Modulation of Pacific Decadal Oscillation on the relationship of El Niño with southern China rainfall during early boreal winter

Gang Li,1 Jiepeng Chen,2*, Xin Wang,2,3* Yanke Tan4 and Xiaohua Jiang1

1Xichang Satellite Launch Center, Xichang, China
2State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, China
3Laboratory for Regional Oceanography and Numerical Modeling, Qingdao National Laboratory for Marine Science and Technology, Qingdao, China
4College of Meteorology and Oceanography, PLA University of Science and Technology, Nanjing, China

Abstract

The modulation of Pacific Decadal Oscillation (PDO) on the relationship of El Niño with southern China rainfall during early boreal winter (November–December) is investigated in this study. When El Niño occurs in positive phase of PDO, significantly positive rainfall anomalies only appears over the southwestern part of southern China. When El Niño occurs in negative phase of PDO, pronounced positive rainfall anomalies are observed over almost the whole southern China. Further analyses revealed that the anomalous Philippine Sea anticyclone (PSAC) and local meridional circulation play an important role in modulating the relationship of El Niño with southern China rainfall by PDO. During the negative PDO phase, under the combined influence of tropical Pacific and Indian Ocean dipole sea surface temperature anomalies pattern, the anomalous PSAC over the western North Pacific and rising motion associated with local meridional circulation over southern China provide sufficient water vapor and dynamical conditions for the formation of rainfall. During positive PDO phase, however, PSAC and local meridional circulation are only influenced by tropical Pacific and they become weak, not favoring the formation of southern China rainfall.

Keywords: Pacific Decadal Oscillation (PDO); El Niño; southern China rainfall; early boreal winter

1. Introduction

Rainfall variability over southern China has been investigated extensively (Chan and Zhou, 2005; Zhou and Chan, 2007; Gu et al., 2009; Feng et al., 2014; Yao et al., 2015; Zhang et al., 2015). Many above studies suggested that the boreal winter rainfall over southern China also shows significant variability on subseasonal, interannual and interdecadal scales. Moreover, the variability of boreal winter rainfall over southern China can induce disruptive weather and climate hazards, which cause seriously damage to agriculture and socio-economic development (Zhou et al., 2011). Therefore, it is necessary to study the variability of boreal winter rainfall over southern China.

The variability of boreal winter rainfall over southern China is influenced by many factors (Zhou, 2011; Zhang et al., 2015; Zhang et al., 2017). In particular, the El Niño-Southern Oscillation (ENSO) may have the most significant relationship with boreal winter rainfall over southern China (Wang et al., 2000). In fact, it should be mentioned that the relationship between El Niño and southern China climate is influenced by the Pacific Decadal Oscillation (PDO; Mantua et al., 1997; Mantua and Hare, 2002) (Chan and Zhou, 2005; Wang et al., 2008; Feng et al., 2014; Kim et al., 2014).

Although many above studies have focused on the modulation of PDO on the relationship between ENSO and East Asian winter monsoon (EAWM), the direct modulation of PDO on the relationship of El Niño with boreal winter rainfall over southern China has not been sufficiently studied. Especially, considering the significantly subseasonal variability of boreal winter rainfall over southern China (Yao et al., 2015), it is reasonable to hypothesize that the modulation of PDO on the relationship between El Niño and rainfall during early boreal winter (November–December) may be different from that during the boreal winter, which is usually defined as December–January–February or January–February–March. Therefore, the main purpose of this study is to investigate the direct modulation

*Correspondence to:
X. Wang, State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, China
E-mail: wangxin@scsio.ac.cn
J. Chen, State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, China
E-mail: chenjinp@scsio.ac.cn

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of PDO on the relationship of El Niño with southern China rainfall during early boreal winter. The article is organized as follows. Section 2 describes the datasets and methods used in this study. In Section 3, we investigate the influence of PDO on the relationship of El Niño with southern China rainfall in during early boreal winter. The summary and discussion are provided in Section 4.

2. Datasets and methods

The monthly sea surface temperature (SST) data is provided by the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST1.1) dataset (Rayner et al., 2003). The monthly atmospheric data is taken from the National Oceanic and Atmospheric Administration-Cooperative Institute for Research in Environmental Sciences (NOAA-CIRES) 20th Century Reanalysis V2c dataset (Compo et al., 2011). The first dataset is the full data analysis (V7) rainfall dataset (Schneider et al., 2015) and the Climatic Research Unit (CRU) Time Series (TS) 3.24.01 rainfall dataset (University of East Anglia Climatic Research Unit et al., 2017) are used as the rainfall datasets.

This study covers the period from 1901 to 2010 for the consistency of the above datasets. The average of November and December is defined as the early boreal winter. In addition, all datasets are detrended before analyses. The composite analysis is used in our study. The statistical significance of composite is examined by Student’s t-test.

The PDO index from University of Washington is used to describe the interdecadal variability of Pacific (Mantua et al., 1997) (figure not shown). To reveal the interdecadal variability of PDO, we apply the 11-year running mean to the time series of original PDO index during early boreal winter. Here, the positive (negative) phase of PDO is defined as the years that the 11-year running mean PDO index is above (below) 0. Therefore, the periods of 1903–1943 and 1978–1992 are referred to as the positive phase of PDO, while the periods of 1944–1977 and 1993–2010 are referred to as the negative phase of PDO.

The Niño-3.4 index is defined as area-averaged SST in the tropical central-eastern Pacific (5°S–5°N, 170°–120°W) (figure not shown). El Niño years are selected when the normalized Niño-3.4 index is greater than 0.5. Following this definition, 16 (16) El Niño years occurred during the positive (negative) phase of the PDO (Table 1). For convenience, El Niño that occurs with the positive (negative) PDO phase is referred to as El Niño + positive PDO (El Niño + negative PDO).

3. Results

3.1. Rainfall anomalies

Figure 1 shows the composite of rainfall anomalies over southern China for El Niño + positive PDO and El Niño + negative PDO, respectively. During El Niño + positive PDO (Figure 1(a)), the northeast-southwest-oriented positive rainfall anomalies appear over the whole southern China with a centre around (25°N, 110°E). Significant rainfall anomalies mainly appear over the southwestern part of southern China and rainfall anomalies over the eastern part of southern China are not significant. During El Niño + negative PDO (Figure 1(b)), the magnitude of the northeast-southwest-oriented rainfall belt increases significantly. Almost the whole southern China except for the coast of southeast China is dominated by significantly positive rainfall anomalies. Besides, it should be mentioned that the whole rainfall belt moves northeastward to some extent. Figures 2(c) and (d) show that composite results based on GPCC V7 dataset clearly reproduce the results based on CRU TS 3.24.01 dataset.

The above results suggest that the influence of El Niño on southern China rainfall during early boreal winter is different during the different PDO phase. El Niño can exert significant influence on southern China rainfall for negative phase of PDO. However, the influence is very weak for the positive phase of PDO.

3.2. SST

Figure 2 shows the composite of early boreal winter SST anomalies (SSTA) for El Niño + positive PDO and El Niño + negative PDO, respectively. During El Niño + positive PDO (Figure 2(a)), positive SSTA dominates in the tropical central-eastern Pacific, extratropical South Pacific, Indian Ocean and South China Sea (SCS). Negative SSTA dominates in the North and South Pacific and the tropical western Pacific. Comparing SSTA between El Niño + positive PDO and El Niño + negative PDO (Figure 2(b)), three significant features can be emphasized. First, although spatial distribution of positive SSTA in the tropical central-eastern Pacific is similar for different PDO phase, the extent of maximum SSTA (>1.5°C) for El Niño + negative PDO is larger and extends more westward than that for El Niño + positive PDO. Second, the magnitude of negative SSTA in the tropical western Pacific is larger for El Niño + negative PDO than that for El Niño + positive PDO. Third, a basin-wide positive SSTA pattern dominates in the tropical Indian Ocean for El Niño + positive PDO; however, a Indian

Table 1. Classification of El Niño years in concurrent with positive and negative phase of the PDO during early boreal winter for the period 1901–2010.

| Positive PDO phase | Negative PDO phase |
|--------------------|-------------------|
| El Niño years      |                   |
| 1904, 1905, 1911, 1913 | 1902, 1951, 1957, 1963, 1914, 1918, 1923, 1925 |
| 1930, 1940, 1941, 1979     | 1976, 1977, 1994, 1997, 1982, 1986, 1987, 1991 |
| 2002, 2004, 2006, 2009     |                   |

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Ocean dipole (IOD) SSTA pattern, with positive SSTA in the western Indian Ocean and negative SSTA in the eastern Indian Ocean, dominates in the tropical Indian Ocean for El Niño + negative PDO.

3.3. Possible mechanism

Figure 3 shows the composite of 850 hPa wind anomalies during early boreal winter for El Niño + positive PDO and El Niño + negative PDO, respectively. Previous studies have suggested that the anomalous Philippine Sea anticyclone (PSAC) can convey the influence of El Niño to southern China during boreal winter (Wang et al., 2000). During El Niño + positive PDO (Figure 3(a)), PSAC appears over western North Pacific (WNP) with a centre at (17.5°N, 132°E). Significant southwesterly anomalies to the northwestern side of the PSAC dominate over southern China, favoring moisture transport from SCS to this region. The western part of southern China is associated with significantly anomalous moisture convergence (figure not shown), which induces the related rainfall anomalies in Figure 1(a). During El Niño + negative PDO (Figure 3(b)), PSAC strengthens and moves southwestward with a centre at (16°N, 128°E). Southwesterly anomalies over southern China are much stronger. Besides, moisture can be transported from not only SCS but also the Bay of Bengal (BOB) to southern China and significantly anomalous moisture convergence dominates the whole southern China (figure not shown). Therefore, significantly positive rainfall anomalies are observed over southern China (Figure 1(b)).

During El Niño + positive PDO, significant westerly anomalies control the tropical western-central Pacific and easterly anomalies prevail over the Maritime Continent and tropical eastern Indian Ocean (Figure 3(a)). The anomalous divergence over the tropical western Pacific results in anomalous sinking motion (Figure 4(a)), which excites an anomalous local Hadley circulation over East Asia (110°–120°E) (Figure 4(c)). However, the anomalous rising motion associated with this local Hadley circulation over southern China (25°–30°N) is insignificant, thus not providing sufficiently dynamical condition for southern China rainfall. During El Niño + negative PDO (Figure 3(b)), significant westerly anomalies over the tropical western-central Pacific move westward slightly. Besides, easterly anomalies over the Maritime Continent and tropical eastern Indian Ocean intensify significantly and extend more westward. The anomalous divergence over the tropical western Pacific can induce significant sinking motion (Figure 4(b)), which results in an anomalous local Hadley circulation over East Asia (Figure 4(d)).
Modulation of relationship between El Niño and rainfall by PDO

Figure 2. Composite of the early boreal winter SSTA (unit: °C) during (a) El Niño + positive PDO and (b) El Niño + negative PDO, respectively. The white contours filled with white dots represents significance exceeding the 95% confidence level based on the Student’s t-test.

Figure 3. Composite of the early boreal winter wind anomalies (unit: m s⁻¹) at 850 hPa during (a) El Niño + positive PDO and (b) El Niño + negative PDO, respectively. The red vectors indicate zonal winds exceeding the 95% confidence level based on the Student’s t-test.

associated with local Hadley circulation over southern China becomes significant compared to that during El Niño + positive PDO, and thus providing a dynamical condition for southern China rainfall.

4. Summary and discussion

The modulation of PDO on the influence of El Niño and southern China rainfall during early boreal winter from 1901 to 2010 is investigated in this study. Results show that, significantly rainfall anomalies only appear over the southwestern part of southern China during El Niño + positive PDO. However, during El Niño + negative PDO, almost the whole southern China is dominated by pronounced positive rainfall anomalies.

During El Niño + positive PDO, an anomalous PSAC can transport anomalous water vapor from SCS to southern China. Meanwhile, the anomalous rising motion associated with this local meridional circulation over southern China is insignificant. The above atmospheric circulation is unfavorable for the formation of rainfall over the eastern part of southern China. During El Niño + negative PDO, the anomalous PSAC
intensifies significantly and moves southwestward. Besides, moisture can be transported from not only SCS but also BOB to southern China. Anomalous sinking motion over the tropical western Pacific excites a stronger rising motion over southern China. Therefore, more rainfall appears over southern China.

The distinct features of PSAC over WNP and local meridional circulation over East Asian can be attributed to the different SSTA in the tropical Pacific and Indian Ocean. First, the location and intensity of PSAC depend on the maximum warm SSTA in tropical Pacific (Wang and Zhang, 2002). The extent of maximum SSTA in the tropical Pacific during El Niño - negative PDO is larger and extends more westward, and induces a stronger PSAC. Besides, negative SSTA in the tropical western Pacific can induce a stronger local meridional circulation over East Asia than that during El Niño-positive PDO.

Second, during El Niño + positive PDO, Indian Ocean shows a basin-wide warming. Previous studies have demonstrated that the basin-wide warming in Indian Ocean lags the mature phase El Niño and it is an important ‘capacitor’ during the decaying phase of El Niño (Yuan et al., 2008). It may increase the intensity and persistence of PSAC during El Niño decaying years based on both observational and modeling analyses (Annamalai et al., 2005). However, during El Niño - negative PDO, Indian Ocean shows a positive IOD, which usually appears in the developing phase of El Niño. The boreal autumn positive IOD can induce a strengthened PSAC with a westward-extending position during the following boreal winter (Xie et al., 2009; Zhang et al., 2017).

However, the above mechanism should be further investigated by using a coupled atmospheric and oceanic general circulation model. Besides, it should be mentioned that there exists two types of El Niño (Ashok et al., 2007; Kao and Yu, 2009). Recent studies have suggested that the tropical central (CP) El Niño occurs more frequently and its intensity increases significantly (Lee and McPhaden, 2010). The influence of two types of El Niño on China rainfall is widely investigated (Feng et al., 2011; Li et al., 2013; Li et al., 2014). For example, the El Niño-induced more southern China rainfall only appears during the tropical eastern (EP) El Niño, not during the CP El Niño (Feng et al., 2014).

Figure 4. Composite of vertical circulation anomalies (unit: m s$^{-1}$) during early boreal winter in cases of El Niño - positive PDO (left panel) and El Niño - negative PDO (right panel). The top row is zonal vertical circulation anomalies by averaging zonal wind and vertical velocity (scaled by $-100$) between $10^\circ$S and $10^\circ$N. The bottom row is meridional vertical circulation anomalies by averaging meridional wind and vertical velocity (scaled by $-100$) between $110^\circ$E and $120^\circ$E. The red vectors indicate vertical velocity exceeding the 95% confidence level based on the Student’s t-test.
et al., 2010). Therefore, further studies are needed to understand the modulation of PDO on the relationship between two types of El Niño and southern China rainfall.

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