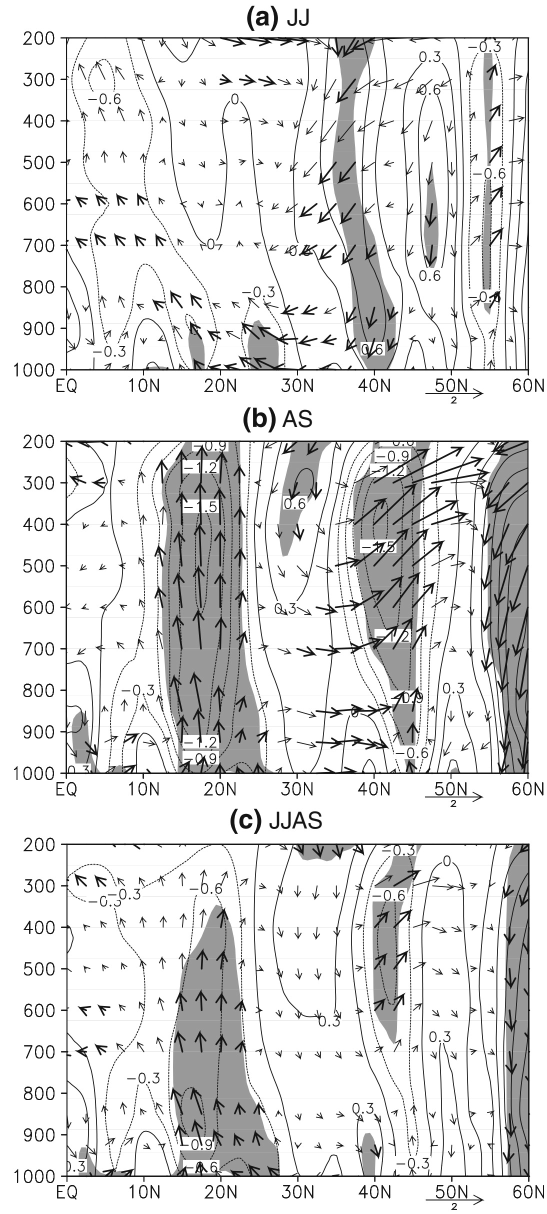

Fig. 11 Composite difference in latitude-pressure cross-section of vertical velocity (*contour*) and meridional circulation (*vector*) averaged along 120°–145°E between the positive and negative AO phases in **a** JJ, **b** AS, and **c** JJAS. The values of the vertical velocity are multiplied by −100. The values of the *shaded areas* and *thick arrows* are significant at the 95 and 90% confidence levels, respectively. The contour interval is 0.3^{-2} h Pas^{-1}

6 Summary and conclusion

This study analyzes the correlation between summer TC frequency and preceding spring AO in East Asia. To analyze the correlations between the two variables in detail, the East Asian region is divided into the four areas of Japan, Korea, Taiwan, and the Philippines, and the second half of the year is divided into the three TC seasons of JJ (early TC season),

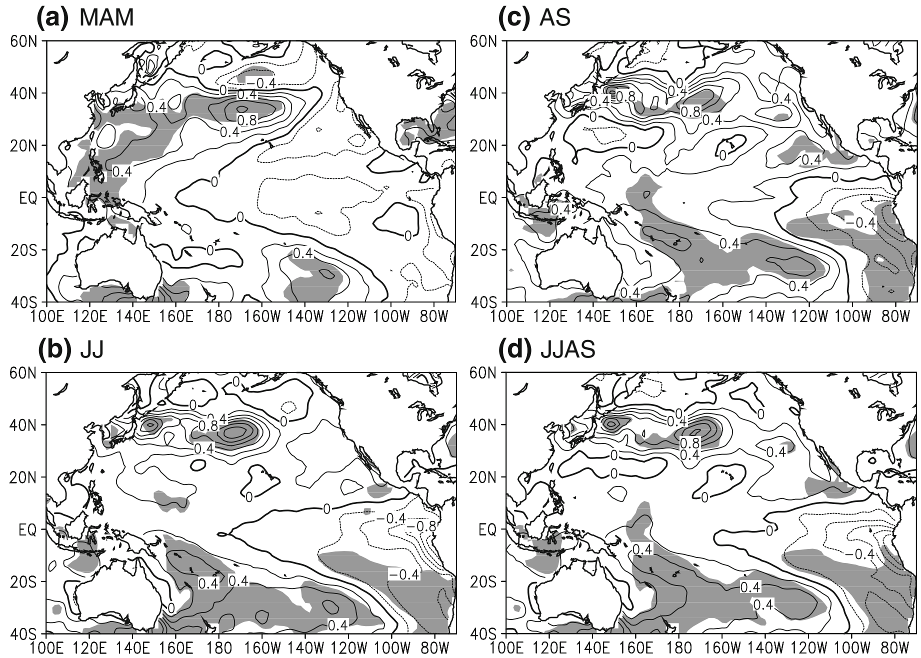

Fig. 12 Same as in Fig. 8, but for SST. Shaded areas are significant at the 95% confidence level. The contour interval is 0.2°C

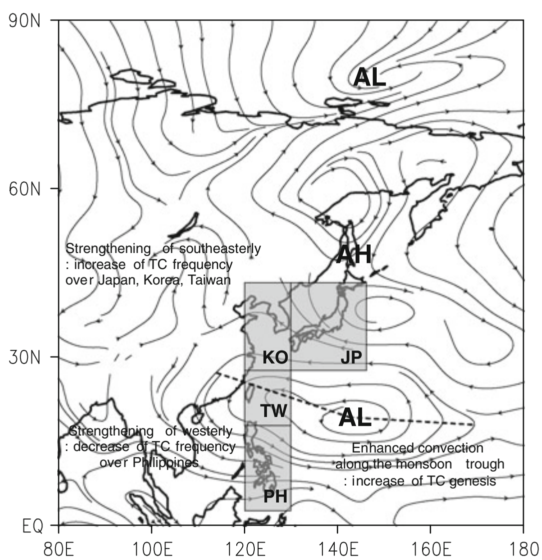

Fig. 13 Schematic illustration of atmospheric changes occurring during the positive years affecting the TC frequency over East Asia (Japan: JP, Korea: KO, Taiwan: TW, and the Philippines: PH). The abbreviations of 'AC' and 'AA' indicate 'anomalous cyclone' and 'anomalous anticyclone'. The *dashed line* denotes a monsoon trough

AS (peak TC season) and ON (late TC season). As a result of this correlation analysis, the TC frequencies occurring during JJ and AS in the Japan, Korea, and Taiwan areas, and the TC frequency occurring during AS in the Philippine area, show highly positive and highly negative correlations with the preceding MAM AO index, respectively. Therefore, this study analyzes the differences between the two phases by selecting the highest (positive AO phase) and lowest 8-year periods (negative AO phase) among the preceding MAM AO indices. Here, each of 8-year period is selected from neutral ENSO years defined from the Niño-3.4 index for JJAS.

In TC genesis, the TCs during a positive AO phase show a tendency to occur a little further toward the northeastern side of the WNP. For a TC track, while many TCs occurring during a positive AO phase tend to move toward Korea and Japan via Taiwan from the sea northeast of the Philippines, TCs during a negative AO phase move mainly to the west from the Philippines toward southern China or the Indochina Peninsula. Because of this difference in TC track between the two AO phases, a spatial distribution similar to a dipole pattern in TCPF is formed between the northeastern (Korea and Japan) and southwestern (Philippines, South China Sea, and southern China) regions in East Asia. In addition, this difference in TC track between the two AO phases affects the TC recurvature location, and the TCs of a negative AO phase recurve a little further toward the southwestern side in the WNP. In particular, many TCs of this AO phase show a weaker intensity than those of a positive AO phase because of the terrain effect generated while moving and recurving in mainland China. After all, TCs of a positive AO phase move and recurve a little further toward the northeastern side in the WNP than those occurring during a negative AO phase. These characteristics of TC activity during a positive AO phase are related to differences in the development of WNPSH between the two AO phases. That is, while the WNPSH of a positive AO phase is positioned a little further toward the northeast in the WNP, the WNPSH of a negative AO phase expands toward the southwest side.

As a result, TC activity during a positive (negative) AO phase is reinforced a little further toward the northeastern (southwest) side.

A 700-hPa streamline is also analyzed in order to discover the characteristics of large-scale atmospheric circulation, which cause these differences in TC activity between the two AO phases. During a positive AO phase, favorable atmospheric environments for high TC frequency in the Japan, Korea, and Taiwan areas, and for low TC frequency in the Philippine area, are already formed from the preceding MAM. A huge anomalous cyclone is reinforced in the SWNP, and an anomalous anticyclone is reinforced in the middle latitude region of East Asia. Because of these two anomalous circulations positioned in the low and middle latitude regions of East Asia, easterlies are strengthened in the Japan, Korea, and Taiwan areas, and play a role in steering the flows that move TCs easily into these regions. On the contrary, westerlies are reinforced in the Philippine area, which plays a role in preventing TCs from moving toward this region during a positive AO phase. In particular, a huge anomalous cyclone reinforced in the SWNP is related to a strong convection or monsoon trough, and more TCs eventually occur during a positive AO phase. These characteristics are revealed by analyzing the differences in OLR and vertical circulation in the meridional direction between the two AO phases. Moreover, as anomalous warm SSTs are located in the majority of regions, except for some areas of the WNP, during a positive AO phase, a favorable environment is created in which more TCs can be generated and their intensity can be reinforced during this phase. The characteristics of atmospheric circulations related to the strengthening of TC activity during a positive AO phase are described in Fig. 13.

On the other hand, AO is robust during winter and spring while it becomes weak in summer because of the short memory of atmosphere. Fan (2007) found more sea ice cover over North Pacific lead to the decrease of WNP TC genesis frequency, they noted that large sea ice cover during MAM is associated with the tropical circulation and SST anomalies in the North Pacific via North Pacific Oscillation (NPO) and strong seasonal persistency of tropical circulation, which may lead to unfavorable dynamic and thermal conditions for TC genesis over WNP from June to October (JJASO). In addition, Fan and Wang (2009) develop an effective prediction model for seasonal TC genesis frequency containing Sea ice cover over North Pacific and NPO.

Finally, this study focused on analyzing the correlation between preceding MAM AO and summer TC activity in East Asia. In future studies, the predictability of summer TC activity over East Asia using preceding MAM AO will be investigated.

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