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Arctic Oscillation signals in the East Asian summer monsoon

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Abstract. The present study examines the relationship between the Arctic Oscillation (AO) and the East Asian summer monsoon. Two rainfall data sets are used. One is obtained from ten stations along the Yangtze River to the southern Japan, and the other from gridded global land rainfall data for the period 1900–1998. All data are high-pass filtered before analyzing to highlight the interannual variability. Results show that the AO significantly influences on year-to-year variations in the East Asian summer monsoon rainfall. When AO leads by one month, the correlation between May-July AO and summer total rainfall is −0.44. When AO leads by two months, correlation becomes −0.32. Of all monthly, May AO shows the strongest connection to the summer monsoon rainfall. Correlation coefficient between them is −0.45. The large-scale atmospheric circulation patterns in East Asia in association with the AO are also evident. A positive phase of the AO in late spring is found to lead to a northward shift in the summertime upper tropospheric jet stream over East Asia. This northward shift of the jet stream is closely related to anomalous sinking motion in 20°–40°N and rising motion in surrounding regions. These changes give rise to a drier condition over the region extending from the Yangtze River valley to the southern Japan and a wetter condition in the southern China. Possible mechanisms connecting the late spring AO and summer monsoon rainfall are suggested.

1. Introduction

In recent years, there has been great interest in the Arctic Oscillation (AO), which was introduced as an annular mode of atmospheric circulation by *Thompson and Wallace* [1998]. This primary mode of internal dynamics in the atmosphere predominates the extratropical Northern Hemisphere circulation from the surface to the lower stratosphere and shows an equivalent barotropic structure during cold seasons (November-April) [*Thompson and Wallace* 2000]. Fluctuations in the AO create a seesaw pattern in which atmospheric pressure and mass in northern polar and mid-latitudes alternate between positive and negative phase [*Wallace* 2000]. Many studies have indicated that the AO significantly influences on mid- to high latitude climate in Northern Hemisphere [*Thompson et al.* 2000, *Kerr* 1999]. For example, the AO-related climate variations involve surface air temperature [*Thompson et al.* 2000, *Rigor et al.* 2000], precipitation [*Thompson et al.* 2000, *Cavazos* 2000], moisture budget [*Boer et al.* 2001], sea-ice over north polar and subpolar regions [*Wang and Ikeda* 2000], lower tropospheric circulation including the East Asian winter monsoon, Aleutian Low, and Siberian High [*Gong et al.* 2001, *Overland et al.* 1999], and extreme climates such as cold waves and blocking activities [*Thompson and Wallace* 2001].

However, most of the previous studies have emphasized the simultaneous climate influence in cold seasons when the AO is most active. It should be noted that the AO also explains a large portion of the total variance in the atmospheric circulation during warm seasons (May–October) [*Thompson and Wallace* 2000]. In addition, many climate system components significantly impacted by winter AO show long memory and may feed back to atmosphere with time lags. Thus, the arisen question is whether the AO can exert influence on warm season (say, summer) climate. Based on the long-term precipitation record observed in China and surrounding regions, here we present evidence showing that there is a significant connection between late spring AO and the East Asian summer precipitation on the interannual time scale for the last one hundred years (1899–1999). In section 2, we describe the precipitation data, AO index, and atmospheric fields. In section 3, the long-term variations of the summertime rainfall in East Asia and the May AO are examined. Further effects of AO on the East Asian summer monsoon circulation are investigated in section 4. The paper is concluded in section 5 with the discussion.

2. Data preparation

AO indices are determined by time series of the leading principal component of monthly mean sea level pressure in Northern Hemisphere (poleward of 20°N) [*Thompson and Wallace* 1998]. There are two kinds of AO index. One has a longer time series for the period 1899–1997, which is derived from observed sea level pressure. The other is available for the period 1958–1999, which is calculated using reanalyzed sea level pressure of the National Centers for Environmental Prediction/the National Center

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for Atmospheric Research (NCEP/NCAR). Here we use the combined series for period 1899–1999 (prior to 1957 based on the observed data and thereafter on the NCEP/NCAR reanalysis data). The data are prepared and provided by David W. J. Thompson and available via internet at http://horizon.atmos.colostate.edu/ao.

Rainfall data at ten stations are selected to investigate the relationship between the AO index and the East Asian summer monsoon precipitation. These stations are located in central China and southern Japan (see Table 1). Time series of seasonal rainfall at the six Chinese stations are available since 1880 [*Wang et al.* 2000]. More information about these data can also be found in *Qian and Zhu* [2001]. Monthly rainfall data at the four Japanese stations are taken from the Global Historical Climatology Network [*Vose et al.* 1992]. The rainfall data at the ten stations represent the *Meiyu* rainfall features faithfully due to the high consistent variations of summer rainfall over the region as revealed in the empirical orthogonal function analysis [see *Nitta and Hu* 1996]. A historical monthly precipitation dataset for global land areas from 1900 to 1998 is also used here, which is gridded at a 5° latitude by 5° longitude resolution [*Hulme* 1992].

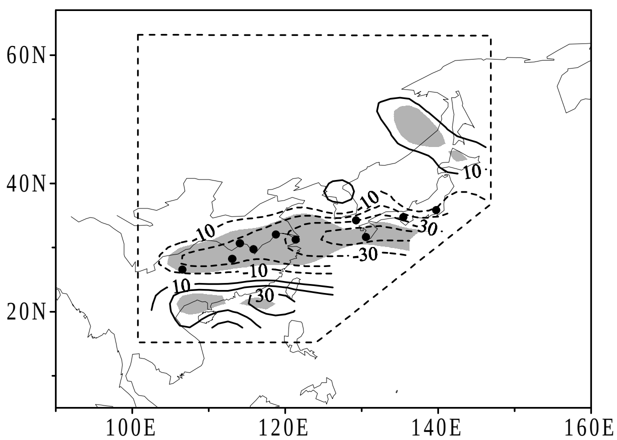

Figure 1. Changes in summer precipitation (mm) corresponding to a one standard deviation of the May AO index for the period 1900-1998. Regions above 95% confidence level are shaded. Gridded global land precipitation data sets [*Hulme* 1992] are used. Ten stations as listed in Table 1 are shown as filled circles. Contour interval is 10 mm. Zero contours are omitted.

The wind velocity and geopotential height data during 1958–1999 are taken from NCEP/NCAR reanalysis [*Kalnay et al.* 1996].

Since there is strong interdecadal variability in the summer monsoon rainfall and circulation due to the tropical sea surface temperature anomalies [e.g., *Hu* 1997, *Weng et al.* 1999], a high-pass filter is necessary to remove the possible influence of these low-frequency variations and get a robust signal at interannual time scale. Thus, a 9-point Gaussian digital filter with weights of 0.01, 0.05, 0.12, 0.20, 0.24, 0.20, 0.12, 0.05 and 0.01 is applied to all data sets. This filter removes variations longer than 10 years and keeps interannual variations only. In the present study all time series are filtered and shown as the departures from the 9-point-weighted moving means. The first and last 4 years are omitted after filtering to avoid the edge effect.

3. Summer rainfall

Summer (June, July and August) rainfall is one of the most important indicators of the East Asian summer monsoon. It is widely recognized that the main rainfall band, known as *Meiyu*, is most prominent from the Yangtze River valley to the southern Japan resulting in the east-west directed pattern. Consequently, the long-term mean of summer precipitation shows that 400–500 mm isohyets extend along the Yangtze River, across southern Japan, to the western North Pacific at about 160°E. Over this region, summer rainfall accounts for 40–50% of the annual total precipitation amount [*Lau et al.* 1988, *Tao and Chen* 1987, *Ding* 1992]. Thus, the strong year-to-year variation of the summer monsoon is of great interest since it is usually responsible for the severe floods and droughts over the regions.

Our analysis based on the gridded precipitation data sets find that the interannual variability in summer rainfall shows

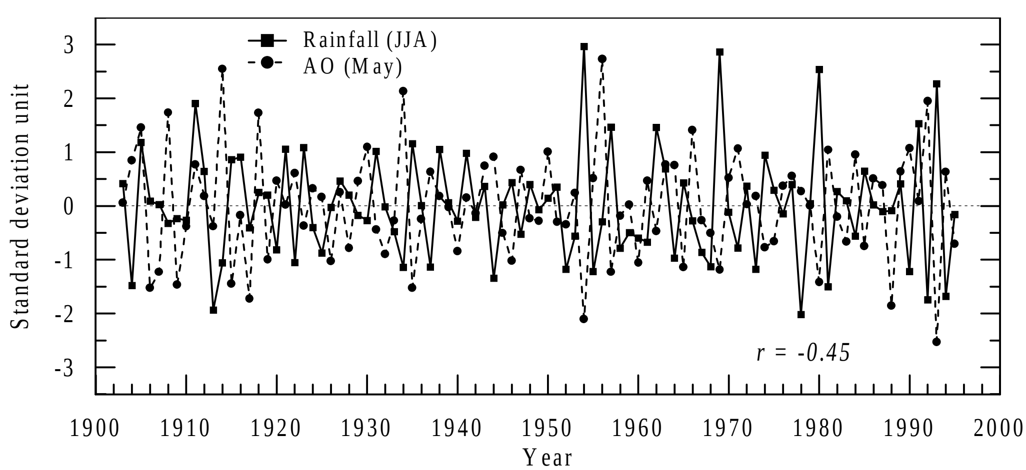

Figure 2. Time-series of May AO index and summer monsoon rainfall over Yangtze River valley and southern Japan. Shown as the results from a high-pass filter, through which the variations longer than 10 years are removed. Rainfall is the mean time-series averaged over the ten stations as listed in Table 1.

Table 1. Correlation coefficients between May AO index and ten stations' summer rainfall for the period 1899–1999. The 95% and 99% confidence levels are ±0.20 and ±0.26, respectively. Correlations shown in parentheses are based on the unfiltered data. Shown in the last column are the rainfall changes (in mm and percent to the summer total) corresponding to a one standard deviation of the AO index. The AO index is normalized before regression.

Station	Longitude	Latitude	Elevation	Correlation	Rainfall change
Shanghai	121.4°E	31.2°N	5m	−0.27(−0.25)	−38.5mm(−8.2%)
Nanjing	118.8°E	32.0°N	9m	−0.24(−0.14)	−77.4mm(−14.5%)
Jiujiang	115.9°E	29.7°N	32m	−0.27(−0.20)	−39.0mm(−7.9%)
Wuhan	114.1°E	30.6°N	23m	−0.42(−0.29)	−36.0mm(−7.8%)
Guiyang	106.6°E	26.5°N	1074m	−0.21(−0.12)	−29.7mm(−6.7%)
Changsha	113.1°E	28.2°N	45m	−0.23(−0.19)	−24.5mm (−4.6%)
Tokyo	139.8°E	35.8°N	36m	−0.20(−0.12)	−30.5mm(−6.4%)
Osaka	135.5°E	34.7°N	50m	−0.37(−0.32)	−52.9mm(−11.2%)
Kagoshima	130.6°E	31.6°N	5m	−0.35(−0.24)	−60.9mm(−6.7%)
Izuhara	129.3°E	34.2°N	22m	−0.21(−0.19)	−93.3mm(−9.5%)
Mean rainfall of 10 stations				−0.45(−0.34)	−48.3mm (−8.4%)

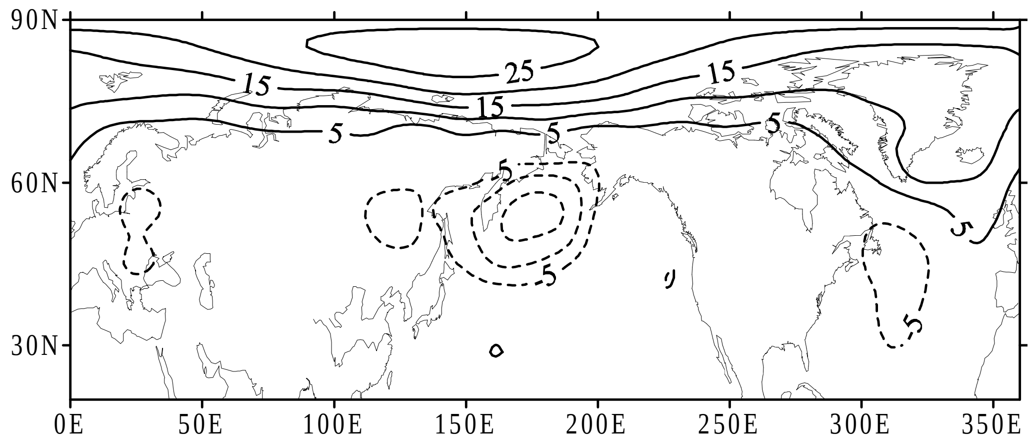

Figure 3. Regression coefficients of 1000hPa height in May upon the normalized summer rainfall series of ten stations' mean. Unit is gpm per one standard deviation of rainfall. Both rainfall and heights series are high-pass filtered before analyzing.

an evident connection to the late spring AO index. In particular, the May AO shows the most significant impact on the subsequent summer rainfall. Figure 1 exhibits the geographical distribution of rainfall changes associated with the May AO, shown as the regression coefficients upon the AO index. Here the AO index is normalized before regressing. As shown in the figure, the AO-related summer monsoon rainfall changes show a well-defined large-scale pattern with a strong east-west direction. With the one standard deviation higher AO index, there are about 20–40 mm decrease in precipitation over the region extending from the Yangtze River valley to the southern Japan and 10–30 mm increase over the southern China.

Rainfall at each of ten stations as well as their mean is also analyzed for comparison with the gridded data sets. As shown in Table 1, correlation coefficients vary from about −0.20 to −0.42. The correspdonding precipitation changes are on average −48.3 mm per one standard deviation of the AO index, which are a little larger than the gridded data due to the higer variance of the individual station records. A comparison of correlation coefficients of unfilterd and filtered data also confirms that the strong relationship is attributable mostly to the interannual covariance (Table 1).

As the individual station's rainfall is usually influenced by many local environmental factors and thus the relation signal between AO and precipitation could be distorted to some degree. This shortcoming will be improved if the regional mean series are used. In fact, the ten stations' mean rainfall shows a much stronger connection to the AO (see Fig. 2). Some anomalous rainfall events, such as the strong positive anomalies in years of 1954, 1969, 1980, and 1993 are outstanding. Impressively, theses events are well correlated with strong negative-phase of May AO. This kind of out-of-phase relationship between AO and rainfall is most predominant in late five decades. For the whole period (93 years), the two timeseries are correlated at the coefficient of −0.45. Given the fact that all data are high-pass filtered, the number of degrees of freedom should be not much less than 90. Autocorrelation of AO also confirms that. Thus, the above correlation is highly significant at the 99% confidence level.

We selected these ten stations based on figure 1, as anomaly center is located over the Yangtze River to southern Japan, over there only six stations with data available for period 1880–1999 in eastern China. In southern Japan there are some long-term observations. In fact, some other stations also show significant correlation coefficient (r) for the same period; for example, Nagasaki (129.9°E, 32.7°N), $r = -0.30$ and -0.21, Miyazaki (131.4°E, 31.9°N), $r = -0.25$ and -0.15, and Shionomisaki (135.8°E, 33.5°N, data available for 1913–1999), $r = -0.31$ and -0.20, for filtered and unfiltered series, respectively. In this study we pick out four evenly distributed stations in order to appropriately cover the *Meiyu* region. In addition, 33 stations

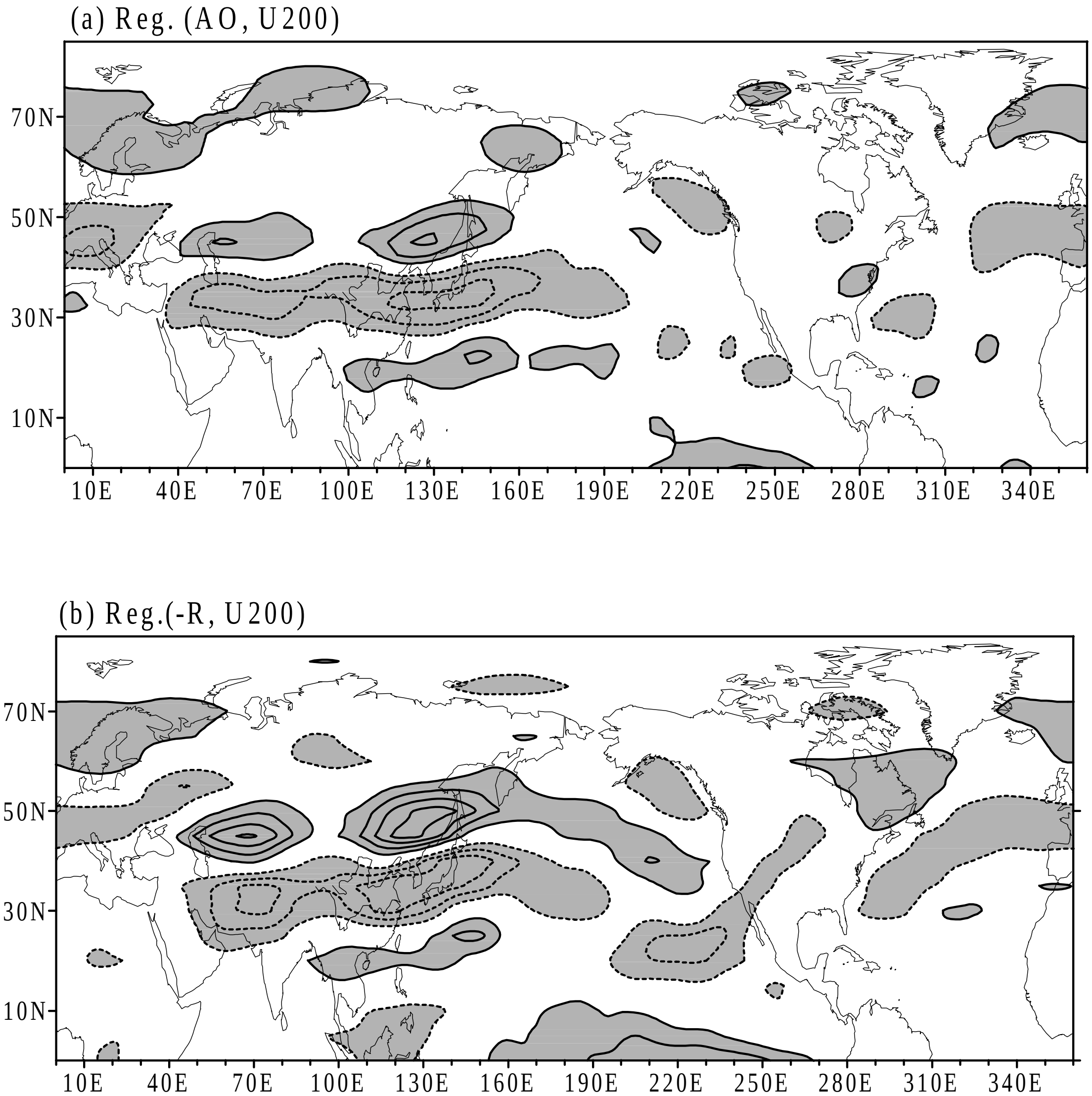

Figure 4. Changes in summer zonal wind (m s^{-1}) at 200 hPa associated with a one standard deviation anomaly in the May AO index (a) and in the simultaneous ten-station-mean rainfall for summer (b) for the period 1958–1999. To facilitate comparison rainfall records are multiplied by -1. The contour interval is 0.5 m s^{-1} per standard deviation of May AO and summer rainfall, respectively. Zero contours are omitted. Regions below -0.5 m s^{-1} and above $+0.5$ m s^{-1} are shaded.

[*Wang et al.* 2000] scattered over the eastern China with long-term record (1800–1999) are examined. The results of regression analysis display the similar pattern as shown in Fig.1 (figure not shown).

We also perform the analysis in reverse, regressing the May 1000 hPa heights upon the summer rainfall time series. As seen in Fig. 3, over entire northern pole and vicinities show positive signs and negative values appear in North Atlantic and North Pacific. The pattern is consistent with the negative-phase-AO. That also provides a nice confirmation of the above results.

4. East Asian summer monsoon circulation

There are at least two major large-scale circulation systems that dominate the East Asian summer monsoon. One is the East Asian westerly jet stream and the other is the western Pacific subtropical high. Previous studies indicated that the north-south displacement of the jet plays an important role in determining the monsoon onset and retreat, therefore the monsoon rainfall anomaly [*Liang and Wang* 1998]. Furthermore, the location of the jet stream is closely related with the fronts that produce an extensive summer monsoon rainfall (*Meiyu*), and thus can be used as a representative circulation for the summer monsoon.

To investigate the associated features in atmospheric circulation with AO, the high-pass filtered summer mean zonal winds at 200 hPa are regressed upon the late spring (May) AO index and spring (March-May) AO index, respectively. They show similar results; but the late spring AO exhibits stronger signals. Covariance of summer zonal wind with the late spring AO index shows a north-south movement of the middle latitude zonal jet at many latitudes in the Northern Hemisphere (Fig. 4a). The covariance over East Asia is more remarkable than other regions. The evident west-east

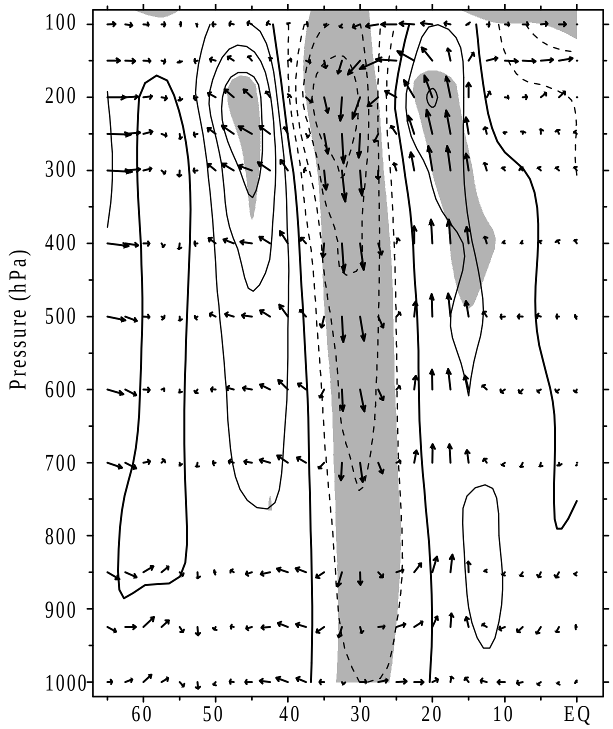

Figure 5. Cross section of the zonal mean zonal wind (u), meridional wind (v) and vertical motion (ω) over East Asia (110°E–150°E) regressed onto the May AO index. The u is shown as the contours with interval of 0.3 m s^{-1}. Zero lines are bold and easterly are shown in dashed lines. Regions above 95% confidence level are shaded. The covariance of v and ω are shown as vectors. Values are m s^{-1} (for u and v) and hPa s $^{-1}$ (for ω), corresponding to a one standard deviation anomaly in the May AO index. Before regression the AO index are normalized. The values of largest vectors are 0.47 m s^{-3} for v and 4.3×10^{-3} hPa s^{-1} for ω.

oriented bands over East Asia are of particular interest since this statistically significant pattern is the strongest anomaly center in the entire Northern Hemisphere. With a positive phase of the AO, stronger westerly wind appears in regions of 40°–50°N and 15°–25°N. Latitudes between these two westerly zones are dominated by strong easterlies. This feature indicates that the fluctuation of AO in late spring is associated with a strong meridionally oriented trough-ridge system spanning the coastal region of East Asia and western North Pacific in summer. This also implies that the anomalous East Asian jet associated with the AO undergoes meridional displacement. The climatological location of the East Asian jet core is around 40°N in summer. For the high positive phase AO years, the jet is displaced poleward and an anomalous westerly center appears at about 45°N, five degrees northward of its normal position. Compared to the late spring AO, the spring AO index shows a little weaker correlation with the zonal wind in mid-latitudes over East Asia (figure not shown).

Figure 4b shows the zonal wind changes that are associated with the summer rainfall fluctuation (ten stations' mean series) on the interannual time scale. Obviously, there is a remarkable similarity between the two figures (Figs. 4a versus 4b). Both show similar patterns and indicate a consistent northward shift of the East Asian jet stream. That suggests the importance of the upper tropospheric zonal flow in conncting the late spring AO and the summer rainfall.

In the latitude-height sections, the East Asian summer monsoon is characterized by the multi-cellular meridional circulation over the East Asian sector, extending from the tropics to the mid-latitudes. This multi-cellular structure is referred to as the dominant meridional characteristics of the East Asian summer monsoon. *Lau et al.* [2000] defined the strength of the East Asian summer monsoon as the difference in zonal wind at 200 hPa between average value over the domain of 40°–50°N and 110°–150°E and the domain of 25°–35°N and 110°–150°E. They indicated that the East Asian jet plays an essential role in the dynamical aspect of the summer monsoon. The aforementioned pattern associated with the positive phase of AO is in good agreement with the strong East Asian summer monsoon years (cf. *Lau et al.*[2000]'s Fig.4b).

The anomalous zonal mean zonal wind, meridional and vertical wind in the summer over the domain of 110°–150°E

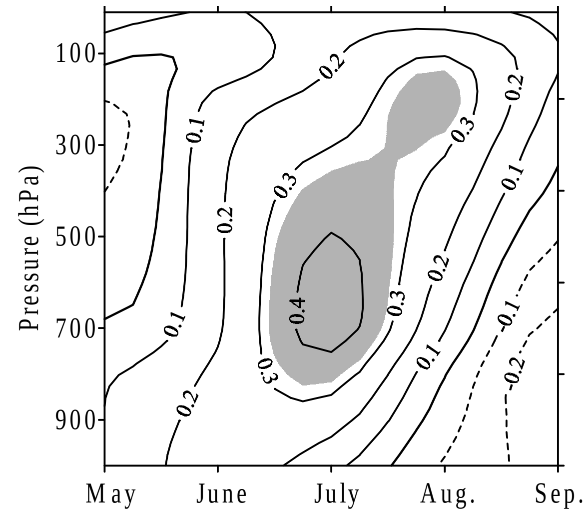

Figure 6. Cross correlation between the May AO index and the regional averaged geopotential height over the domain 100°E–160°E and 30°N–40°N. Values exceeding the 95% confidence level are shaded..

Table 2. Correlation coefficients between AO index and summer rainfall for the period 1899–1999. Each month from January to August is separately correlated with summer rainfall to highlight the importance of each single month's AO. The correlation for the three-month mean AO is also calculated, with different leading times from 0 (JJA) to 5 (JFM) months.

AO	Cor (AO, JJA rainfall)
January	−0.04
February	−0.01
March	−0.10
April	0.06
May	−0.45
June	−0.24
July	−0.08
August	−0.13
JFM	−0.07
FMA	−0.04
MAM	−0.21
AMJ	−0.32
MJJ	−0.44
JJA	−0.25

are regressed onto the May AO. Results are displayed in Fig. 5. Compared with *Lau et al.*[2000]'s Fig.8, the altitude-latitude monsoon structure is evidently similar. Three cells are clearly described. Anomalous easterly with the concurrently strong descending motion are predominant around 30°N. The strong westerly to the north and the relatively weaker one to the south are also significant in the upper troposphere, whereas the contours extend to the lower troposphere. The wind anomaly structure generally shows an equivalent barotropic oscillation with the largest covariance at about 200 hPa. Clearly, the north-south displacement of the zonal wind appears at almost all pressure levels in the troposphere and is more evident in the upper troposphere above 500 hPa. These features in atmospheric circulation are consistent well with that in precipitation. Thus, furthermore confirm the existence of AO-monsoon rainfall connection.

5. Discussion

The mechanisms that are responsible for the AO-related monsoon variability are still an open question. Some recent results show that the AO signal can propagate downward from stratosphere to troposphere. However, the propagation usually appears in cold seasons when two layers are coupled [*Baldwin and Dunkerton* 2001]. Anomalies in lower boundary conditions in the mid- and high latitudes also would impact the monsoon system. *Lau et al.* [2000] indicated that the variability of the summer time East Asian jet is only weakly related with the tropical sea surface temperature anomalies. On the other hand, previous results show that there is a significant influence of Asian continental land surface condition on the East Asian summer monsoon [e.g. *Yang and Lau* 1998]. Preliminary result of correlation coefficient between the May AO and regional averaged geopotential height over the domain 110°E–150°E, 30°N–40°N in the troposphere shows an upward propagation with time (Fig. 6). This upward propagation of AO signal from the lower troposphere may be related to surface influence. Given the well-known strong influence of AO on the surface climate in mid- and high latitudes in winter and spring, there are possibilities that the AO-related boundary anomalies would in turn impact the atmospheric circulation and give rise to the anomalous East Asian summer monsoon. In addition, there might exist weak or strong coupling between AO, East Asian jet, Eurasia surface and adjacent North Pacific sea surface temperature anomalies, and some other related atmospheric circulation systems such as the Okhotsk high. For example, *Liang et al.* [1995] addressed that these later processes are closely linked. However, it is hard to unravel this complicated problem and beyond the object of the present study.

The internal dynamical process in the troposphere may be one very important reason for the relation. The AO is weak in late spring compared to winter, but it is not as weak as indiscernible. It is still the leading mode in inactive seasons. Percentages of variance in monthly mean sea level pressure explained by the AO modes for active and inactive seasons are 21% and 16%, respectively [*Thompson and Wallace* 2000]. Correlation analysis display that winter AO shows no influence on summer monsoon rainfall. The summer AO shows a considerable correlation to summer rainfall in the concerned region ($r = -0.25$ for period 1899–1999). However, compared to the simultaneous correlation, the AO-leading connection is much stronger (see Table 2). When AO leads by one month, the correlation between May-July AO and summer rainfall is -0.44. When AO leads by two months, correlation is -0.32. By three months, correlation down to -0.21. Obviously, the late spring to early summer AO is most important. The large-scale atmospheric circulation changes in association with the AO also show the consistent patterns in East Asia. Thus, dynamic process, including the persistency (between May and June there is significant correlation in AO indices with a value of 0.30), might also play considerable role.

It must be mentioned that the involved AO-monsoon rainfall mechanisms would be non-linear. Unfortunately, the linear correlation analysis might be unable to tell anything about that. Clearly, we need more works on the mechanisms for the details. We are investigating aforementioned possible mechanisms using a general circulation model and will analyze the results in a separate paper. Here we primarily address the significant relationship between AO and summer monsoon rainfall and the associated circulation features.

In conclusion, our observations reveal that there is a significant influence of late spring AO on the East Asian summer monsoon circulation and rainfall. This precursory signal will be helpful for us in predicting summertime rainfall over East Asia.

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