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Interannual Variation of the Onset of Yunnan's Rainy Season and Its Relationships with the Arctic Oscillation of the Preceding Winter

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Abstract

Based on an analysis of the circulation in May associated with the interannual variation of the onset of Yunnan's rainy season, this study examined the relationship between Arctic Oscillation (AO) and the onset timing of the rainy season by using the NCEP/NCAR reanalysis and observational precipitation data for 1961-2010. The results indicated that, on an interannual time scale, intense Asian summer monsoon and an active EU-pattern wave train circulation in its positive phase, associated with a cold cyclonic cell covering the western part of the East Asian subtropical westerly jet (EASWJ), jointly contributed to the onset of the rainy season in May. Otherwise, the onset might be suppressed. The cold cyclonic cell over East Asia likely led to the southward shift and enhancement of EASWJ as well as its secondary circulation around the jet entrance, which could provide a favorable dynamic and thermal condition for rainfalls in Yunnan as was revealed in previous studies on 10 - 30-day time scale. Further examination showed that the preceding wintertime AO played a significant role in the timing of the onset of the rainy season before the mid-1980s' by mostly modulating the wave-train-like circulation over East Asia in May. During that time period, when the AO index of the previous winter was positive (negative), Yunnan's rainy season tended to begin earlier (later) than normal. Correspondingly, the precipitation in May was also closely linked to wintertime AO.

Keywords

Onset of Yunnan's Rainy Season, East Asian Subtropical Westerly Jet (EASWJ), Arctic Oscillation (AO), Interannual Variation

1. Introduction

One of the most prominent climatological features of Yunnan Province is the alternation of dry and wet seasons, with low-level westerly wind prevailing all year round [1]. The precipitation in the wet season, generally from May to October, accounts for about 85% of the total amount of one year [2]. However, the onset of the rainy season in Yunnan shows prominent interannual variation, and late onsets often cause droughts in spring and early summer, which have serious negative impacts on crop planting and livelihood. Severe droughts have frequently hit Yunnan Province in recent decades against the backdrop of global warming [3] [4], and the riskiest period for drought is usually before the rainy season begins. Therefore, this is one of the most concerning issues for climatologists to study and predict the timing of the onset of Yunnan's rainy season as well as the related precipitation in May.

As Yunnan Province is situated in the buffer zone of the Indian summer monsoon and the East Asian summer monsoon [5] [6], the impact of low-latitude climate systems on the onset of the rainy season are the focus of most research, including the seasonal march of the Asian summer monsoon [7] [8] [9], the influence of water vapor transport [1], the link with storms in the Bay of Bengal [10], and MJO modulation [11] [12]. Nevertheless, a number of studies have noted that not only tropical regimes but also the circulations at mid- and high-latitude have notable influences [13] [14], although most of the findings are obtained by case studies and little is known about the physical mechanisms. Recently, Chen Y. *et al.* have revealed that on a 10 - 30-day time scale, the East Asian subtropical westerly jet (EASWJ) tends to shift southward rather than jumping northward during the onset of Yunnan's rainy season, associated with a cold low-frequency cyclone cell in the EU-pattern-like wave-train moving towards East Asia [15] [16]. **Figure 1** shows the schematic circulation for the onset of Yunnan's rainy season and the wave-train pattern in this figure is referred to as its positive phase [16]. The authors argue that against the backdrop of seasonal

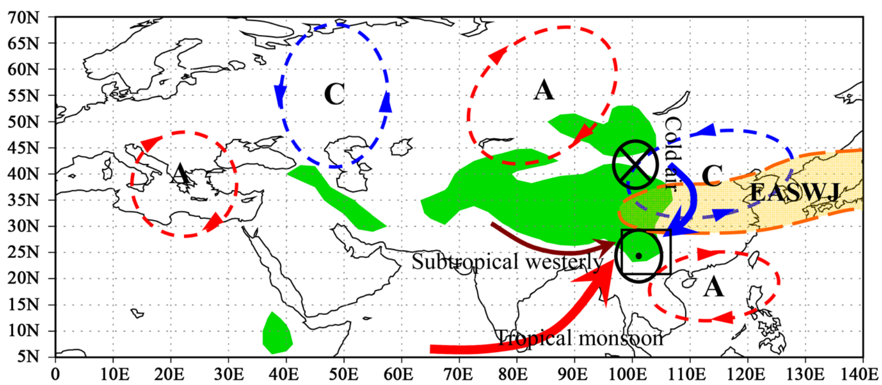


Figure 1. Schematic circulation for the onset of Yunnan's rainy season (dashed lines represent atmospheric systems in the upper-level troposphere; real-line-arrows show airflow in the mid- and low-level troposphere; ⊙ and ⊗ denote the up current and down current around the EASWJ entrance respectively; a black rectangle shows the location of Yunnan Province and green areas show plateau higher than 1500 m).

transition of the atmospheric circulation from spring to summer, the southward shift of EASWJ can trigger the onset of Yunnan's rainy season through intensifying its secondary vertical circulation around the jet entrance and enhancing the interaction between the summer monsoon and cold air. However, it is not clear whether the onset of Yunnan's rainy season on an interannual time scale is also related to the abnormal displacement of EASWJ.

As the leading mode of extratropical circulation from the surface to the lower-level stratosphere in the Northern Hemisphere [17], the Arctic oscillation (AO) has a profound impact on the weather and climate of East Asia [18] [19]. Many researchers have demonstrated that abnormal AO in winter can influence synchronous temperature and precipitation and also those in the succeeding months or seasons [20] [21] [22] [23] [24]. With regard to Yunnan, some surveys have suggested a close relationship between AO and the precipitation in winter and spring [25] [26], but the mechanism causing abnormal precipitation is not yet involved, and it is unclear whether the interannual variation of the onset of Yunnan's rainy season is related to it. So, this study is designed to explore the anomalous circulation leading to the interannual onset of Yunnan's rainy season using long-term data, investigating the abnormal signals of EASWJ variation, and examining the possible relationship between AO and the timing of the onset of Yunnan's rainy season in the expectation of obtaining some antecedent clues for prediction.

2. Data and Methods

The data used in this study are the daily rain gauge precipitation of Yunnan Province and gridded atmospheric circulation reanalysis products from the NCEP/NCAR for the period of 1961-2010 [27]. Considering that the complicated topography and the diversity of climate types in Yunnan Province may blur the various mechanisms leading to the onset of the rainy season, the capital city of Yunnan Province, Kunming, and 9 other nearby stations in the same climatic zone are selected [15] [28]. The precipitation time series of the other 9 stations are closely correlated to that of Kunming, with the correlation coefficients all beyond 0.5 from April to July 1961-2010. Then, a daily precipitation index for Yunnan is defined by averaging the 10-station rainfall data [15]. So, the precipitation index is relatively homogeneous compared with a one-station time series and it can represent the rainfall of central Yunnan.

The operational criteria of the onset of the rainy season adopted by the Yunnan Provincial Meteorological Bureau are applied in this study. The criteria are defined by the following formula:

$$K = \left(R_5 / R_c\right) \geq 1 \tag{1}$$

Here, R_5 is the running 5-day accumulated precipitation and R_c is the precipitation of the climatological pentad mean in the rainy season (from May to October). That is, from April 21 onwards, if (1) is met and there is another $K \geq 1$ within the following 15 days, then the first day on which the precipitation is greater or equal to 10 mm in the former 5 days is defined as the onset day of the rainy season.

3. Circulations Associated with the Onset of the Rainy Season in May

According to the definition described above, the mean onset date of Yunnan's rainy season is May 23rd with a standard deviation of 15 days, which is in agreement with other results [29]. The onset date has a high correlation coefficient of up to 0.831 with the average 124-station rainy season onset date provided by the Yunnan Climate Center. Notably, most of the rainy seasons begin in May and June as shown in **Table 1**, except in 1964 and 2006, which were both on April 30th. Early and normal onset in May (hereafter referred to as timely onset) is conducive for crop planting, whereas a late onset in June (hereafter referred to as late onset) enhances the risk of early summer drought resulting from suppressed circulation in May. Therefore, whether or not the atmospheric circulation in May is favorable for the onset of the rainy season is critical. It may be somewhat arbitrary but reasonable to study the May circulation that is responsible for timely onset compared with the suppressed situation. On the other hand, the precipitation in May is also a primary item for operational climate prediction, and it shows a significant negative relationship with the rainy season's onset date (**Figure 2**).

Figure 3 presents the wind and temperature differences of May between the 34 timely onset years and 14 late onset years. **Figure 3(a)** does not show the temperature difference, since the circulation at 200 hPa over the mid- and high-latitude is actually in the stratosphere, and the temperature there is not as cohe-

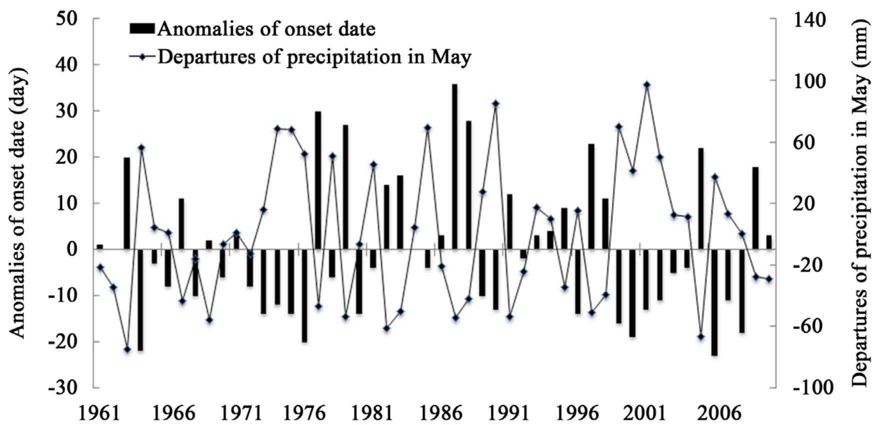
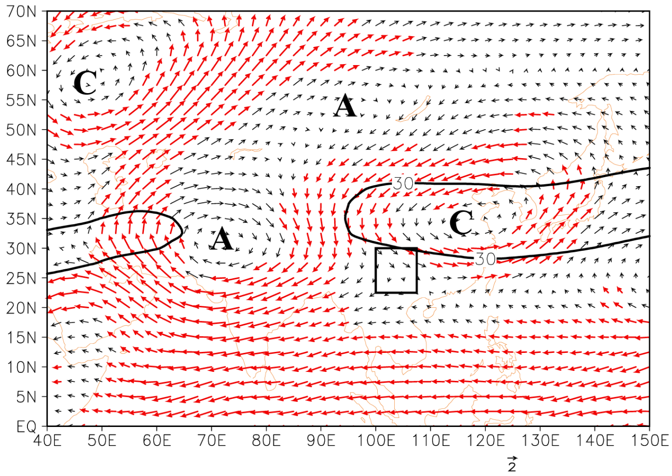


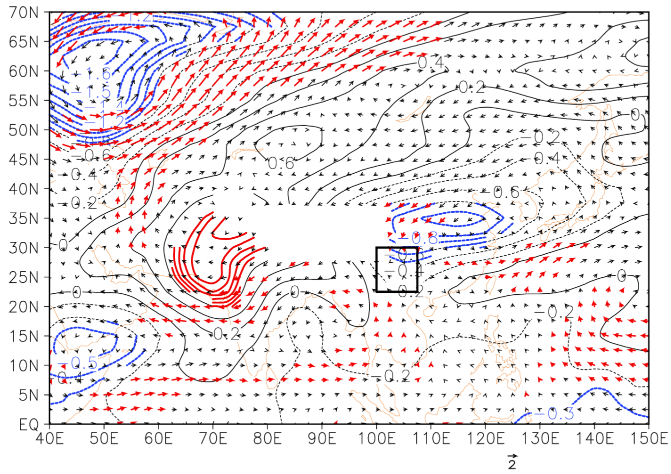
Figure 2. Time series of the onset date anomaly and those of the precipitation departure in May for 1961-2010.

Table 1. Years in which the rainy season beganin April, May and June for 1961-2010.

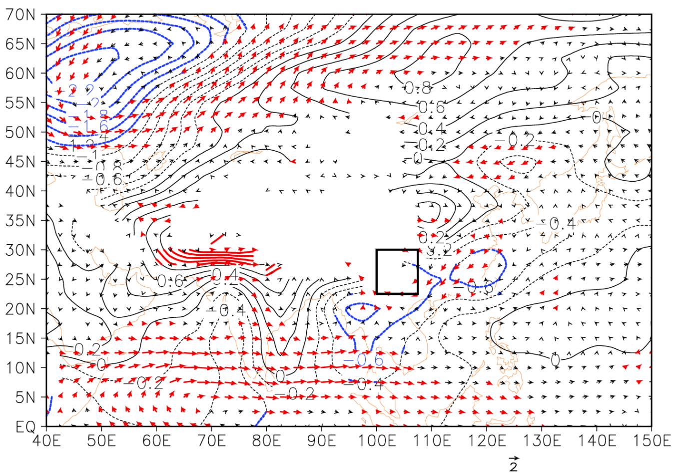
April	May	June
1964 2006	1961 1962 1965 1966 1968 1969 1970 1971 1972 1973 1974 1975 1976 1978 1980 1981 1984 1985 1986 1989 1990 1992 1993 1994 1996 1999 2000 2001 2002 2003 2004 2007 2008 2010	1963 1967 1977 1979 1982 1983 1987 1988 1991 1995 1997 1998 2005 2009



(a)



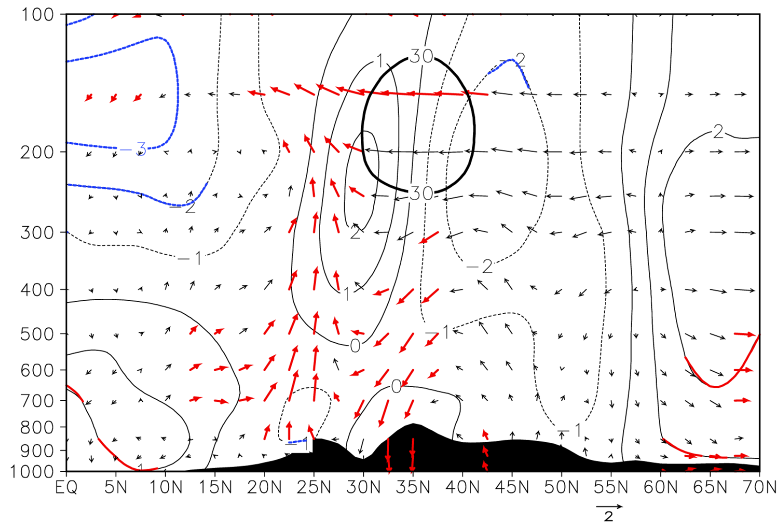
(b)



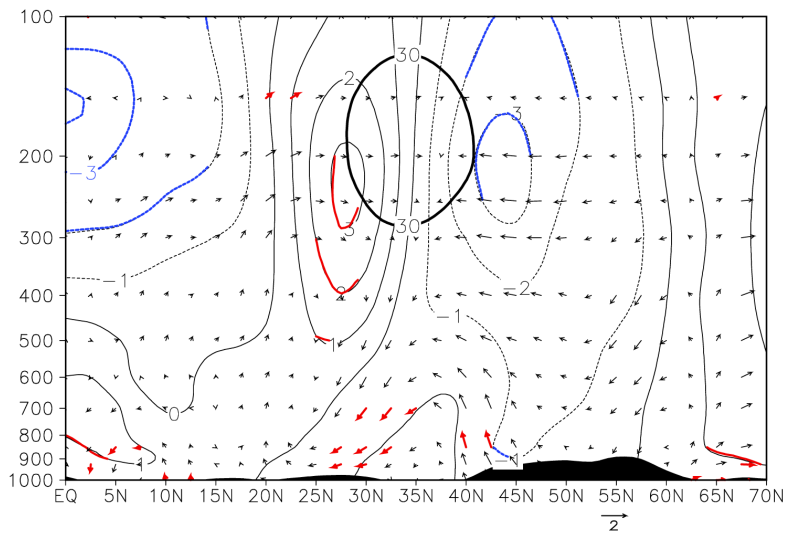
(c)

Figure 3. Differences of wind (unit: m·s^{-1}) and temperature (unit: K) of May between timely-onset years and late-onset years at (a) 200 hPa; (b) 500 hPa and (c) 850 hPa. Vectors and thick curves in red and blue are significant at 95% confidence level. The blank areas indicate plateaus above 4000 m in (b) and 1500 m in (c). The bold black lines of 30 m/s in (a) present the climatological mean location of EASWJ, and the rectangle shows the location of Yunnan Province (the same in other figures).

rent with the circulation as it is in the troposphere [30]. In any case, two prominent features in **Figure 3** are obvious. Firstly, a quasi-barotropic wave-train pattern exists over the mid- and high-latitudes, which emanates from Europe and extends to East Asia. It can be seen that there is an anomalous elongating cyclonic cell around 35˚N over East Asia along with cold air in the middle troposphere (**Figure 3(b)**) covering the western part of EASWJ, which may result in the enhancement and southward displacement of the jet (**Figure 4**). The enhancement and southward shift of EASWJ are more obvious near the jet stream core as shown in **Figure 4(b)** and **Figure 5** along 120˚E. Meanwhile, salient upward flow emerges over the latitudes from 20˚N to 30˚N where Yunnan Prov-



(a)



(b)

Figure 4. Latitude-height cross sections of wind differences (the vertical velocity ω is multiplied by 100 and the isolines are zonal wind differences, unit: $m \cdot s^{-1}$) along (a) 105˚E and (b) 120˚E between timely-onset years and late-onset years. The thick circle of 30 m/s shows the climatological mean location of EASWJ and the black areas represent the orographic height.

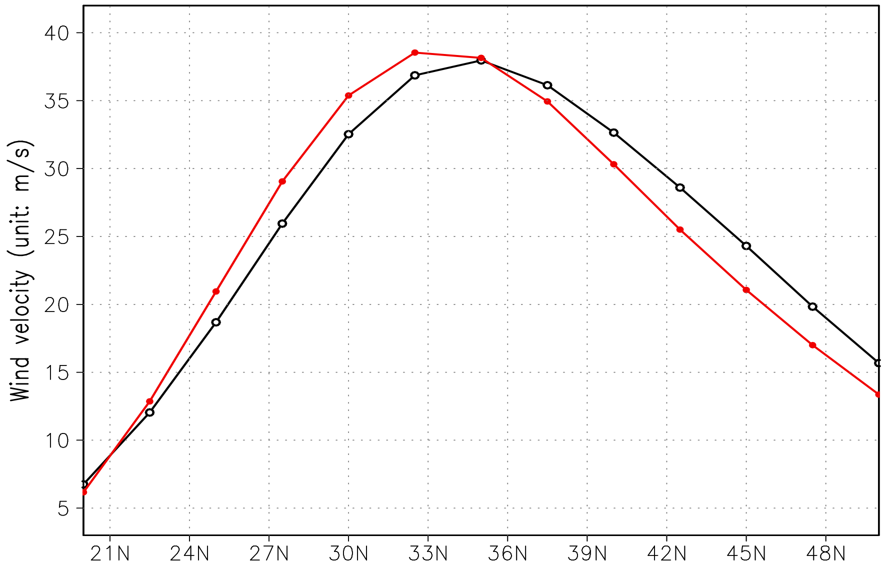


Figure 5. Composite zonal wind velocity (unit: m/s) of May at 200 hPa for timely-onset years (red curve) and late-onset years (black curve) along 120˚E.

ince is located, and downward flow can be detected under the EASWJ in **Figure 4(a)**, indicating a strong secondary circulation around the EASWJ entrance. This anomalous circulation largely resembles the pattern that favors the onset of Yunnan's rainy season revealed in previous studies on a 10 - 30-day timescale [15] [16]. Secondly, an anomalous warm anticyclone covers the Afghanistan-western Tibetan Plateau, which is recognized as one of the precursory features for the onset of the Asian summer monsoon in some pioneer research [31]. Climatologically speaking, the center of the South Asian High is situated over the Indo-China Peninsula during this period, so the anomalous high center over this region implies an earlier northwestward extension associated with early establishment of the summer monsoon. Moreover, evident easterly at 200 hPa (**Figure 3(a)**) and westerly at 850 hPa (**Figure 3(c)**) also cover a broad tropical zone from the western Pacific to almost all the Indian Ocean, suggesting an anomalous thermal wind shear and intense summer monsoon as well [32]. At the lower troposphere (**Figure 3(c)**), monsoonal westerlies from low latitudes and cold northerlies from the mid-latitude of East Asia converge over Yunnan Province and its vicinity, which is a principal condition for rainfalls.

In short, the above differences suggest that on the interannual timescale, strong monsoons from lower latitudes and favorable wave-train circulation associated with the enhancement and southward displacement of EASWJ in the higher latitudes jointly contribute to the timely onset of the rainy season in May by intensifying the vertical circulation around EASWJ entrance and enhancing the interaction between summer monsoon and cold air from the mid-latitudes.

4. Relationship between the AO Index and the Date of the Onset of the Rainy Season

The correlations between the antecedent AO index and the onset date of the rainy season for 1961-2010 were examined. It was found that the preceding wintertime AO index is linked to the timing of the onset of Yunnan's rainy season as shown in Table 2. The correlation between the DJF AO index and the rainy season's onset date is −0.289, which is significant at 95% despite the relatively weak correlation in December and February. However, there is no persistent relationship between spring AO and the onset date. Correspondingly, the rainfall in Yunnan in May is significantly linked to the DJF AO with a positive correlation up to 0.293.With regard to the onset of Kunming's rainy season, which used to be the operational symbol of the onset of Yunnan's rainy season [29] [33], is more closely related to the preceding wintertime AO, with a coefficient of the DJF AO index up to −0.442, exceeding the significant 99% level. The results suggest that when the AO index in the previous winter is positive (negative), Yunnan's rainy season tends to begin earlier (later) and the rainfall in May be more (less) than normal. However, the relationship presents a clear inter-decadal variation from the 21-year moving correlation, with the correlation coefficients being significant before the mid-1980s and weakening since then (Figure 6). So, the wintertime AO index can be regarded with caution as a precursor for predicting the timing of the onset of Yunnan's rainy season.

In an attempt to explore the possible mechanism of how AO influences the onset of the rainy season, correlations between the preceding wintertime AO index and the monthly mean circulation of May during 1961-2010 and 1961-1985 are exhibited in Figure 7. Obviously, there exists a wave-train pattern at mid-

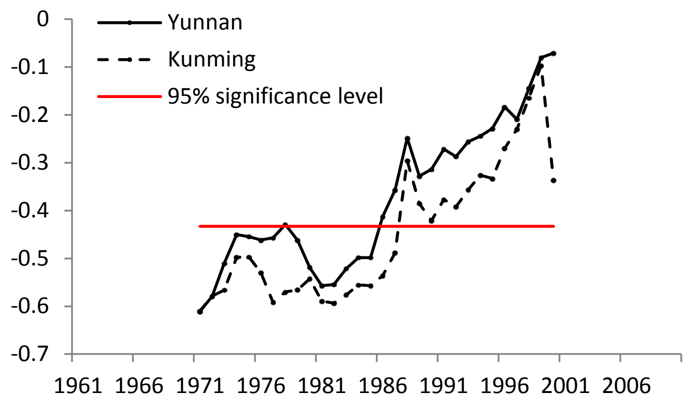


Figure 6. 21-year moving correlation between preceding DJF AO index and the rainy season's onset date

Table 2. Correlations between the preceding AO index and the onset dates of Yunnan's rainy season as well as the precipitation in May.

	DJF	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*
Onset date in Yunnan	**−0.289**	−0.132	**−0.280**	−0.253	0.005	0.033
Yunnan's precipitation in May	**0.293**	0.082	**0.302**	**0.281**	0.04	0.102
Onset date in Kunming	**−0.442***	**−0.305**	**−0.342**	**−0.391***	0.048	0.148
Kunming's precipitation in May	**0.304**	0.172	**0.259**	**0.277**	−0.03	0.042

Numbers in bold indicate correlations that are significant at 95% confidence level and those marked with * are significant at 99% level.

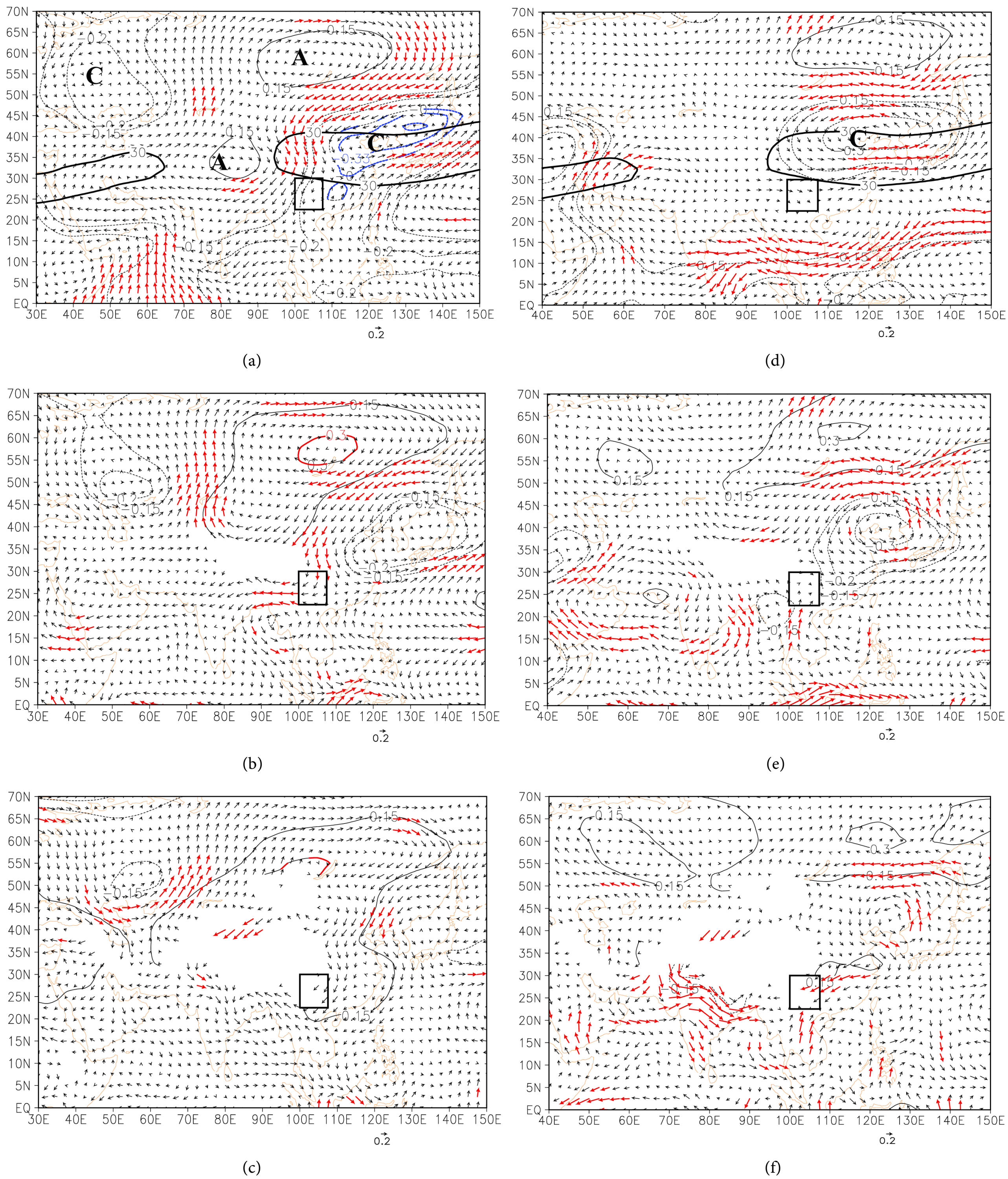


Figure 7. Correlations between preceding winter (DJF) AO index and the circulations of May at (a) 200 hPa; (b) 500 hPa; (c) 850 hPa during 1961-2010 (vectors indicate the wind fields and isolines indicate the geopotential height fields). The same in (d)-(f), but for 1961-1985.

and high-latitudes over Eurasian continent almost throughout the troposphere for 1961-2010 (Figures 7(a)-(c)), which resembles the anomalous circulations causing timely rainy season onset in May. Furthermore, the southward shift of

EASWJ along 120˚E and the intensification of the vertical cell around the EASWJ entrance are detectable (figures omitted). The results indicate that when the AO index in the preceding winter is positive, the circulation over the Eurasian continent in May is likely to present a positive-phase wave-train pattern in which the cyclonic cell over East Asia may lead to the southward shift of EASWJ and intensify the vertical circulation around the entrance. In addition, positive wintertime AO may also, to a certain extent, enhance the South Asian high in the upper troposphere and a cyclonic circulation over the northeastern Bay of Bengal in the middle troposphere, although the correlations are generally less distinct at the low latitudes.

As for the period before mid-1980s' (**Figures 7(d)-(f)**), a singular west-east-oriented cyclone appears to the north of 30˚N over East Asia covering most part of EASWJ, and the cyclone at the upper troposphere in **Figure 7(d)** is more conspicuous than that in **Figure 7(a)** though the wave train pattern is not very clear. At 850 hPa in **Figure 7(f)**, subtropical westerly alone the southern flank of Tibetan Plateau, monsoonal southerly from Indo-China Peninsula and northeasterly from East China converge over Yunnan Province and its vicinity. The above circulation features from the lower to the upper troposphere are all favorable for the onset of Yunnan's rainy season so that it presents significant relationship between preceding wintertime AO index and the onset timing during that time period, which further demonstrates the important role of the interaction between the cyclonic cell and the EASWJ for the rainy season onset besides the opportune low-level convergence of different airflow as show in **Figure 1**.

5. Summary

This study analyzed the anomalous circulations related to interannual variation of the onset of Yunnan's rainy season using long-term data, and examined the relationship with the preceding AO index. The results show the important role of the EU-pattern wave-train circulation at middle and high latitudes associated with a cyclonic cell covering the western part of EASWJ during the onset of Yunnan's rainy season, besides the dominant influence of the summer monsoon. It confirmed that on an interannual timescale, the southward shift of EASWJ along with its enhancement also contributes to the onset of Yunnan's rainy season. Nevertheless, more exploration is needed concerning the interaction between mid- and high-latitude systems and the summer monsoon.

The precursor signals of wintertime AO were explored. The results indicate that a lag negative relationship exists between the wintertime AO index and the timing of the onset of Yunnan's rainy season, especially before the mid-1980s. Further analysis suggested that the preceding AO anomaly might influence the onset time by modulating the EU-pattern-like wave-train in May and the cold cyclonic cell in the wave-train over East Asia may play a crucial role. Hence, the wintertime AO index could be regarded with caution as a precursor for predicting the onset of Yunnan's rainy season.

A time-lag relationship between AO and the climate variability has been noticed in some research despite the various time intervals [18] [24]. However, it is still an open question with regard to the mechanism. It is possible that the changes of AO-related surface conditions in winter may subsequently induce anomalous low-frequency oscillations, and further statistical exploration and numerical simulation are needed to reveal the detailed physical dynamics.

Acknowledgements

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