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# Short Communication

# Unstable relationship between spring Arctic Oscillation and East Asian summer monsoon

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**ABSTRACT:** The relationship between spring (March to May) Arctic Oscillation (AO) and East Asian summer monsoon (EASM, May to July) on interannual timescale has a remarkable decadal variation in late 1990s, and their correlation coefficient abruptly turns from +0.77 during 1979–1997 to −0.62 during 1998–2007. In the following summer after a spring positive AO phase, the lower-troposphere over East Asia (EA) features a cyclonic anomaly before 1997 but an anticyclonic anomaly after 1997, which results from different simultaneous air–sea features imposed by spring AO and distinctive evolution from spring to summer. In pre-1997, the spring AO-associated signal is mainly memorized and persists over Pacific, because the spring AO-associated wave activity prefers the high-latitude propagation from North Atlantic to Pacific. In contrast, a subtropical wave train from North Atlantic Ocean to Indian Ocean (IO) is evidently enhanced in post-1997 epoch, and accordingly the IO plays a dominant role in memorizing and extending the influence of spring AO on EASM. This subtropical route of spring AO-EASM teleconnection is a new finding. The strengthening of the subtropical wave train in post-1997 epoch could be partly attributed to the strengthening signals of spring AO over North Atlantic Ocean.

KEY WORDS Arctic Oscillation; East Asian summer monsoon; decadal variation; wave train

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## 1. Introduction

East Asian summer monsoon (EASM) prediction is very important for both society and climate science but far from successful yet (e.g. Wang *et al.*, 2013). The winter-to-spring Arctic Oscillation (AO)/North Atlantic Oscillation (NAO) has been found to be one of the most important precursory signals for EASM prediction (e.g. Yang *et al.*, 2004; Sung *et al.*, 2006; Wu *et al.*, 2009). The impact of winter-to-spring AO/NAO on the following summer EASM circulation has been attributed to the persistent anomalies of underlying surface thermal conditions over north polar regions and Eurasian continent [sea ice, sea surface temperature (SST) and surface air temperature] (e.g. Ogi *et al.*, 2004; Shen and Masahide, 2007) and western Pacific (Gong *et al.*, 2011).

Recently, more analysis have found that the spring AO/NAO index had better correlation with EASM than the winter AO/NAO (e.g. Gong *et al.*, 2002; Wu *et al.*, 2009). For example, Wu *et al.* (2009) built up an efficient empirical model to predict year-to-year EASM strength by combining El Niño/South Oscillation (ENSO) and spring NAO index. They proposed that a tripole SST pattern in the North Atlantic induced by spring NAO anomaly served as a bridge to link spring NAO and EASM. Gong *et al.* (2011) further confirmed the close linkage between spring AO and EASM and found that the positive air–sea feedback over the western North Pacific was a key process to maintain the impact of spring AO/NAO on EASM.

The close relationship between spring AO/NAO and EASM has been confidentially reported. However, if their relationship is stable or not has not been well known yet, which is very crucial for the stability of EASM prediction. In the past 30 years, a remarkable decadal change has been noticed around 1990s. Kwon *et al.* (2005) first found that the negative correlation between the intensities of the East Asian and western North Pacific summer monsoon abruptly changed near 1994. Afterwards, the decadal change around 1990s are reported in many variables, including the circulation, water vapour transport and rainfall patterns over the EA (e.g. Ding *et al.*, 2008), the west African summer monsoon (Li *et al.*, 2012), tropical–extratropical teleconnection associated with ENSO (Fogt and Bromwich, 2006), the relationship between tropical cyclone frequency and the SST

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variations in the tropical Pacific (Yeh *et al.*, 2010) and intraseasonal variability over the South China Sea (SCS) (Kajikawa *et al.*, 2009).

Therefore, the question is if the relationship between spring AO/NAO and EASM change around 1990s? If yes, how does the relationship change and why do they change? This study aims to answer these questions.

## 2. Datasets and methodology

The datasets used in this study consist of (1) ERA-interim datasets with a 2.5° spatial resolution and 37 pressure levels in vertical direction from 1979 to 2011 produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Dee *et al.*, 2011), (2) SST of Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST) with a 1° spatial resolution provided by Met Office Hadley Centre from 1870 to 2011 (Rayner *et al.*, 2003) and (3) Global Precipitation Climatology Project monthly precipitation dataset (GPCP) compiled for the period of 1979–2011 by National Ocean and Atmospheric Administration (NOAA) (Adler *et al.*, 2003).

The AO index is the corresponding time coefficients of the first empirical orthogonal function (EOF) of the monthly sea level pressures (SLP) north of 20°N (Thompson and Wallace, 1998). The EASM index was defined by the $U_{850}$ in (5°N–15°N, 90°E–130°E) minus $U_{850}$ in (22.5°N–32.5°N, 110°E–140°E), where $U_{850}$ denotes the mean zonal wind at 850hPa (Wang and Fan, 1999). The spring AO index is the average for March, April and May (MAM), while the summer monsoon is the average for May, June and July (MJJ). We also checked JJA (June, July and August), MJ (May to June), JJ (June to July) and JA (July to August) seasons, and the following-mentioned results are all well presented in these seasons but exhibit most significant in MJJ. Hence, we only demonstrate the results for MJJ in this study.

To confirm what we have found in this study, we made several sensitive analysis through using different reanalysis data (e.g. National Centers for Environmental Prediction-Department of Energy (NCEP-DOE) Reanalysis 2 (Kanamitsu *et al.*, 2002)) and different EASM indices (e.g. Zhang *et al.*, 2003; Wang *et al.*, 2008), and replacing AO by NAO and Northern Hemisphere Annular Mode (NAM) indices. Generally speaking, all the other results (figure ignored) can well exhibit the major finding of this study but less significant than what we show here (Figure 1).

As we only focus on their inter-annual variations, high-pass filter via Butterworth filter (Butterworth, 1930) is applied to the time series of all variables, and only the components with time periods shorter than 8 years remain in the following analysis. In addition, we removed ENSO and Indian Ocean (IO) dipole signals in the variables of interest by means of regression analysis. Then the residuals are regarded as the parts which are statistically independent of ENSO and IO dipole.

## 3. Results

### 3.1. Temporal changes in spring AO and EASM relationship

The year-to-year variation of spring AO as well as the summer East Asian monsoon indices are shown in Figure 1(a). We found that their relationships were almost in phase during the period of 1979–1997 but out of phase between 1998 and 2007. Their correlation coefficients also show a significant difference between the two epochs, being +0.77 before 1997 but −0.62 after 1997. Therefore, the relationship between spring AO and EASM is unstable in the past 30 years, because a negative correlation occurs during the recent 10 years from 1998 to 2007 that is different from several previous studies (e.g. Gong *et al.*, 2011).

To directly show such an abrupt change of their relationship before and after 1997, we first illustrate the circulation anomalies of EASM associated with spring AO through regression analysis. We calculated the regression coefficients of spring AO index with precipitation and 850 hPa wind anomalies in early summer over EA region, respectively for the two epochs: 1980–1997 (called as pre-1997 hereafter) and 1998–2007 (called as post-1997 hereafter) (Figure 1(b) and (c)). The results show large differences between two epochs. In pre-1997 epoch, a low-level cyclonic anomaly with an east–west extension emerges over western Pacific, stretching from SCS to Philippine Sea (PS). This cyclonic anomaly weakens the western Pacific subtropical high (WPSH), which suppresses the rainfall over the low reach of Yangtze River and South Japan but enhances the rainfall over South China, SCS and PS. In contrast, during the period between 1998 and 2007, there is an anomalous anticyclone, over southeastern China and SCS, which represents the westward extension and strengthening of WPSH. Correspondingly, wet anomalies appear over middle reaches of the Yangtze River while drought anomalies occur over the coastal area of southeastern China and western PS. The opposite circulation anomaly of EASM associated with spring AO corresponds to the opposite correlation between spring AO and EASM during the two epochs.

### 3.2. Distinct simultaneous spring AO-associated features over Indo-Pacific region in two epochs

The simultaneous low-level circulation, precipitation and SST anomalies associated with spring AO are shown in Figures 2(a), (b) and 3(a), (b), respectively for the periods of 1979–1997 and 1998–2007. In pre-1997 epoch, the most prominent feature is an anomalous cyclone over North Pacific (centering around 180°E, 30°N) in the lower-troposphere (Figure 2(a)). Accordingly, the significant westerly wind anomalies take place over central tropical north Pacific, north of New Guinea and SCS, and the evident northerly wind anomalies appear over northern SCS and western Pacific. Large positive SST and significant positive rainfall covers the tropical northern central Pacific, while pronounced negative SST locates over northwestern Pacific (Figure 2(a) and (b)).

 

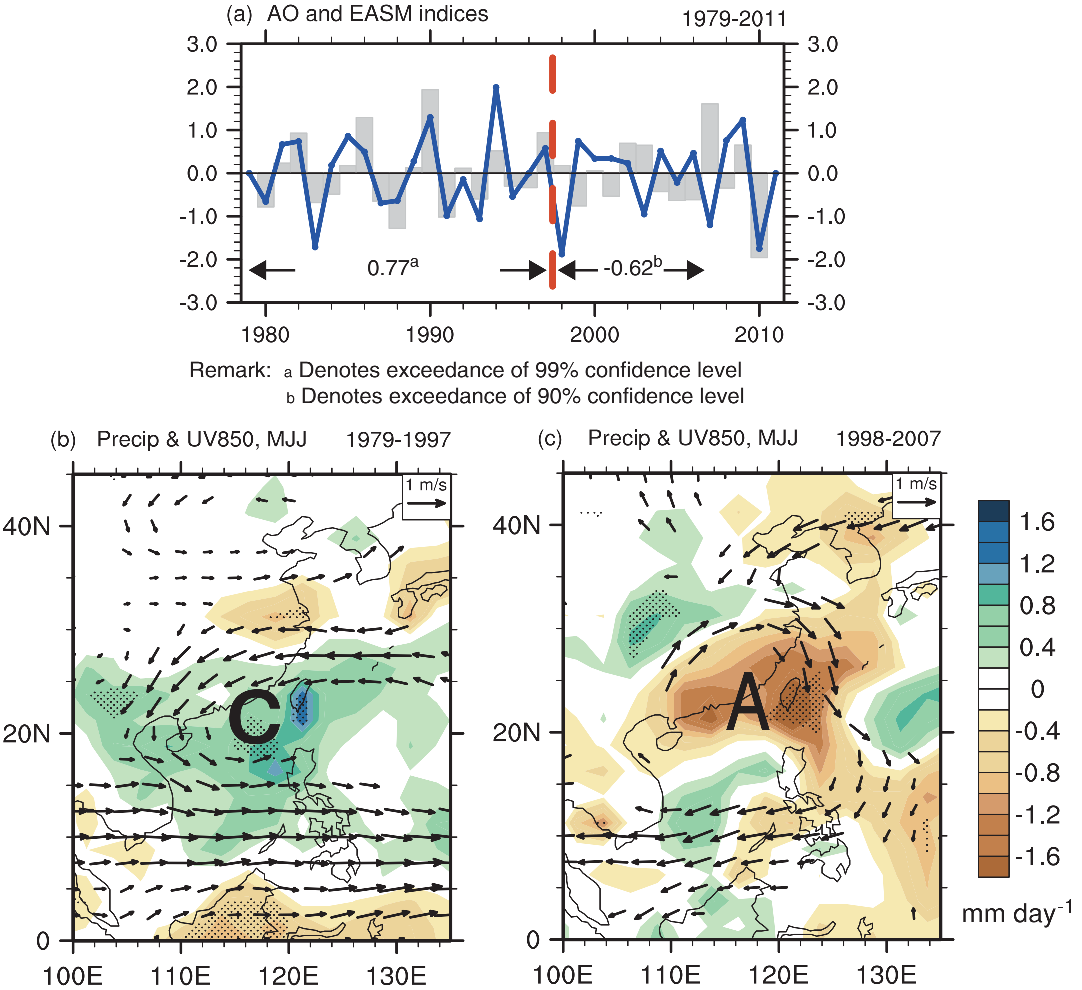


Figure 1. (a) Time series of spring AO (shaded bar) and EASM indices (blue lines) from 1979 to 2011. Regressed anomalies of 850 hPa winds (vectors: m/s) and precipitation (colour shadings: mm/day) in summer against spring AO index during the periods of (b) 1979–1997 and (c) 1998–2007, after removing ENSO and Indian Ocean dipole (IOD) signals. The areas exceeding 90% confidence level are dotted and only the wind vectors that are statistically significant above 90% *t*-test confidence level are plotted.

During post-1997 epoch, there is also a cyclonic anomaly over Pacific but with the southwestward relocation and reduced intensity in contrast with pre-1997 epoch (Figure 3(a)). The westerly wind anomalies are displaced over tropical western Pacific spanning from 130°E to 160°E and the northerly wind anomalies prevails over northern PS. Below the westerly wind anomalies over tropical western Pacific, SST anomalies are positive while the precipitation anomalies are negative (Figure 3(a) and (b)). Meanwhile, the cooling SSTs over western Pacific migrate southwestward from northern Pacific before 1997 to northern PS after 1997 due to the relocation of northerly wind anomalies.

The most notable difference occurs over IO comparing two epochs. In pre-1997 epoch, the negative SST anomalies almost cover the whole tropical IO basin (Figure 2(a)). But the circulation does not show much significant signal over northern IO. However, remarkable easterly wind anomalies appear over tropical western IO between equator and 10°N after 1997, accompanied with a dipole of two anticyclonic anomalies, respectively located to the north and the south (Figure 3(a)). The positive SST anomalies appear over Arabian Sea (AS) and tropical southwestern IO, while the precipitation exhibits negative anomalies over AS and positive anomalies over tropical southwestern IO (Figure 3(b)).

### 3.3. Distinct evolving spring AO-associated features through summer over Indo-Pacific region in two epochs

Figures 2 and 3 shows the results of low-level circulation, precipitation and SST anomalies regressed with spring AO from spring to summer during the two periods. In pre-1997 epoch, the most significant anomaly, imposed by simultaneous AO, is a giant cyclonic anomaly over Pacific in spring (Figure 2(a)). We notice that the cyclonic anomaly persists from spring to summer, and its position gradually displaces westward (Figure 2). Correspondingly, the westerly wind anomalies persistently moves westward and becomes prevalent over Bay of Bengal, southern SCS and tropical western Pacific in MJJ, spanning from 90°E to 180°E along 10°N; both the SST warming over tropical central Pacific and the SST cooling over northern central Pacific are sustained from spring to summer.

 

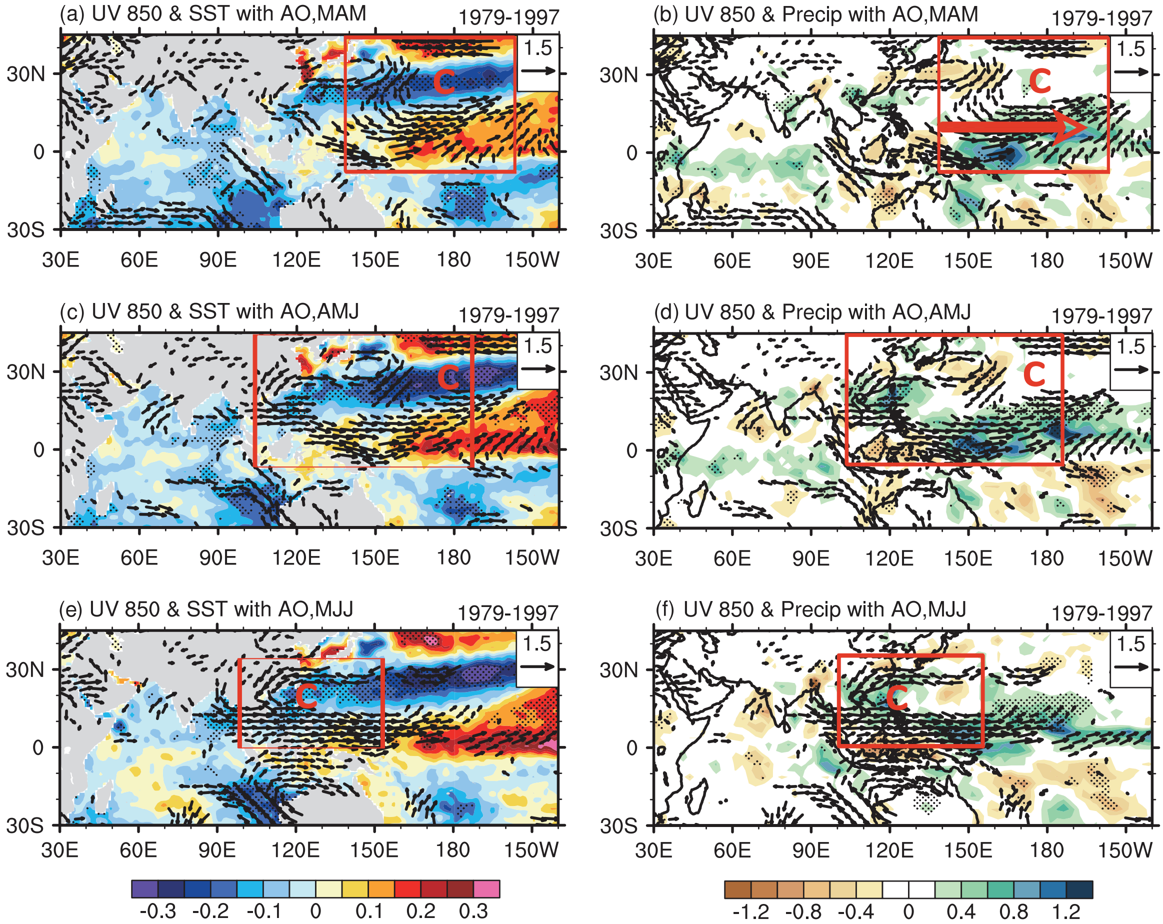


Figure 2. Seasonal evolving anomalies of 850 hPa winds (vectors: m/s), ((a), (c), (e)) SST (colour shadings: degree) and ((b), (d), (f)) precipitation (colour shadings: mm/day) regressed with spring AO index for the period of 1979–1997, respectively in ((a) and (b)) MAM, ((c) and (d)) AMJ and ((e) and (f)) MJJ. The areas exceeding 90% confidence level are dotted and only the wind vectors that are statistically significant above 90% *t*-test confidence level are plotted. ‘A’ and ‘C’, respectively donate the centres of anticyclonic anomaly and cyclonic anomaly and red colour boxes indicate key region.

In post-1997 epoch, there is also an AO-associated simultaneous cyclonic anomaly over Pacific in spring, but it fails to be maintained over tropical western Pacific through summer (Figure 3). Instead, the westerly wind anomalies over tropical western Pacific are noticeably reduced from MAM to April–May–June (AMJ), and disappear through summer. Another most distinguishable feature, compared with the previous epoch, is the eastward propagation of the easterly wind anomalies from tropical western north IO to maritime continent. At the same period, the associated anticyclonic anomaly experiences eastward migration from AS via Bay of Bengal to northern SCS-PS. The positive SST anomalies over AS and tropical southern IO persist through summer; while the warming SST anomalies over Bay of Bengal and SCS just commence in AMJ and are intensified in summer. The positive precipitation anomalies occur to the south of AS anticyclone in spring, move eastward from southwestern IO to tropical central IO from spring to summer. Due to the different simultaneous imposed air–sea features and evolutions, the EA region is dominated by an anticyclonic anomaly in summer after 1997 while a cyclonic anomaly before 1997.

## 4. Summary and discussion

In the two epochs, the distinctive evolutions result from the different simultaneous air–sea features imposed by spring AO. During pre-1997 epoch, the spring AO-associated signal is mainly memorized and persists over Pacific. Gong *et al.* (2011) has comprehensively described the evolving processes, that is the decreased total wind speed over tropical central northern Pacific warms the ocean surface via the reduced surface evaporation and wind stirring, and the warming SST in turn excites ascending atmospheric Rossby waves that reinforce the cyclonic anomaly in their journey to the west from spring to summer (Gill, 1980; Wang *et al.*, 2000). However, the above-mentioned positive air–sea feedback vanishes in post-1997 epoch, which could be ascribed to two possible reasons. The first is that the correlation between the anomalies of SST and rainfall is negative implying the local SST is not the main anchor for the decreased precipitation and is not favourable for the positive local air–sea feedback (Wang *et al.*, 2005). And the second is that the remarkable anomalous divergence and subsidence over maritime continent through spring

 

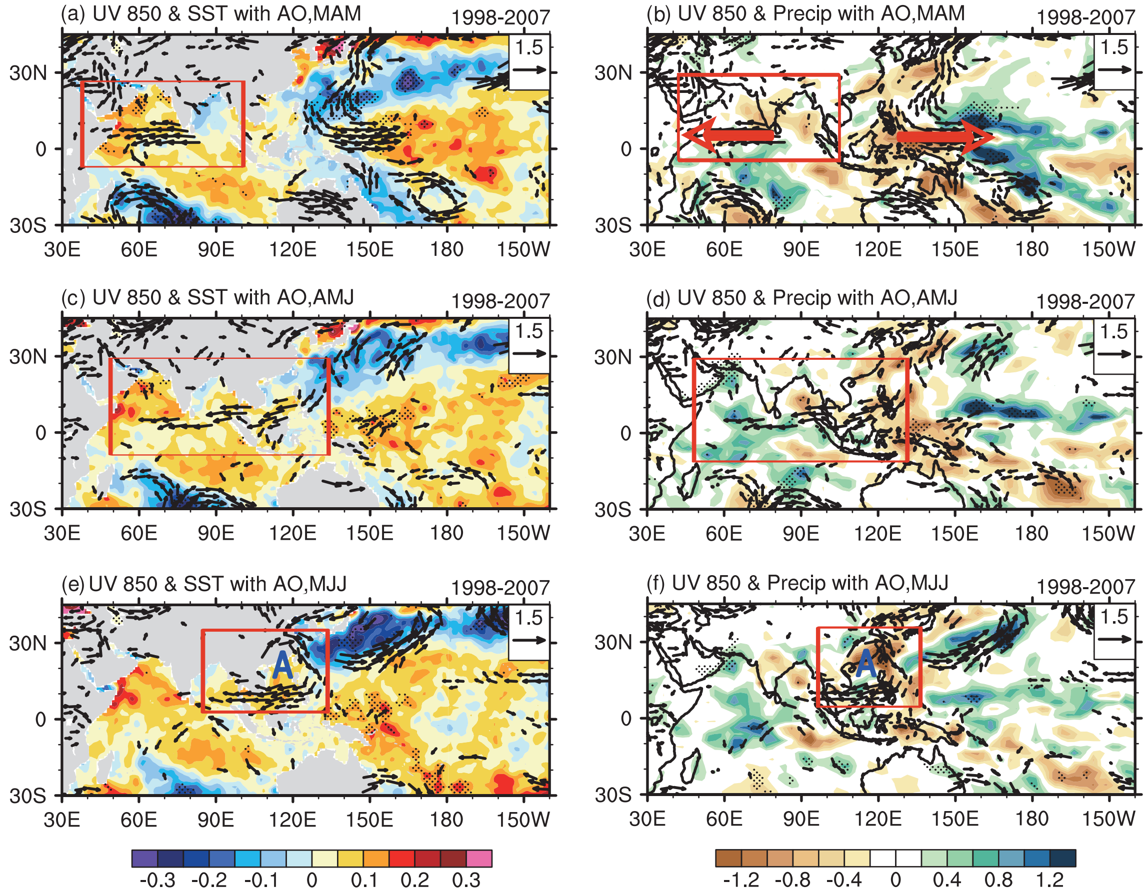


Figure 3. Seasonal evolving anomalies of 850 hPa winds (vectors: m/s), ((a), (c), (e)) SST (colour shadings: degree) and ((b), (d), (f)) precipitation (colour shadings: mm/day) regressed with spring AO index for the period of 1998–2007, respectively in ((a) and (b)) MAM, ((c) and (d)) AMJ and ((e) and (f)) MJJ. The areas exceeding 90% confidence level are dotted and only the wind vectors that are statistically significant above 90% *t*-test confidence level are plotted. 'A' and 'C', respectively donate the centres of anticyclonic anomaly and cyclonic anomaly and red colour boxes indicate key region.

(figure ignored), which is associated with both the easterly anomalies over tropical IO and westerly anomalies over tropical western Pacific (Figure 3(a)), is also unfavourable for local cyclonic anomaly persistence over tropical western Pacific.

A new subtropical linkage between spring AO and EASM through IO is found during the epoch from 1998 to 2007. During this epoch, the anomalous anticyclone over AS and associated easterly winds over tropical IO are the most distinguishable anomalies that are different from pre-1997 epoch. It has been reported in several previous studies that the winter AO can induce the anomalous AS anticyclone (Mao *et al.*, 2011; Yang *et al.*, 2012; Gong *et al.*, 2013). The easterlies associated with AS anticyclone induce cyclonic shear vorticity to the south of the AS anticyclone, which leads to enhanced equatorial IO precipitation (Figure 3(b)). It is this equatorial central IO precipitation that generates and enhances the anticyclone over South Asia and northern SCS through in the following summer (Figure 3(f)), which is consistent with the numerical result of Wu and Liu (1995).

Why the simultaneous extension of the spring AO signal over far downstream regions has such large differences between two epochs? We found that the spring AO-associated wave activity (Plumb, 1985) preferred the high-latitude propagation from North Atlantic via Eurasian continent toward north Pacific along the high latitude in pre-1997 epoch (Figure 4(a) and (b)). In contrast, the subtropical pathway of wave activity is evidently enhanced for both negative and positive AO phases in post-1997 epoch, which propagates from North Atlantic via Middle East toward South Asia (Figure 4(c) and (d)). This subtropical propagation has also been reported in several previous studies (Yang *et al.*, 2004; Mao *et al.*, 2011; Yang *et al.*, 2012).

The next question is why the downstream wave activities associated with spring AO are different in two epochs. In other words, why is the subtropical route intensified in post-1997? First, we examined the simultaneous atmospheric anomalies imposed by spring AO in two epochs and found that the spring anomalies were remarkably amplified over North Atlantic Ocean but weakened over Greenland in both positive and negative AO phases in the later epoch (Figure 4(e)–(h)). A close linkage between Arctic/North Atlantic anomalies and tropical IO has been also found on intraseasonal to interannual time scales (Ding and Wang, 2005; Lin and Brunet, 2011). Therefore, we can speculate that

 

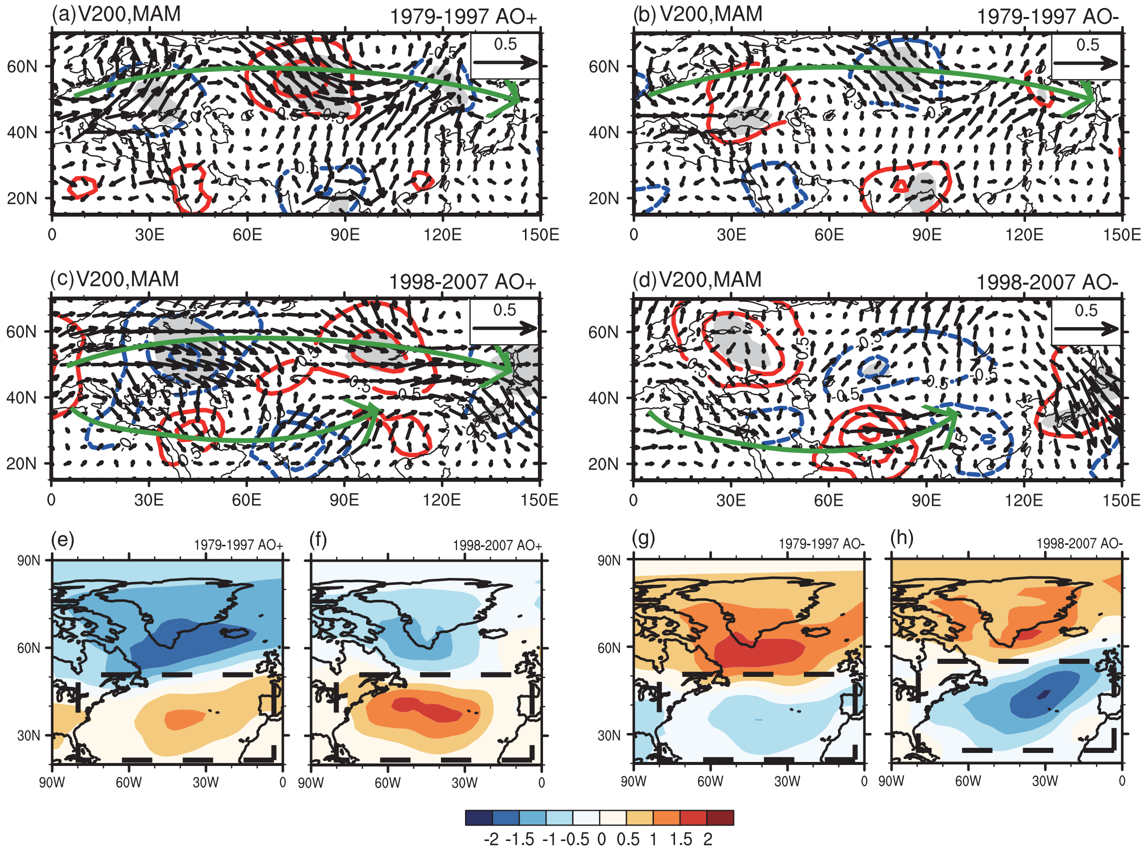


Figure 4. Anomalous wave activity flux (vectors: $m^2/s^2$) and meridional wind anomalies (contours: m/s) at 200 hPa in ((a) and (c)) all positive AO and ((b) and (d)) all negative AO springs during two epochs. Solid contours indicate that the values are positive and dash contours indicate the values are negative, and the areas exceeding 90% confidence level are shaded. Green arrows indicate the wave train. Sea level pressure anomalies (hPa) in ((e) and (f)) all positive AO and ((g) and (h)) all negative AO springs during two epochs.

the strengthened anomalies loading over North Atlantic Ocean, as the source of the wave activity, could enhance the linkage between spring AO and IO through the subtropical wave train, which needs to be further clarified with numerical experiment. The change of atmospheric anomalies over Arctic/North Atlantic in mid-1990s might be ascribed to the predominance of standing Central Pacific warming after late 1990s (e.g. Lin *et al.* 2009; Xiang *et al.*, 2012), which also needs to be further examined. We also attempted to diagnose if the mid-latitude westerly jet had any change because previous studies have had proposed that the Asian jet acted as a waveguide to extend the influences of the AO/NAO over downstream (e.g. Watanabe, 2004), but failed to find unified results.

Using National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis 1 (Kalnay *et al.*, 1996), we found another interesting result that the spring AO-EASM relationship was unstable in the past 60 years. The correlation coefficient between 1948 and 1978 is far below a significant level (−0.05) which has been reported in previous study (e.g. Gong *et al.*, 2011), and after 2008 the correlation coefficient again turns back to be positive (Figure 1). What controls the spring AO-EASM relationship and whether the unstable spring AO-EASM relationship can be reproduced in modelling are worthwhile to be investigated.

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