P2.11 DOES THE ANTARCTIC OSCILLATION MODULATE TROPICAL CYCLONE ACTIVITY IN THE NORTHWESTERN PACIFIC

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1. INTRODUCTION

Since the pioneer work of Thompson and Wallace [1998] for Arctic Oscillation (AO) in the Northern Hemisphere (NH), many AO studies have been accomplished to investigate its relevant climate influences particularly over mid-latitudes [Kerr, 1999; Overland et al., 1999; Thompson et al., 2000; Gong et al., 2001; Thompson and Wallace, 2001; Gong and Ho, 2003]. The AO is represented by the leading empirical orthogonal function (EOF) mode for sea level pressure (SLP) in the region from 20ºN to 90ºN. This mode depicts a zonally symmetric configuration alternating positive and negative phases between high-latitude and mid-latitude regions.

Analogous to the AO, there is a large-scale swinging of SLP between polar and mid-latitude regions in the Southern Hemisphere (SH). This huge atmospheric mass exchange in the SH is referred to the Antarctic Oscillation (AAO) or High Latitude Mode [Karoly, 1990; Thompson and Wallace, 2000]. The AAO index is defined as time series of the leading EOF mode for SLP or 850 hPa geopotential height in the SH. It can be also obtained from the difference of zonal mean SLP between 40ºS and 65ºS [Gong and Wang, 1999]. The AAO may be one of important climate modulators in the SH, similar to the AO that influences on overall climate from the surface to lower stratosphere in the NH. When compared to the AO, however, its existence is recently found and thus its influences on overall climate have not been well documented yet.

In the positive phase of AAO, the subtropical highs develop stronger and the subpolar lows develop deeper in the SH [Gong and Wang, 1999; Thompson and Wallace, 2000; Kwok and Comiso, 2002]. For the reason that a growth of subtropical high coincides with an extension of the high to tropics and pole, the upper tropospheric jet moves pole, and consequently the polar vortex is confined in polar regions during a strong positive phase. At the same period, two anticyclonic circulations are built up in the mid-latitudes of the SH at surface (see Fig. 1 in Gong and Wang, 1999): one is in Indian Ocean (west of Australia) and other in Pacific Ocean (east of Australia). Thus there may be some modifications in the subtropical trade wind in the north of Australia and further cross equatorial flow in the northwestern Pacific, associated with variations of AAO. In addition, changes in the trade wind may lead those in the Inter-tropical Convergence Zone and tropical cyclone activity over the region. This has motivated the present study.

In this study, we present evidence of relationship between tropical cyclone activity and AAO phase for austral winter (July, August, and September), based on analyses of AAO index, moisture flux, and typhoon data.

2. DATA

We utilize tropical cyclone data archived by the Regional Specialized Meteorological Centers－Tokyo Typhoon Center. The data consist of names, longitude and latitude positions, minimum surface pressures, and maximum wind speeds of tropical cyclones in every six-hour interval. Tropical cyclones are generally divided into three stages depending on their maximum sustained wind speed: tropical depression, tropical storm, and typhoon. In the present study, tropical cyclones refer to both tropical storms and typhoons, so analyzed tropical cyclones have maximum sustained wind speeds greater than 17 m s^{-1} during their lifetime.

We also use the SLP, horizontal wind, and specific humidity data reanalyzed by the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) [Kalnay *et al*., 1996; Kistler *et al*., 2001]. The NCEP/NCAR reanalysis data have a horizontal resolution of $2.5^o \times 2.5^o$ longitude-latitude and are available for the period 1949-present. As documented by Kwok and Comiso [2002], the AAO index is determined by time series of the leading principal component of monthly mean SLP in the SH (see Fig. 1a). Alternatively, the AAO index can be taken from the leading EOF mode of 850 hPa geopotential height [Thompson and Wallace, 2000] and the difference of the normalized zonal mean SLP between 40^oS and 65^oS [Gong and Wang, 1999]. These three AAO indices are nearly identical; their correlation coefficients are larger than 0.95. Thus, different usage of the three AAO indices does not have an effect on the present results at all.

While the tropical cyclone data is accessible for

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the period 1950-present, there may be some problems on the reliability of typhoon data in the 1950s and early 1960s prior to the weather satellite era. The NCEP/NCAR reanalysis data are also affected by two major changes, upper-air networks and satellite observations, in the observing system [Kistler *et al*., 2001]. To avoid possible impacts of the usage of different data reliability on the present result, all calculations are confined for the period 1965-2002 since weather satellites operated.

3. CHANGES IN TROPICAL CYCLONE ACTIVITY ASSOCIATED WITH AAO

Prior to investigation of a connection between tropical cyclone activity and AAO, we examine the variation of AAO index. Figure 1 shows the time series of leading EOF mode of SLP in the SH for austral winter and these refer to the AAO index. Although not shown in the present study, the spatial structure of the leading mode depicts a zonally elongated north-south dipole pattern over Pacific, Indian, and Atlantic Oceans, from the subtropics to polar region [Gong and Wang, 1999; Kwok and Comiso, 2002]. The time series indicate that the AAO contains strong interannual and long-term trends (Fig. 1a). Also, there is almost no correlation among months even in the same year. Therefore, the AAO shows a strong month-to-month variation as well.

Due to changes in the observing system of the NCEP/NCAR reanalysis for the analysis period, long-term variations might be contaminated (or artificially made), in particular, over the SH (see Kistler et al. [2001] for detail information). Thus we remove a linear trend of the time series (Fig. 1b) and mainly focus on its interannual variability. This de-trended time series are utilized as the AAO index in the following.

The present study examines relation between the AAO and tropical cyclone activity by comparing the composite map for high AAO periods and low AAO periods. Many previous studies documented that tropical cyclone activities are greatly influenced by variations of sea surface temperature in the equatorial central-eastern Pacific, i.e. El Nino versus La Nino [Wu and Lau, 1992; Chen *et al*., 1998; Chan, 2000; Wang and Chan 2002]. Accordingly, we firstly select El Nino (La Nina) periods when Nino 3.4 sea surface temperature is greater (smaller) than +0.5 (-0.5)°C (Table 1). The selected years are always qualified for the given criteria during the whole austral winter. Secondly, we choose eight highest AAO years and eight lowest AAO years, respectively, each month. High and low AAO periods occur alternately even in the same year due to a strong month-to-month variation, e.g., 1968, 1974, 1978, 1983, 1984, 1990, 1994, 1995, 2001. On the contrary, some years maintain high and low values for the entire austral winter, e.g., 1969, 1985, 1993 for high AAO and 1977, 1981, 1996 for low AAO. In the following, all analyses are based on composites of the eight highest AAO periods and the eight lowest AAO periods. Comparison of El Nino and La Nina periods is also examined.

Figure 2 shows the climatological distribution of passage number (2a) and difference of high AAO periods and low AAO periods (2b) of tropical cyclones within each $5^o \times 5^o$ longitude-latitude grid box. Each six-hourly tropical cyclone position is binned into the corresponding $5^o \times 5^o$ grid box and the same tropical cyclone entering the same grid box is counted only once. The climatological values of tropical cyclone passage are defined by dividing the total number of tropical cyclone for austral winter for whole analysis period by 38 (38 years from 1965 to 2002). Since tropical cyclones generally migrate the western periphery of the subtropical North Pacific high, the tropical cyclone passage number is higher over the South China Sea and East China Sea (Fig. 2a). Over the two regions, more than 3 tropical cyclones appear in each $5^o \times 5^o$ grid box every austral winter (3 months). The passage number also indicates an elongated passage track (areas more than 2 tropical cyclones) extending toward Korea and Japan.

Corresponding differences of tropical cyclone passages between high AAO and low AAO periods (the eight highest AAO years minus the eight lowest AAO years) are shown in Fig. 2b. The difference values are divided by 8 (8 years) to represent the number of tropical cyclone passage per austral winter. The primary change is observed over the East China Sea, Japan, and Philippine. The change is as large as 2 and matches a 50-100% increase from the climatology during high AAO period compared to low AAO period. Also, these are significant at the 95% confidence level. While the tropical cyclone passage decreases in southeastern China, they are scattered. On the whole, the regions of increased passage number dominate the analysis domain.

The changes in tropical cyclone passage may be due to those in genesis location between the two periods. Figure 3 shows the spatial distribution of climatology (3a) and its difference between high AAO years and low AAO years (3b). Many tropical cyclones are originated from the Philippine Sea where sea surface temperature is high and overlying atmosphere indicates extremely low stability (Fig. 3a). Over the region of 115^o-150^oE and 10^o-20^oN, about 0.5 tropical cyclone forms every austral winter within each $5^o \times 5^o$ longitude-latitude grid box.

Surrounding this region, fewer tropical cyclones are developed. There is no region where appears more than 0.2 tropical cyclones per austral winter in north 25^{o}N. The difference of tropical cyclone genesis number between the two periods is displayed in Fig. 3b. The number of tropical cyclone genesis increases over the Philippine Sea and decreases over the South China Sea. In the region east of 140^{o}E, the change signs do not show a spatially characterized pattern. Although the increase of genesis along the east and north of Philippine is not vast area, its magnitude is as large as about 0.8. This value corresponds to a 80% increase from the climatology. Many of the tropical cyclones originated from the Philippine Sea move into the East China Sea and further Korea and Japan, thus parts of the increase of tropical cyclone passage over the East China Sea and Japan may be explained.

The present results indicate that tropical cyclone activities are enhanced (decreased) over the East China Sea and Japan for austral winter in the high (low) AAO periods. Parts of these changes result from those in tropical cyclone genesis over the regions along the east and north of Philippine. However, all results are obtained based on the composite analysis between the high AAO periods and the low AAO periods. The high and low AAO periods are alternative even in the same year (Table 1). Interestingly, as seen in Table 1, there are three years for the high AAO and the low AAO, respectively, that have consecutive months for the whole austral winter. Using the 3 years data sets, the same calculations of Figs. 2b and 3b are performed (figure not shown). Overall, the spatial distribution of the new calculations is comparable to the composite analysis in Figs. 2b and 3b. This consistency gives another support for a coherent connection between AAO and tropical cyclone activity in East Asia.

Although not the main scope of the present study, the influence of El Nino/Southern Oscillation (ENSO) on the tropical cyclone activity in the northwestern Pacific is briefly documented in the rest of this section. In association with the changes in sea surface temperature in the central and eastern tropical Pacific, large-scale circulations, e.g., the Walker Circulation, local Hadley Circulation, and East Asian jet stream, would be modified. In particular, it is well known that the Walker Circulation shifts to east during El Nino episodes [Chan 1985, Wu and Lau 1992]. Also, responded to the changes in the large-scale circulations, focal factors such as vertical wind shear and thermodynamic instability that influence tropical cyclone activity may be changed.

Figure 4 shows the difference in passage number (4a) and genesis number (4b) of tropical cyclones between seven El Nino years and seven La Nina years (see Table 1 for detail information of those years). The difference of the passage number (El Nino minus La Nina) denotes that the number of tropical cyclone occurrence increases up to 2.5 in the east half (east of 135^{o}E) as seen in Fig. 4a. Such large changes correspond to 100% increase from the climatology in the maxim region (Fig. 4b versus Fig. 2a). While the passage number decreases in south of Korea and Japan and increases in the South China Sea, their significance is not strong.

Most of changes in the passage number associated with ENSO can be explained by the eastward shift of genesis location (Fig. 4b). The relation between ENSO and genesis location is examined by many studies [Lander, 1994; Chen *et al*., 1998; Chan, 2000; Chia and Ropelewski, 2002; Wang and Chan, 2002]. Wang and Chan [2002] demonstrated that low-level shear vorticity is generated in the southeast quadrant of the northwestern Pacific during El Nino and it leads to the enhanced tropical cyclone genesis. On the other hand, upper-level convergence induced by the deepening of the East Asian trough and strengthening of the subtropical northwestern Pacific high suppressed tropical cyclone generation over the northwest quadrant at the same time.

By comparing AAO and ENSO for the passage number (Fig. 2b versus Fig. 4a) and the genesis number (Fig. 3b versus Fig. 4b) of tropical cyclones, it is found that their magnitudes are comparable. Particularly, while the impact of ENSO on the passage number over the East China Sea and East Asia is at best moderate, that of AAO is noteworthy. However, the response areas are much larger in the ENSO because it influences global climate.

4. DYNAMICAL EXPLANATION AND SUMMARY

As discussed in above section, the variations of tropical cyclone activity connected with the AAO over the East China Sea and Japan are partially explained by corresponding changes in the genesis locations of tropical cyclone. However, although there is a considerable increase of the genesis number along the east and north of Philippine, its spatial extension is limited. Therefore, it is suggested that the relation AAO-tropical cyclone activity in the East China Sea and Japan may be understood by changes in large-scale circulation over the region. Hines and Bromwich [2002] presented atmospheric teleconnection between the SH and the NH, particularly western mid-latitude Pacific areas in both hemispheres, for the month of August. They explained that the teleconnection arises from the result of tropical convection on the intraseasonal time scale. Corresponding to a development of tropical convection in the equatorial western Pacific, two anomalous anticyclones are built up in the subtropical western Pacific in the NH and near southeastern Australia in the SH.

Figure 5 shows the difference of moisture flux at 850 hPa and outgoing longwave radiation (OLR) between high AAO years and low AAO years. The OLR data is retrieved from the series of NOAA satellites and is available since June 1974 with a missing period March-December 1978. Details of the OLR data can be found in the NOAA web site http://www.nesdis.noaa.gov. The difference map shown in the figure is calculated based on accessible data sets only. As seen in Fig. 5, OLR decreases (convection activity increases) in vast areas, along the equator, East Asia and Australia, and surrounding oceans. In particular, over East Asia OLR decrease is pronounced and may be linked to the increase of tropical cyclone activity. Arrows indicate the 850 hPa moisture flux in forms of direction and magnitude. The moisture flux difference clearly indicates two anomalous anticyclonic circulations in the SH and NH mid-latitudes: a huge anticyclone in south of Australia and a relatively small anticyclone in East China Sea. Overall, these changes are similar to the atmospheric responses in both mid-latitudes to tropical convection shown in Hines and Bromwich [2002] (see their Fig. 6d). In association with the formation of anticyclonic anomaly in the SH, the trade wind becomes stronger in the SH subtropics and convection activity increases along equatorial region. The increased convection activity is represented by the decreased OLR.

The present study also examines the differences of low-level vorticity and vertical wind shear between 200 hPa and 850 hPa for high AAO years and low AAO years (figures not shown). Consistent with the increase of tropical convection, the 850 hPa vorticity increases and the vertical wind shear decreases during the high AAO years.

In a summary, the present study examines the influence of AAO on tropical cyclone activity in the northwestern Pacific. For the high AAO years, a huge anticyclonic circulation is developed in the SH mid-latitude (south of Australia) and leads to a stronger trade winds in the SH subtropics and convection activity increases along equatorial region. In relation with increased convection activity, anomalous anticyclonic circulation is built up in the northwestern Pacific. This leads the tropical cyclone tracks more frequent over the East China Sea and Japan.

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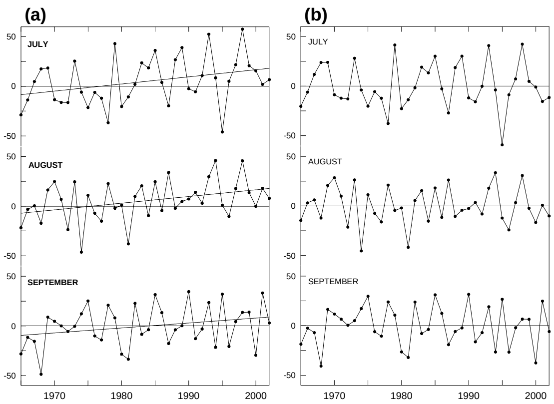

Fig. 1. Time series of leading EOF of monthly sea level pressure over the Southern Hemisphere (a) and de-trended time series by subtracting the trend (b) for the period 1965-2002. The trends of the time series are shown in (a). The units are arbitrary.

Table 1. List of high AAO, low AAO, El Nino, and La Nina periods for austral winter (July, August, September) for the period 1965-2002. Firstly, El Nino (La Nina) periods are chosen when Nino 3.4 sea surface temperature is larger (smaller) than +0.5 (-0.5)°C. Secondly, high (low) AAO periods are selected when the AAO index is ranked within the eight highest (lowest) value each month for the rest years.

	July	August	September
El Nino	1965, 1972, 1982, 1987, 1991, 1997, 2002		
La Nina	1970, 1971, 1973, 1975, 1988, 1998, 1999		
High AAO	1968, 1979, 1983, 1984, 1989	1966, 1967, 1978, 1983, 1994	1974, 1978, 1990, 1995, 2001
	1969, 1985, 1993		
Low AAO	1978, 1980, 1990, 1995, 2001	1968, 1974, 1984, 1995, 2000	1968, 1980, 1983, 1994, 2000
	1977, 1981, 1996		

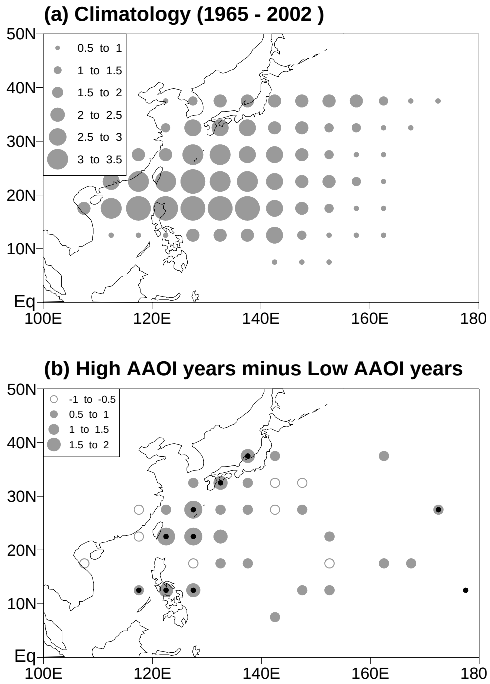

Fig. 2. Climatological distribution of tropical cyclone passage number (a) and difference between high AAO periods and low AAO periods in each $5^{o}\times5^{o}$ longitude-latitude grid area (b). See Table 1 for detail information of high and low AAO periods. Mark • indicates that the differences are significant at the 95% confidence level.

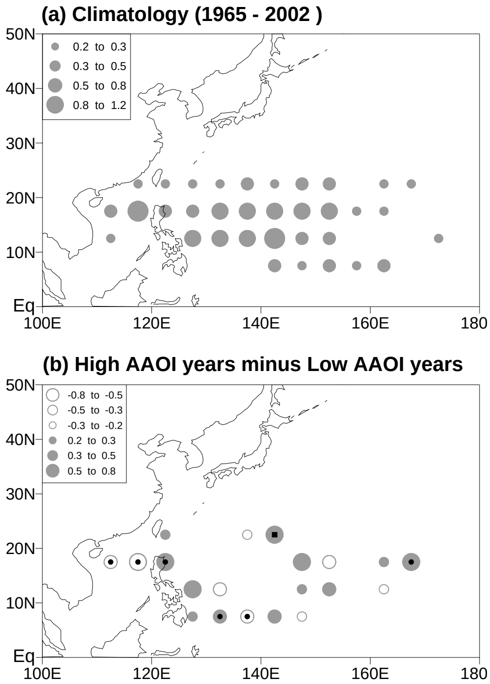

Fig. 3. Same as in Fig. 2 except for tropical cyclone genesis.

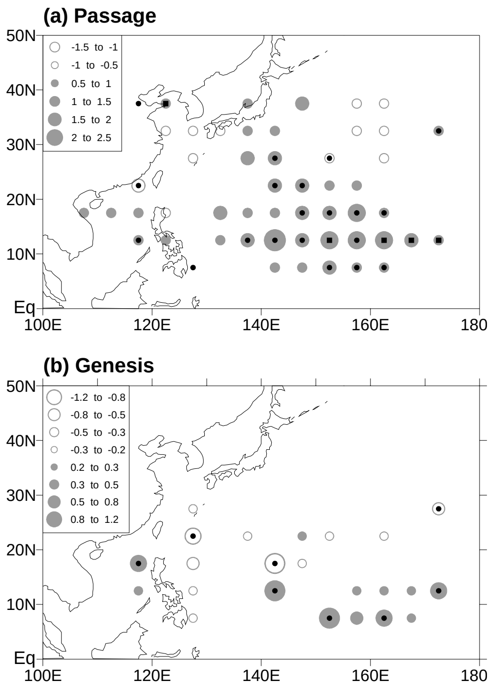

Fig. 4. Same as in Fig. 2 except for El Nino and La Nina years.

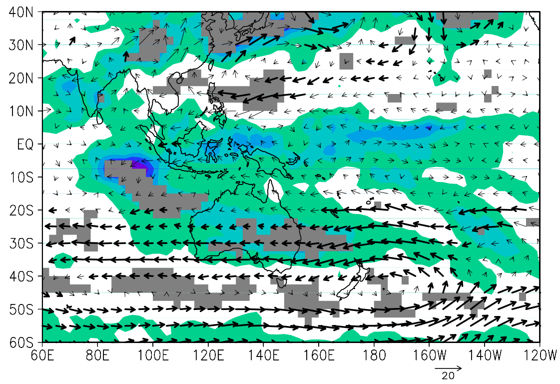

Fig. 5. Composite of moisture flux between high AAO years and low AAO years at 850 hPa. Decreased OLR is represented by shading.
gray shaded (95%), Moisture flux: thick arrow (95%)
OLR unit: W/m^2, Moisture flux: kg/kg*m/s * 10^{-3}