Relationship between Antarctic Oscillation and the genesis activity of the yearly latest tropical cyclone in the western North Pacific

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Abstract

We find a significant negative correlation between the Antarctic Oscillation (AAO) and the genesis longitude of the last TC of the year (hereafter the last TC) in the western North Pacific (WNP). We also find that the mean longitude of the last TC genesis has experienced a significant westward shift since 1997-98. That means both a positive AAO phase and AAO phase of the recent epoch (1998-2015) favor the last TC occurring more frequently in the western part of the WNP. Thus, we compared the differences between the positive and negative AAO phases on interannual time scale and the epochal differences between the 1998–2015 and 1983–1997 periods to find the common factors responsible for the more frequent occurrence of the last TCs in the western WNP. The common differences in the 850 hPa stream flows reveal that an anomalous cyclone occurs in the South Indian Ocean, whereas an anomalous anticyclone appears in the WNP. The anomalous northerlies from the Southern Indian Ocean anomalous cyclone move northward, enhancing the cross-equatorial flows and associated westerlies. The enhanced anomalous westerlies extend eastward and meet the anomalous easterlies originated from the WNP anomalous anticyclone at the South China Sea (SCS). As a result, the anomalous cyclone are strengthened in the SCS and around the Philippines. Further analysis of the differences in the outgoing longwave radiation (OLR), 850 hPa relative vorticity, 200–850 hPa vertical wind shear, sea surface temperature (SST), horizontal divergence, 500 hPa omega and velocity potential and divergent winds between the two phases and the two epochs confirm that favorable environments for generation of the last TC take place in the western WNP during the positive AAO phase and in the 1998–2015 epoch.

Key words : Tropical cyclone; Antarctic Oscillation; statistical change-point analysis

1. Introduction

A tropical cyclone (TC) refers to a meteorological phenomenon that accompanies heavy rainfall and strong winds. When TCs make landfall in coastal regions, a large amount of economic damages and casualties can be incurred (Kim *et al*., 2005; Park and Lee, 2007; Pan *et al*., 2010; Kossin *et al*., 2014). According to a study by Park *et al*. (2015), approximately 13,600 casualties and USD 22.0 billion in damages have been caused every year around the world by TCs. More recently, in 2016, TC Chaba landed in Korea and caused enormous damage in Jeju, Busan, and Ulsan. It is of utmost importance to investigate how TC activities are evolving according to climate changes in order to countermeasure the damages caused by TCs in the future.

In recent years, abnormal climate phenomena attributed to global warming have occurred so frequently that studies on a trend of changes in TC activity due to global warming have been zealously conducted (Emanuel, 2005; Webster *et al*., 2005; Knutson *et al*., 2010; Weinkle *et al*., 2012; Walsh *et al*., 2016). Although studies on changes in TC genesis frequency, TC intensity, and TC track have been conducted, studies on the main activity periods for TCs and their changes have been insufficient. Climatologically, TCs may occur throughout the year; however, approximately 90% of TCs occur between May and November, which can be considered as the main activity period for TCs (Watterson *et al*., 1995; Royer *et al*., 1998; Emanuel and Nolan, 2004; Camargo *et al*., 2007; Tippett *et al*., 2011). In particular, the annual variability of TC termination following the main activity period has been known to be significantly large. For example, the last TC in 2010 occurred in October, which was the earliest month of the last TC occurrence along with the one in 1999. In contrast, the last TC in 1952 occurred in late December (December 28). TCs that occur during the winter season do not affect the mid-latitude regions in East Asia, whereas strong TCs can develop as they stay in the low-latitude region, where the sea surface temperature (SST) is high, and can cause enormous damage in the low-latitude region in East Asia (Wiles *et al*., 1990; Saji *et al*, 1999; Webster *et al*., 1999; Yu and Rienecker, 2000; Wang and McPhanden, 2001).

A previous study on hurricanes reported that the total main activity period has been lengthened due to an increase in the SST in the North Atlantic, where hurricanes mostly occur, causing the main activity period for hurricanes to start earlier and terminate later in the year than usual (Kossin, 2008). However, few studies have been conducted in relation to changes in the main activity period for TCs in the western North Pacific. Recently, Kim *et al*. (2017) suggested a close correlation between when the main activity of TCs starts and the tropical pacific SST distribution in the western North Pacific.

The present study examined the relationship between Antarctic Oscillation (AAO) and the genesis activity of the last tropical cyclone of the year in the western North Pacific.

AAO is a representative annular mode circulation that appears in the Southern Hemisphere during boreal summer and is characterized by large-scale seesaw oscillation in atmospheric circulation between the middle and high latitudes of the Southern Hemisphere (Kidson, 1988; Gong and Wang, 1999; Thompson and Wallace, 2000). Regarding a relationship between the TC activity and AAO, Ho *et al*. (2005) examines the influences of the AAO, an extensive mass exchange between the Southern Hemisphere midlatitudes and Antarctic regions, on large-scale circulations and TC activity in the subtropical western North Pacific. They showed that convection enhanced just along the equator in the positive AAO phase. Choi et al. (2010) developed a statistical model for seasonal prediction of TC genesis frequency in the western North Pacific using teleconnection pattern and they stressed that AAO is a key predictor for statistical model.

In Section 2, data and methods are introduced; in Section 3, a correlation between various climate indices and the last TC activity of each year is analyzed. In Section 4, the characteristics of interdecadal variation with regard to the last TC activity in every year are investigated. Finally, in Section 5, the conclusions of the study are summarized.

2. Data and methods

The TC data in this study were obtained from the best-track data provided by the Regional Specialized Meteorological Center (RSMC)–Tokyo Typhoon Center. The data provide meteorological information every six hours, including latitude, longitude, central pressure, and maximum sustained wind speed (MSWS) of TCs occurring in the western North Pacific since 1951. In the present study, a TC was defined as a developed TC transforming into a tropical storm (TS) whose MSWS was more than 17m/s among TCs that occurred in the western North Pacific.

For analysis on large-scale environments pertaining to the causes of TC activity, Reanalysis-2 (R-2) monthly average data distributed by the National Centers for Environmental Prediction (NCEP)–Department of Energy (DOE) were employed (Kanamitsu, 2002). The data consist of latitude-longitude 2.5° × 2.5° grid spaces and a total of 17 layers vertically. The data since 1979 are provided.

For the SST data, Extended Reconstructed Sea Surface Temperature (ERSST) V3b (Smith *et al*., 2008) data were employed. The ERSST refers to the monthly average data from 1854 up to now, which consist of 2° × 2° grid spaces.

The present study investigated the last month of TC occurrence in every year during the years 1951–2015 as follows: 1 in October, 15 in November, and 49 in December. All of the last TCs in every year occurred between October and December. Thus, the present study employed average data during the period from October to December. Furthermore, the climate indices used in the present study employed average data during the period from October to December. The climate indices were provided by the NOAA Climate Prediction Center (CPC). In particular, The AAO index is constructed by projecting the 700mb height anomalies poleward of 20°S onto the loading pattern of the AAO.

For variables to determine whether convective activities occurred or not, the outgoing longwave radiation (OLR) data were analyzed (Liebmann and Smith, 1996). Since the air temperature becomes lower with higher altitude in the troposphere, convection becomes active. Thus, the higher the altitude of cloud top, the smaller the OLR becomes.

The date of the last TC occurrence in every year was defined as the first day when the TC had the intensity of a TS.

The present study employed a statistical technique of Student's *t* test to analyze the reliability of the study result (Wilks, 1995). Furthermore, the present study applied statistical change-point analysis to determine whether a climate regime shift existed in the time series (Elsner *et al*., 2000; Chu, 2002; Ho *et al*., 2004). A climate regime shift exists at the time when the absolute value of *t*-value obtained from the above analysis result is the largest.

The AAO index in this study was derived from National Oceanic and Atmospheric Administration (NOAA)'s Climate Prediction Center (CPC).

3. Interannual variation

3.1 Correlation analysis

The present study first analyzed a correlation with the climate indices that can affect the last TC activity of every year in the western North Pacific during the period from 1951–2015 (65 years). The climate indices used were Arctic Oscillation (AO), North Pacific

Oscillation (NPO), Pacific/North American Pattern (PNA), Antarctic Oscillation (AAO) and El Niño-Southern Oscillation (ENSO, Niño-3.4). As presented in Table 1, the results of the analysis on a 14-year sliding correlation during the 1951–2015 period showed that a low correlation (below ±0.25) was revealed between the climate indices and genesis date, genesis latitude, and longitude locations of the last TC, except for a high negative correlation between the AAO and the genesis longitude location of the last TC since 1983. Thus, it indicated that as the AAO became stronger (weaker), the genesis longitude location of the last TC tended to be located in the west (east) side of the western North Pacific. Thus, the present study focused on a relationship between the AAO and the genesis date, genesis latitude, and longitude locations of the last TC of each year. A correlation of the genesis date of the last TC in every year with the genesis latitude and longitude locations demonstrated that a high negative correlation was revealed with genesis latitude of -0.44 (Table 1). This correlation is statistically significant at the 95% confidence level. This result indicated that as the genesis date of the last TC occurred earlier (later), TC genesis latitude location was determined at a higher (lower) latitude. This was because the sun moved in a southerly direction toward the equator in the northern hemisphere as the winter season approached.

Figure 1a shows the time series of genesis longitude location of the last TC in every year and the average AAO during the period from October to December, respectively. Overall, both of the time series indicated clear interannual variation. Furthermore, a clear out-of-phase relationship between two variables was revealed, indicating a high negative correlation of -0.51. This correlation is statistically significant at the 95% confidence level. A trend of the AAO time series showed no significant change overall, but a trend of genesis longitude location in the last TC in every year tended to decrease weakly. Nonetheless, this decreasing trend was not statistically significant. Thus, a correlation between the two variables was re-analyzed after eliminating a trend from the time series of the genesis longitude location of the last TC in every year. As a result, a correlation between two variables was -0.50, which was not significantly different from the original one. The correlation was also significant at the 95% confidence level. Thus, from then on, large-scale environments were analyzed to determine the causes of the negative correlation between the two variables.

3.2 Large-scale environments

The present study selected years whose correlation was ±0.5 or higher in the AAO index to determine the cause of the negative correlation between the AAO and genesis longitude location of the last TC in every year (Table 2). The number of years whose value was ±0.5 or higher was nine. In the next analysis, these nine years whose value was +0.5 or higher were defined as a positive AAO phase, while the nine years whose value was -0.5 or lower were defined as a negative AAO phase. The mean genesis location of the last TC in every year in the positive AAO phase was 10.8°N, 128.2°E, while in the negative

AAO phase, it was 10.4°N, 145.8°E, which revealed that the last TC in every year in the positive (negative) AAO phase was generated further west (east) in the western North Pacific (Table 3). A longitude difference between the two phases was significant at the 99% confidence level, whereas a latitude difference was rarely revealed, indicating no statistical significance. A difference in the mean genesis date in the last TC between the two phases was three days, which was also not statistically significant.

Next, a mean difference between positive AAO and negative AAO phases was analyzed to determine the cause of the last TC occurrence in every year in the further west (east) of the western North Pacific in the positive (negative) AAO phase. Only one occurrence of a TC generated east of 140°E during the positive AAO years was found in the analysis on TC genesis location (left panel in Figure 2a). In the negative AAO years, more than half of the TCs were generated east of 140°E.

The differences between the two phases with regard to the 850 hPa stream flows showed that anomalous cyclonic circulations were strengthened from the east coast of Australia to the South Indian Ocean, whereas anomalous anticyclonic circulations were strengthened in the western North Pacific (left panel in Figure 2b). This characteristic is typically displayed in the positive AAO phase (Mo, 2000). The anomalous northerlies from the anomalous cyclonic circulations in the southern hemisphere moved north along the east coast of Africa and crossed the equator. Then, the cross-equatorial flows changed into anomalous westerlies, which moved east. The anomalous westerlies converged with the anomalous easterlies from the anomalous anticyclonic circulations, which were strengthened in the western North Pacific, at the South China Sea, and then moved north. As a result, the anomalous cyclonic circulations were strengthened in the South China Sea. Thus, favorable environments were formed in which TCs were generated further west in the western North Pacific in the positive AAO phase than TCs in the negative AAO phase. A spatial distribution in the anomalous pressure systems at a difference in 500 hPa stream flows between the two phases was similar to a spatial distribution at 850 hPa (left panel in Figure 2c). The anomalous anticyclonic circulations were strengthened in the east-west direction from the east coast of Australia to the South Indian Ocean, and the anomalous anticyclonic circulation was strengthened in the western North Pacific. Furthermore, as anomalous westerlies and anomalous easterlies converged over the South China Sea, anomalous cyclonic circulations were strengthened.

Next, a difference in various environmental factors that affected TC genesis between the two phases was analyzed. First, in the analysis on the OLR, negative anomalies were strengthened in the area west of 130°E, except for East Asia, and positive anomalies were strengthened in the east (left panel in Figure 3a). The smaller the OLR was, the more active the convection was. Thus, this result indicated that favorable environments were formed in which TCs were generated further west in the western North Pacific in the positive AAO phase than TCs in the negative AAO phase. In the analysis on the 850 hPa relative vorticity, positive anomalies were strengthened in the area west of 130°E in the western North Pacific, and negative anomalies were strengthened in the east (left panel in Figure 3b). Furthermore, in the analysis on the 200–850 hPa vertical wind shear, negative anomalies were strengthened from the south east sea in the Philippines to the South China Sea, and positive anomalies were strengthened in the far east area of the Philippines (left panel in Figure 3c). As the vertical wind shear becomes smaller, the vertical structure between upper and lower layers of TCs grows stable, thereby providing a favorable environment for TC genesis. In the analysis on the SST, warm anomalies were strengthened in the west sea of the western North Pacific, whereas cold anomalies were strengthened in the east sea (left panel in Figure 3d). Thus, the results of the analysis on various environmental factors that affected TC genesis showed that favorable environments in which TCs were generated in the west area of the western North Pacific in the positive AAO phase more frequently.

A difference in the horizontal divergence between the two phases was analyzed (Figure 4). First, negative anomalies were evident in the South China Sea and the east sea of the Philippines, whereas positive anomalies were located in the area east of the western North Pacific (left panel in Figure 4a). A spatial distribution at the 200 hPa horizontal divergence showed an opposite distribution compared with that of the 850 hPa horizontal divergence (left panel in Figure 4b). Positive anomalies were evident in the South China Sea and the east sea in the Philippines, and negative anomalies were evident in the area east of 140°E. Thus, it can be seen that the anomalous atmospheric circulation, which ascended in the South China Sea and the east sea of the Philippines during the positive AAO phase and then descended in the area east of the western North Pacific, was strengthened by both the upper and lower tropospheres simultaneously. These features are shown in 500 hPa omega (Figure 4c). Negative anomalies were evident in the South China Sea and the east sea of the Philippines, whereas positive anomalies were located in the area east of the western North Pacific. Accordingly, TCs were generated in the west area of the western North Pacific in the positive AAO phase more frequently.

In order to determine the characteristics of the global-scale atmospheric circulation, the difference in velocity potential and divergent winds between the two phases was analyzed (Figure 5). The analysis on the 850 hPa velocity potential and divergent winds showed that anomalous convergent winds were strengthened from the east sea of Australia, where anomalous cyclonic circulations were located, to the South Indian Ocean, and from the Arabia Peninsula to the South China Sea (left panel in Figure 5a). In contrast, anomalous divergent winds were located in the area east of 180°E. A spatial distribution of the 200 hPa velocity potential and divergent winds showed an opposite distribution to that of the 850 hPa velocity potential and divergent winds (left panel in Figure 5b). Anomalous divergent winds were located in the area east of 160°E, whereas anomalous convergent winds were strengthened in the area east of 180°E. Thus, it can be seen that the anomalous atmospheric circulation, which ascended in the Maritime Continent during the positive AAO phase and then descended in the equatorial central Pacific, was strengthened by both the upper and lower tropospheres simultaneously. Accordingly, TCs were generated in the area west of the western North Pacific in the positive AAO phase more frequently.

4. Interdecadal variation

4.1 Statistical change-point analysis

Figure 1b shows a time series of genesis longitude location of the last TC in every year and the average AAO index during the period from October to December, respectively. The two time series showed clear interdecadal variation. Therefore, statistical change-point analysis was conducted with regard to the two time series to determine whether climate regime shift existed in the two time series. The largest and smallest *t*-values existed in 1997 in both of the time series (brown and green lines). A mean value of genesis longitude location in the last TC in every year during the 1983–1997 period was 146.6°E (red solid line), whereas a mean value during the 1998–2015 period was 132.1°E (blue solid line), indicating that TCs in the latter (former) period were generated at the further west (east) side of the western North Pacific (Table 3). A difference between the two periods was 14.5°, and this difference was statistically significant at the 99% confidence level. A mean value of AAO index during the 1983–1997 period was -0.12 (red dashed line), and a mean value during the 1998–2015 period was 0.14 (blue dashed line). A difference in average AAO index between the two periods was statistically significant at the 90% confidence level. TCs were generated 10 days later on average during the latter period in the analysis on the mean genesis date of the last TC in every year (Table 3) and this difference between the two periods was statistically significant at the 90% confidence level. However, a difference in TC genesis latitude location between two periods was -0.9°, which was not statistically significant.

A correlation of the AAO index with genesis date, genesis latitude, and longitude locations of the last TC in every year was analyzed in the two divided periods (Table 4). The AAO index during the 1983–1997 period showed a high positive correlation with the TC genesis date in the same period. This correlation was statistically significant at the 90% confidence level. This meant that as the AAO grew stronger (weaker), the genesis date of the last TC in every year occurred later (earlier). A correlation between the AAO index and genesis location of the last TC in every year showed that a low correlation was revealed in the case of TC latitude location, whereas a high negative correlation was revealed in the case of TC longitude location (-0.68). This negative correlation is statistically significant at the 95% confidence level. This meant that as the AAO grew stronger (weaker), it was likely to have the last TC in every year at the west (east) side of the western North Pacific. The AAO index during the 1998–2015 period showed a low negative correlation with the TC genesis date in the same period, and this correlation was not statistically significant. A correlation between the AAO index and the genesis location of the last TC in every year showed that a low correlation was revealed in the case of TC latitude location, whereas a high negative correlation was revealed in the case of TC longitude location (-0.43). This negative correlation is statistically significant at the 90% confidence level. Thus, the AAO index was closely related to the TC genesis longitude location and the two periods had this in common.

A correlation between the genesis date and genesis location of the last TC in every year in each of the two periods was analyzed (Table 4). The TC genesis date during the 1983–1997 period showed a negative correlation (-0.38) with the TC genesis longitude location, and this correlation was statistically significant at the 90% confidence level. This meant that as the last TC in every year was generated earlier (later), TCs tended to be generated at the east (west) side of the western North Pacific. The TC genesis date during the 1998–2015 period showed a rather high negative correlation with the TC genesis latitude location, and this correlation was statistically significant at the 95% confidence level. This meant that as the last TC in every year was generated earlier (later), TCs tended to be generated at the north (south) side of the western North Pacific. In summary, the genesis date of the last TC in every year was related to the TC genesis longitude location during the 1983–1997 period, whereas it was closely related to the TC genesis latitude location during the 1998–2015 period.

Thus, the present study analyzed a mean difference between 1998–2015 and 1983–1997 periods to determine whether the genesis location of the last TC in every year occurred further west in the western North Pacific during the 1998–2015 period.

4.2 Large-scale environments

The characteristics of the large-scale environments during the 1998–2015 period were highly similar to those of the large-scale environments in the positive AAO phase, as analyzed above. First, many of the TCS during the 1998–2015 period were located west of 140°E in the spatial distribution of the TC genesis location (blue dot in the right panel in Figure 2a). In contrast, more TCs occurred in the area east of 160°E during the 1983–1997 period.

The differences in the 850 hPa stream flows between the two phases showed that anomalous cyclonic circulations were strengthened in the South Indian Ocean, whereas anomalous anticyclonic circulations were strengthened in the western North Pacific (right panel in Figure 2b). This characteristic is also typically displayed in the positive AAO phase (Mo, 2000). The anomalous northerlies from the anomalous cyclonic circulations in the southern hemisphere moved north along the east coast of Africa and crossed the equator. Then, the cross-equatorial flows changed into anomalous westerlies, which moved east. The anomalous westerlies converged with the anomalous easterlies from the anomalous anticyclonic circulations, which were strengthened in the western North Pacific, at the South China Sea, and then moved north. As a result, the anomalous cyclonic circulations were strengthened in the South China Sea. Thus, favorable environments were formed in which more TCs were generated further west of the western North Pacific in the

1998–2015 period than TCs in the 1983–1997 period. A spatial distribution in the anomalous pressure systems at a difference in 500 hPa stream flows between the two phases was similar to a spatial distribution at 850 hPa (right panel in Figure 2c). The anomalous anticyclonic circulations were strengthened in the east-west direction from the east coast of Australia to the South Indian Ocean, and the anomalous anticyclonic circulations were strengthened in the western North Pacific. Furthermore, anomalous cyclonic circulations were strengthened in the South China Sea.

Next, a difference in various environmental factors that affected TC genesis between the two periods was analyzed. First, in the analysis on the OLR, negative anomalies were strengthened in the area west of 130°E, except for East Asia, and positive anomalies were strengthened in the area east (right panel in Figure 3a). Thus, this result indicated that favorable environments were formed in which TCs were generated further west in the western North Pacific in the 1998–2015 period. In the analysis on the 850 hPa relative vorticity, positive anomalies were strengthened in the area west of 130°E in the western North Pacific, and negative anomalies were strengthened in the area east (right panel in Figure 3b). Furthermore, in the analysis on the 200–850 hPa vertical wind shear, negative anomalies were strengthened from the south east sea in the Philippines to the South China Sea, and positive anomalies were strengthened in the far east area of the Philippines (right panel in Figure 3c). In the analysis on the SST, warm anomalies were strengthened in the west sea of the western North Pacific, whereas cold anomalies were strengthened in the east sea (right panel in Figure 3d). Thus, the results of the analysis on various environmental factors that affected TC genesis showed that favorable environments in which TCs were generated in the area west of the western North Pacific in the 1998–2015 period more frequently.

A difference in the horizontal divergence between the two periods was analyzed (Figure 4). First, negative anomalies were evident in the South China Sea and the east sea of the Philippines, whereas positive anomalies were located in the area east of the western North Pacific (right panel in Figure 4a). A spatial distribution at the 200 hPa horizontal divergence showed an opposite distribution compared with that of the 850 hPa horizontal divergence (right panel in Figure 4b). Thus, it can be seen that anomalous atmospheric circulations, which ascended in the South China Sea and the east sea of the Philippines during the 1998–2015 period and then descended in the east area of the western North Pacific, were strengthened by both the upper and lower tropospheres simultaneously. These features are shown in 500 hPa omega (Figure 4c). Negative anomalies were evident in the South China Sea and the east sea of the Philippines, whereas positive anomalies were located in the area east of the western North Pacific. Accordingly, TCs were generated in the area west of the western North Pacific in the 1998–2015 period more frequently.

In order to determine the characteristics of the global-scale atmospheric circulation, the difference in velocity potential and divergent winds between the two phases was analyzed (Figure 5). First, the analysis on the 850 hPa velocity potential and divergent winds showed that anomalous convergent winds were strengthened in the area west of 180°E (right panel in Figure 5a). In contrast, anomalous divergent winds were located in the area east of 180°E. It showed an opposite spatial distribution compared with that of the 200 hPa velocity potential and divergent winds (left panel in Figure 5b). Thus, it can be seen that anomalous atmospheric circulations, which ascended in the Maritime Continent during the 1998–2015 period and then descended in the equatorial central Pacific, were strengthened by both the upper and lower tropospheres simultaneously. Accordingly, TCs were generated in the area west of the western North Pacific in the 1998–2015 period more frequently.

5. Summary and conclusion

The present study found a close relationship between tropical cyclone (TC) genesis location and genesis date of the last TC in every year in the western North Pacific and the Antarctic Oscillation (AAO). The study result showed a significantly large negative correlation between AAO and genesis longitude location of the last TC in every year. This meant that as the AAO became stronger (weaker), the last TC in every year was generated in the west (east) area of the western North Pacific. In addition, TC genesis longitude location in every year during the 1998–2015 period tended to occur at the west side of the western North Pacific more frequently than during the 1983–1997 period. The boundary year of 1997–1998 can be verified through statistical change-point analysis. Thus, differences between the positive AAO phase and negative AAO phase as well as differences between the 1998–2015 and 1983–1997 periods were analyzed to determine the causes for the last TCs to be generated in the western area of the western North Pacific more frequently, as has happened in recent years and when the AAO is stronger.

The differences between two phases as well as two periods with regard to the 850 hPa stream flows showed that anomalous cyclonic circulations were strengthened in the South Indian Ocean, whereas anomalous anticyclonic circulations were strengthened in the western North Pacific. The anomalous northerlies from the anomalous cyclonic circulations in the southern hemisphere moved north along the eastern coast of Africa and the cross-equatorial flows changed to the anomalous westerlies and moved east. The anomalous westerlies converged with the anomalous easterlies from the anomalous anticyclonic circulations, which were strengthened in the western North Pacific, at the South China Sea, and then moved north. As a result, the anomalous cyclonic circulations were strengthened in the South China Sea. Thus, favorable environments were formed in which more TCs were generated further west in the western North Pacific in the positive AAO phase and in the 1998–2015 period than TCs in the negative AAO phase and the 1983–1997 period (Fig. 6). A spatial distribution in the anomalous pressure systems at a difference in 500 hPa stream flows between the two phases was similar to a spatial distribution at 850 hPa.

The analysis of differences in the OLR between the two phases as well as the two periods showed that negative anomalies were strengthened in the area west of 130°E, except for East Asia, and positive anomalies were strengthened in the area east. The analysis on differences in the 850 hPa relative vorticity between the two phases as well as the two periods showed that positive anomalies were strengthened in the area west of 130°E, and negative anomalies were strengthened in the area east. The analysis on the 200–850 hPa vertical wind shear between the two phases as well as the two periods showed that negative anomalies were strengthened from the southeast sea of the Philippines to the South China Sea, and positive anomalies were strengthened in the northeast region of the Philippines. In the analysis of differences in the SST between the two phases as well as the two periods, warm anomalies were strengthened in the west sea of the western North Pacific, and cold anomalies were strengthened in the east sea. Thus, the results from all the above analysis revealed that favorable environments were formed in which TCs were generated in the west area of the western North Pacific during the positive AAO phase and in the 1998–2015 period more frequently.

A difference in horizontal divergence between the two phases as well as the two periods was analyzed. First, the analysis on the 850 hPa horizontal divergence revealed that negative anomalies were evident in the South China Sea and the east sea of the Philippines, whereas positive anomalies were located in the area east of the western North Pacific (right panel in Figure 4a). A spatial distribution at the 200 hPa horizontal divergence showed an opposite distribution compared with that of the 850 hPa horizontal divergence. Thus, it can be seen that anomalous atmospheric circulations, which ascended in the South China Sea and the east sea of the Philippines during the positive AAO phase and in the 1998–2015 period and then descended in the area east of the western North Pacific, were strengthened by both the upper and lower tropospheres simultaneously.

In order to determine the characteristics of the global-scale atmospheric circulation, a difference in velocity potential and divergent winds between the two phases as well as two periods was analyzed. First, the analysis on the 850 hPa velocity potential and divergent winds showed that anomalous convergent winds were strengthened in the area west of 180°E, whereas anomalous diverse winds were located in the area east of 180°E. It showed an opposite spatial distribution compared with that of the 200 hPa velocity potential and divergent winds. Thus, it can be seen that anomalous atmospheric circulations, which ascended in the Maritime Continent during the positive AAO phase and in the 1998–2015 period and then descended in the equatorial central Pacific, were strengthened by both the upper and lower tropospheres simultaneously.

In the end, the last TC genesis longitude location of the year can be largely predicted from statistical models using AAO index if AAO index is calculated from global models in advance

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(b) differences (b) October-December 850 and (c) 500 hPa stream flows between positive and negative AAO phases (left panel) and between 1998-2015 and 1983-1997 (right panel). In (a), red and cross marks indicate average TC genesis locations in positive (10.8°N, 128.2°E) and negative AAO (10.4°N, 145.9°E) (left panel) and in 1983-1997 (9.7°N, 146.7°E) and 1998-2015 (10.6°N, 132.1°E) (right panel), respectively. In (b) and (c), shaded areas are significant at the 95% confidence level.

Figure 3. Same as in Figure 2, but for (a) outgoing longwave radiation, (b) 850 hPa relative vorticity, (c) vertical wind shear between 200 hPa and 850 hPa, and (d) sea surface temperature. Shaded areas in (b) and (c) are significant at the 95% confidence level. Contour intervals are $10^{-6}s^{-1}$ in (b) and 0.5 ms^{-1} in (c).

Figure 4. Same as in Figure 2, but for (a) 850 hPa, (b) 200 hPa horizontal divergence, and (c) 500 hPa omega. Shaded areas are significant at the 95% confidence level. Contour interval is $2s^{-1}*10^7$ for horizontal divergence and $5hPs^{-1}*10^7$ for 500 hPa omega.

Figure 5. Same as in Figure 2, but for (a) 850 hPa and (b) 200 hPa velocity potential and divergent winds. Shaded areas denote negative anomalies. Contour interval is 3 $m^2s^{-1}10^{-6}$.

Figure 6. Schematic illustration of anomalous atmospheric circulation patterns at 850 hPa on effect of positive AAO on western North Pacific tropical cyclone genesis frequency.

Table 1. Correlation coefficients between AAO index and genesis date, genesis latitude, and genesis longitude of the last tropical cyclone in every year for the period from 1983 to 2015.

	Date	Latitude	Longitude
AAO	0.02	0.14	-0.51*
Date	•	-0.44*	-0.03

* is significant at the 95% confidence level

Table 2. Genesis latitude and longitude of the last TC in every year.

Positive AAO phase			Negative AAO phase		
Year	Latitude (°N)	Longitude (°E)	Year	Latitude (°N)	Longitude (°E)
1983	12.0	135.0	1984	9.2	136.9
1985	7.8	114.5	1988	15	124.3
1987	11.7	140.9	1991	8.6	167.8
1993	8.4	132.9	1996	9.4	140.4
1995	9.9	130.3	1997	9.0	179.7
1998	7.3	108.8	2000	10.4	127.8
1999	19.1	130.7	2002	8.7	161.2
2001	1.5	105.2	2003	8.9	156.7
2006	13.4	138.4	2004	13.4	148.5
2008	14.0	138.1	2005	13.2	129.8
2010	16.8	131.2	2009	8.5	147.1
2011	7.5	132.6	2012	10.1	128.8
Average	10.8	128.2	Average	10.4	145.8

Table 3. Statistics on genesis date, genesis latitude, and longitude of the last TS in the WNP.

	Positive AAO phase (A)	Negative AAO phase (B)	A minus B
Genesis date (Julian day)	345	341	3
Genesis latitude(°N)	10.8	10.4	0.4
Genesis longitude(°E)	128.2	145.8	-17.6*

	1983-1997 (A)	1998-2015 (B)	A minus B
Genesis date (Julian day)	350	340	10
Genesis latitude(°N)	9.7	10.6	-0.9
Genesis longitude(°E)	146.6	132.1	14.5*

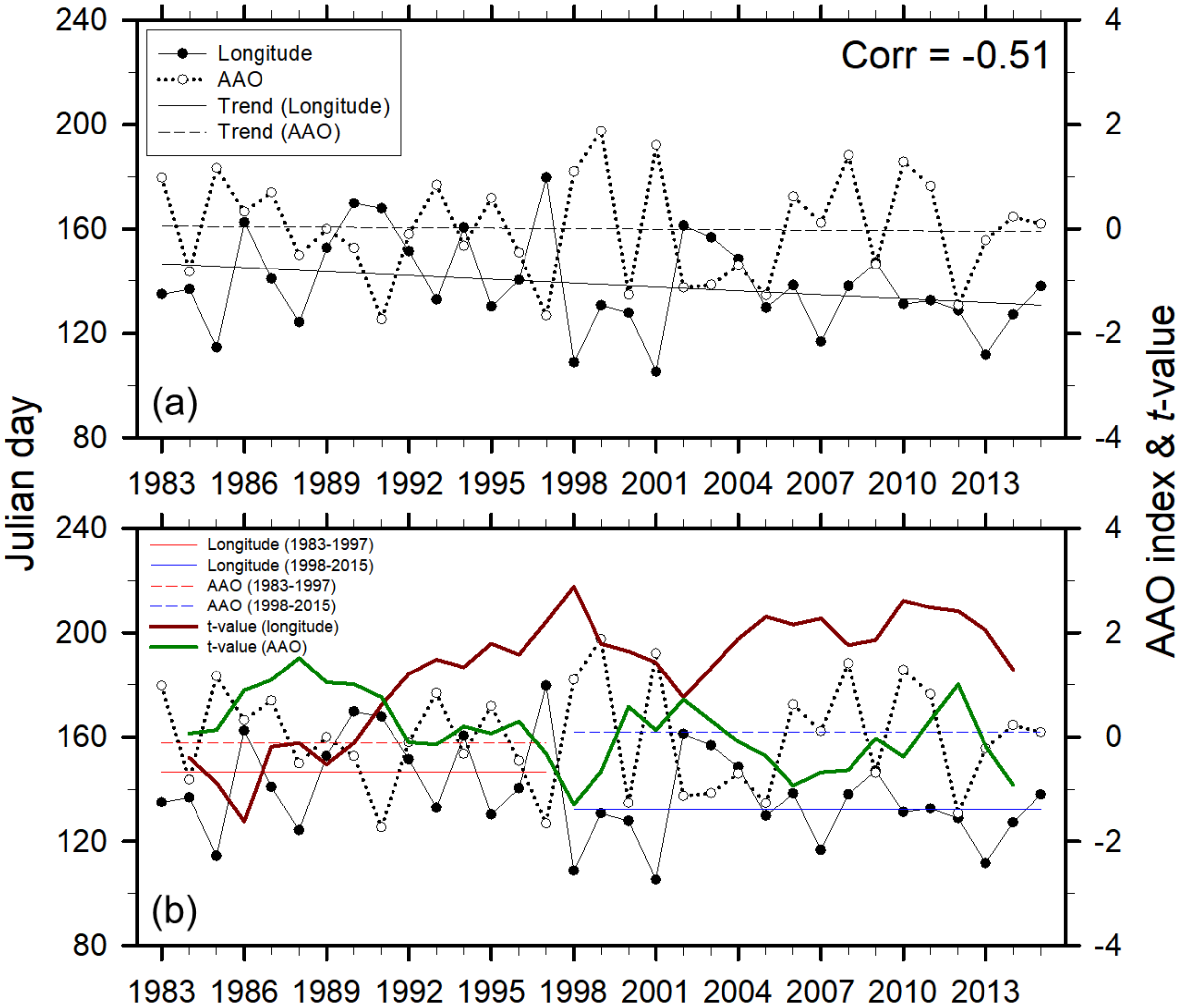
* is significant at the 99% confidence level.

Table 4. Same as in Table 1, bur for in 1983-1997 and 1998-2015.

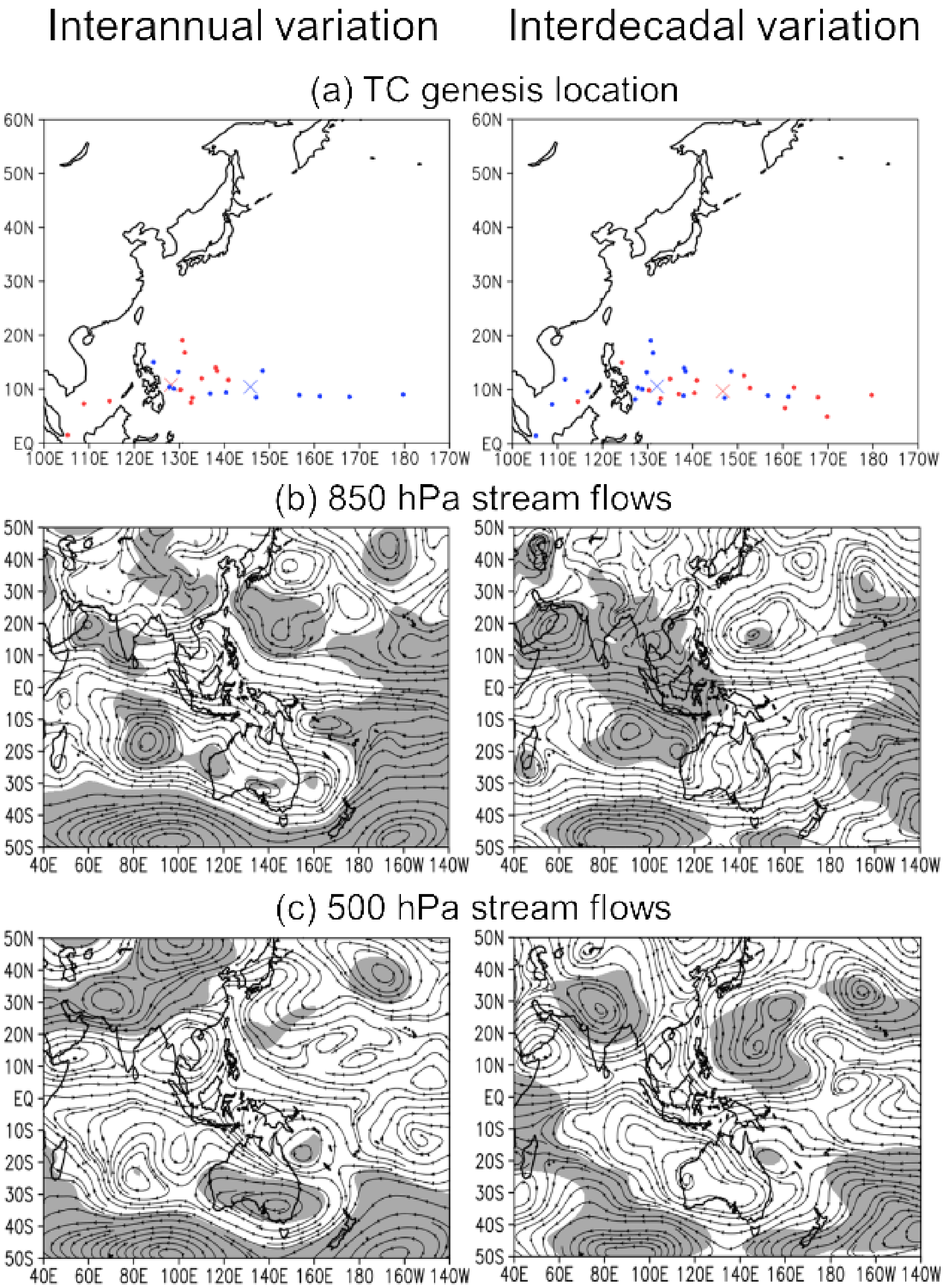
		1983-1997			1998-2015		
		Date	Latitude	Longitude	Date	Latitude	Longitude
1983 -1997	AAO	0.48*	0.13	-0.68**	•	•	•
1998 -2015	AAO	•	•	•	-0.11	0.13	-0.43*
1983 -1997	Date	•	-0.07	-0.38*	•	•	•
1998 -2015	Date	•	•	•	•	-0.57**	-0.08

* is significant at the 90% confidence level.

** is significant at the 95% confidence level.



Longitude
AAO
Trend (Longitude)
Trend (AAO)
Corr = -0.51
(a)
Julian day
AAO index & t-value
Longitude (1983-1997)
Longitude (1998-2015)
AAO (1983-1997)
AAO (1998-2015)
t-value (longitude)
t-value (AAO)
(b)
1983 1986 1989 1992 1995 1998 2001 2004 2007 2010 2013


Interannual variation
Interdecadal variation
(a) TC genesis location
(b) 850 hPa stream flows
(c) 500 hPa stream flows
60N
50N
40N
30N
20N
10N
EQ
100E 110E 120E 130E 140E 150E 160E 170E 180 170W
50N
40N
30N
20N
10N
EQ
10S
20S
30S
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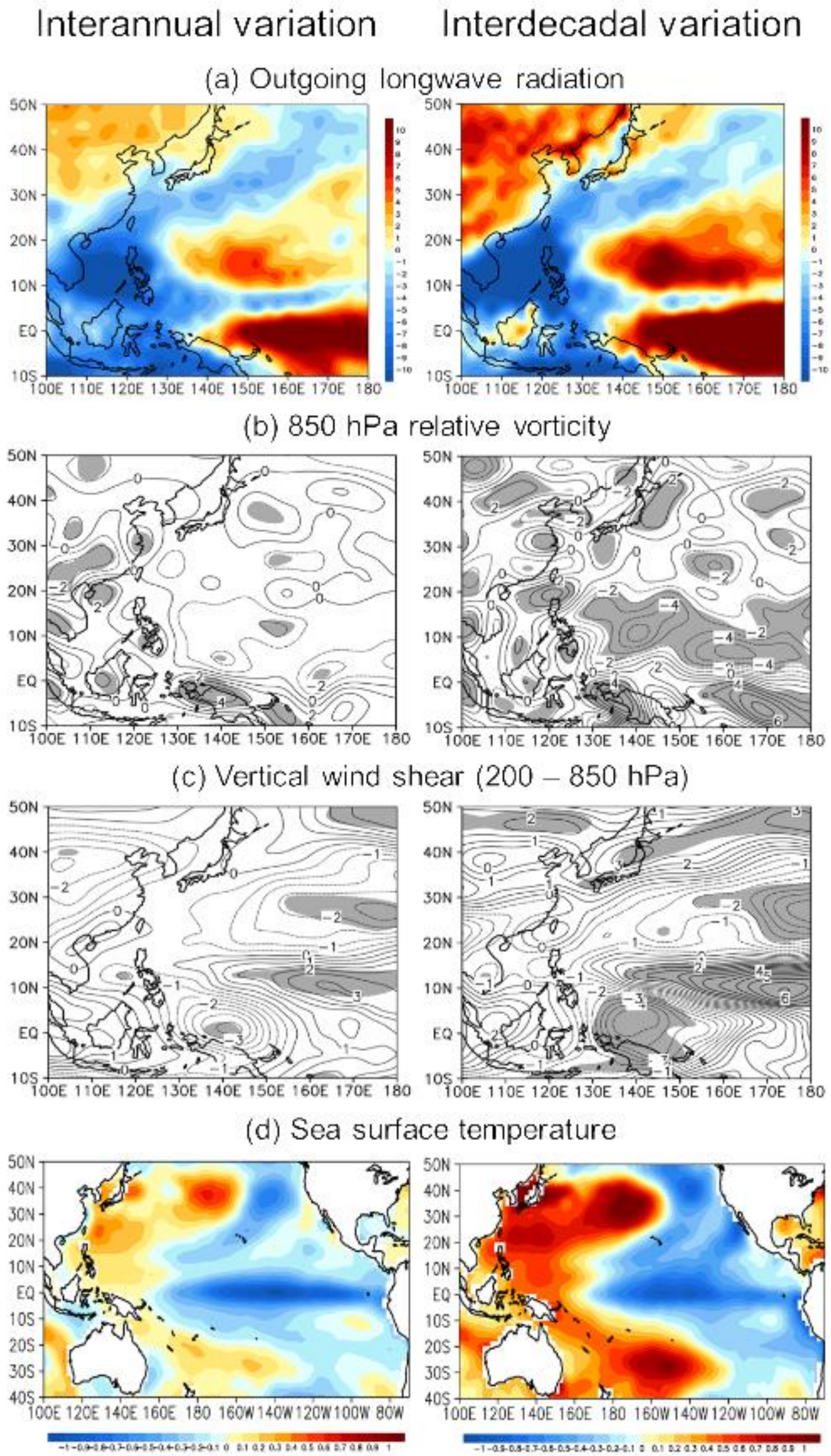
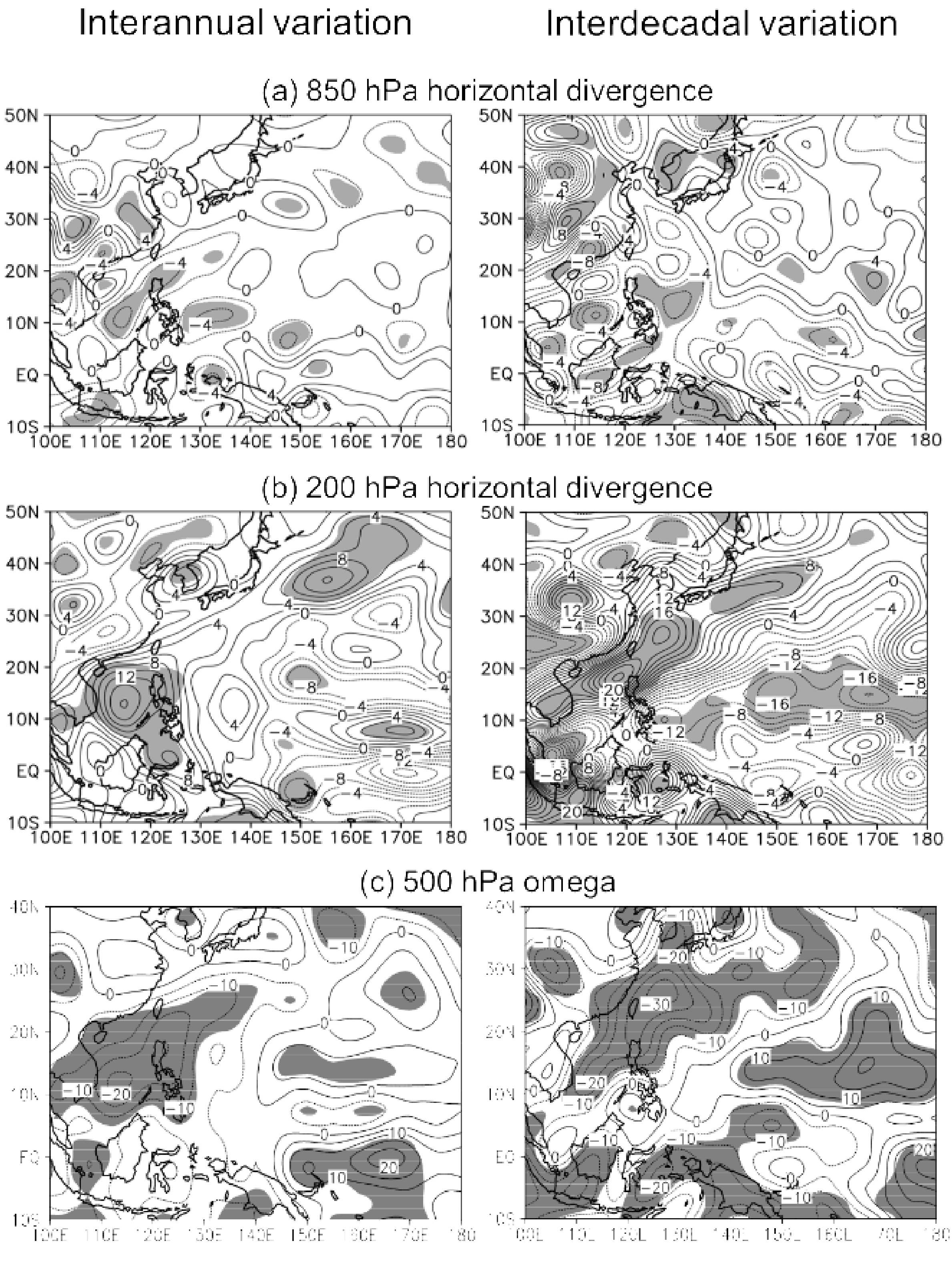
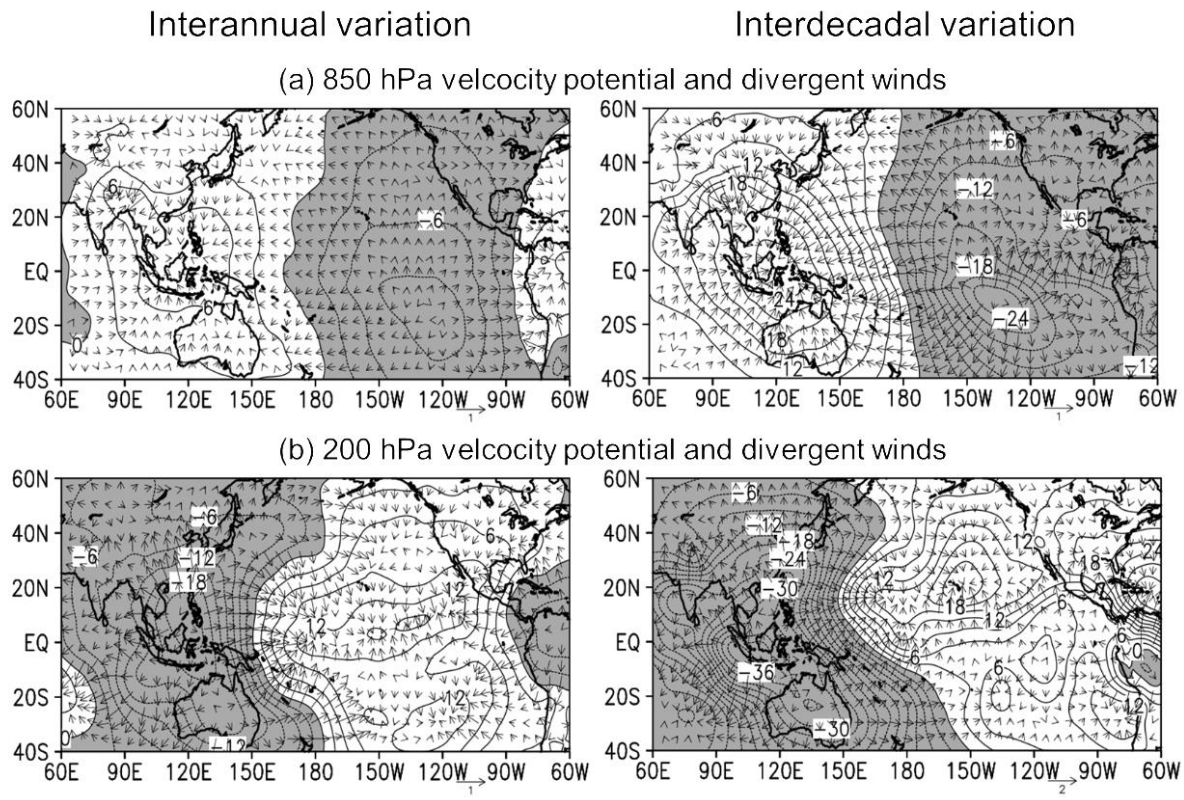
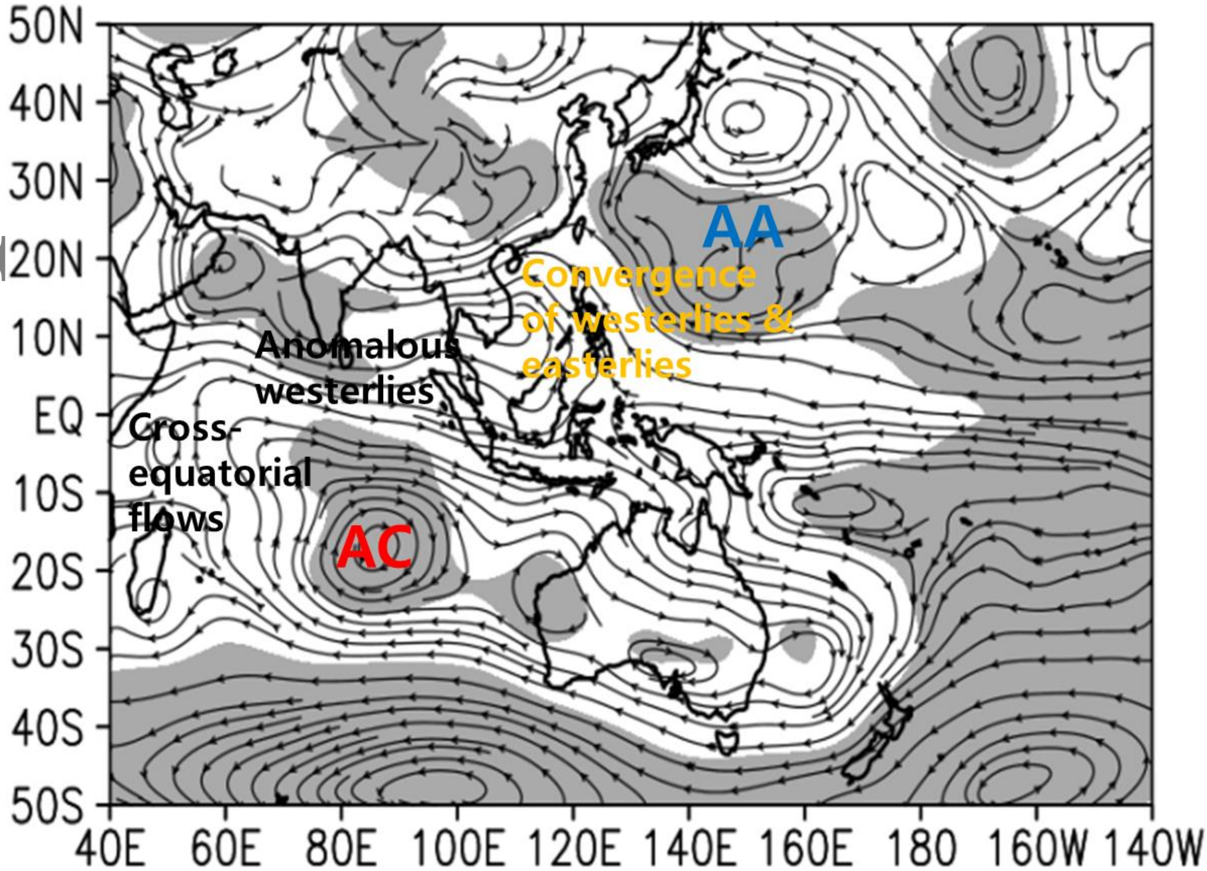
40E 60E 80E 100E 120E 140E 160E 180 160W 140W


Interannual variation
Interdecadal variation
(a) Outgoing longwave radiation
(b) 850 hPa relative vorticity
(c) Vertical wind shear (200 – 850 hPa)
(d) Sea surface temperature



Interannual variation
Interdecadal variation
(a) 850 hPa horizontal divergence
(b) 200 hPa horizontal divergence
(c) 500 hPa omega


Interannual variation
Interdecadal variation
(a) 850 hPa velcocity potential and divergent winds
(b) 200 hPa velcocity potential and divergent winds


AA
Convergence of westerlies & easterlies
Anomalous westerlies
Cross-equatorial flows
AC