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A POSSIBLE IMPACT OF EL NIÑO MODOKI ON SEA SURFACE TEMPERATURE OF CHINA'S OFFSHORE AND ITS ADJACENT REGIONS

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Abstract: El Niño Modoki, similar to but different from canonical El Niño, has been observed since the late 1970s. In this paper, using HadISST and NCEP/NCAR wind data, we analyze the relationship between El Niño Modoki and Sea Surface Temperature (SST) in the offshore area of China and its adjacent waters for different seasons. Our results show a significant negative correlation between El Niño Modoki in summer and SST in autumn in the offshore area of China and its adjacent waters, particularly for regions located in the east of the Kuroshio. It is also found that during El Niño Modoki period, anomalous northerlies prevail over the regions from the northern part of the Philippines to the offshore area of China, indicating that the northerlies are unfavorable for the transport of warm water from the western tropical Pacific to the mid-latitude area. Consequently, El Niño Modoki in summer may play a substantial role in cold SST anomalies in the offshore area of China and its adjacent waters in autumn through the influence of the Kuroshio, with a lagged response of the ocean to the atmospheric wind field.

Key words: offshore area of China and its adjacent waters; SST; El Niño Modoki; Kuroshio; anomalous northerlies

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1 INTRODUCTION

El Niño, a pronounced climate signal in the tropical Pacific, has always been the focus of global meteorologists and oceanologists since its discovery[1]. Characterized by an anomalous warming in the tropical eastern Pacific and a cooling in the tropical western Pacific, El Niño exhibits significant influences on the global climate. For example, some original arid areas may receive surplus rainfall, while humid regions will suffer from extreme drought when El Niño events occur[2-5]. A large number of research papers, aiming at understanding and predicting El Niño as well as its impacts on the global climate, have been published in the past decades. However, recent studies indicate that El Niño has become less frequent and is followed by a new type of the tropical Pacific phenomenon, which has become more common since the late 1970s, named El Niño Modoki[6] (also termed the central Pacific El Niño, CP- El Niño[7] and warm pool El Niño[8]). Then scientists from the world work on El Niño Modoki intensively and their studies clearly show that El Niño Modoki is different from the above mentioned canonical El Niño.

Different from the canonical El Niño associated with evolution of basinwide thermoline, El Niño Modoki is more likely to be a result of surface wind distribution[9]. When it happens, the warmest sea surface temperature anomalies (SSTA) occur in the tropical central Pacific, flanked by colder waters to the east and west, and consequently, there are two anomalous Walker circulation cells in the tropical troposphere. The joint ascending branch of this double Walker circulation is located over the central equatorial Pacific, and the two descending branches are located over the eastern and western equatorial Pacific, respectively. The distinctive atmospheric circulation induced by El Niño Modoki gives rise to different effects from the canonical El Niño on the global climate. For example, during June to September of 2004, which is a typical El Niño Modoki year[11], the north part of India, Japan, South

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Korea and southern Mexico as well as most part of Australia experienced severe drought, while the Philippines, New Zealand and the northern Brazil suffered extreme flood. Therefore, many studies on the relationship between El Niño Modoki and some prominent climate phenomena in different regions in the world, such as ocean circulation in the South China Sea[12], tropical cyclone frequency over western North Pacific[13] and precipitation in the mainland China[14], have examined and noticed that El Niño Modoki plays distinctly different roles from those of the canonical El Niño.

Some work pointed out that the canonical El Niño could impact SST in the offshore area of China and its adjacent waters (hereafter referred to as China's offshore) through the direct heat transport of ocean circulation as well as the atmosphere circulation over East Asia[15-17]. For example, the maximum correlation coefficient between the SST of China's offshore and the canonical El Niño appears about six months after El Niño happens[18.19]. In view of the different influences of El Niño Modoki on the oceanic and atmospheric circulations from the canonical El Niño, it is worth noting how El Niño Modoki exerts impacts on the marine environment in China's offshore. In particular, recent studies indicated that SST in China's offshore has manifested prominent interannual and interdecadal variations since the late 1970s and the causes of SST variations in these waters are complicated[20, 21]. Moreover, the thermal anomaly in these waters has great impacts not only on marine environment and ecosystem in China's offshore, but also on the regional climate in China through energy and water cycle over East Asia[22-24]. Therefore, the objective of this study is to examine the relationships between El Niño Modoki and SSTA in China's offshore and to clarify the possible mechanism. In this paper, we investigate the relationship between the canonical El Niño, El Niño Modoki and SST variations during four seasons in China's offshore and also analyze the possible influences of the El Niño Modoki on the SST of China's offshore.

The paper is organized as follows. Section 2 introduces the data and methods. Section 3 presents the relationships between El Niño Modoki/El Niño and SST of China's offshore. Section 4 explores the possible impact mechanism of El Niño Modoki on the SST of China's offshore. Finally, section 6 provides discussion and conclusion of this study.

2 DATA AND METHODS

For the period of 1979-2009, the Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) with a horizontal resolution of 1°×1°[25] and the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis products, which have a horizontal resolution of 2.5°×2.5°[26], are used to examine the relationships between El Niño/El Niño Modoki and SST variations in China's offshore. Some statistical analysis techniques, such as correlation and regression analysis, the empirical orthogonal function (EOF), power spectrum and composite analysis and an index associated with El Niño Modoki, are also performed in this study. Here the four seasons are defined as follows: the boreal winter includes December of the previous year, January and February (DJF), spring includes March, April and May (MAM), summer includes June, July and August (JJA), and fall includes September, October and November (SON).

3 RELATIONSHIP BETWEEN EL NIÑO/ EL NIÑO MODOKI AND SST OF CHINA'S OFFSHORE

Given that the characteristics of SST variations in China's offshore and its relations to the East Asian monsoon in recent decades have been depicted in detail by CAI et al.[16], here we mainly focus on the relationships between El Niño Modoki as well as El Niño and SST of China's offshore.

We first carry out an EOF analysis based on the SSTA in the tropical Pacific region in summer (JJA) for the period of 1979-2009. The first leading EOF mode (EOF1), which explains 42.9% of the variance, captures the well-known El Niño pattern (Figure omitted). The canonical El Niño generally has onsets in winter or spring and promptly reaches its peak associated with anomalous trade wind and eastward tilting of the thermocline, which induce warming in the tropical eastern Pacific[7]. The second leading EOF mode (EOF2) pattern which explains 15.7% of the variance is referred to as an El Niño Modoki event associated with a zonal tripole SSTA pattern in the tropical Pacific region[6] (Fig. 1a). The maximum SSTA of the EOF2 persists in the central tropical Pacific from boreal summer to winter flanked by a colder SSTA on both sides along the equator. The principal component 2 (PC2) of the EOF2 shown in the Fig. 1b denotes that El Niño Modoki has an obvious interannual variability. Moreover, a typical El Niño Modoki, less related to the thermocline variation and may be influenced by atmospheric forcing, lasts from boreal summer through boreal winter, peaking in one of these seasons[6, 7]. Similarly, the reversed events of the first two EOF modes with the negative phase of their principal components are commonly known as La Niña and La Niña Modoki, respectively.

In view of the fact that the canonical El Niño generally happens in winter and rapidly develops strongly, we adopt the PC1 of the EOF1 SSTA mode for winter (DJF) as the representative of canonical El Niño and then carry out a pattern-correlation analysis between the PC1 and SST during the concurrent winter (DJF) and the following spring (MAM), summer (JJA) as well as fall (SON) SSTA in China's offshore, respectively. Figure 2 illustrates that SST during summer in the north part of South China Sea and the Philippines is significantly positively correlated with the preceding canonical El Niño in winter, with the maximum correlation coefficient reaching up to 0.65, which passes the 99% confidence level. The results shown above are consistent with previous studies which pointed out that the correlation coefficient between SST in China's offshore and El Niño reached its peak lagging by six months[18, 19]. A similar analysis of the relationship between canonical El Niño during summer and SST in China's offshore is also performed. However, we could not find any obvious relationship between the canonical El Niño in summer and SST variations during four seasons in China's offshore (Figure not shown).

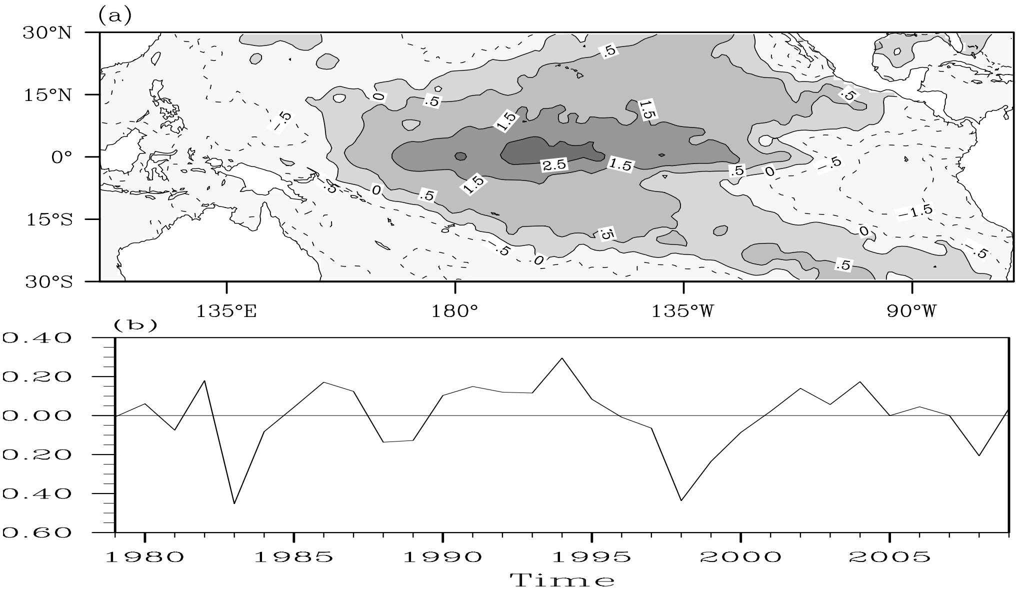

Figure 1. Spatial distribution (a) and time series (b) of the second EOF mode for summer (JJA) SSTA in the tropical Pacific for the period of 1979-2009.

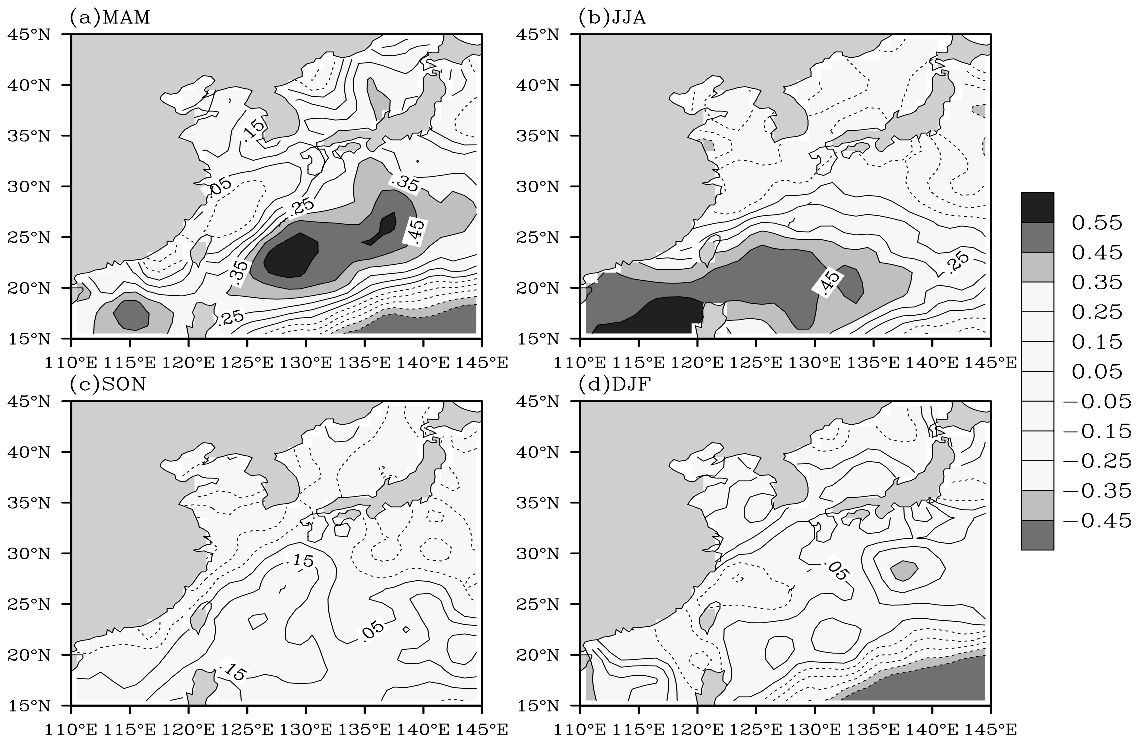

Figure 2. Relationships between El Niño during boreal winter and SST in China's offshore during the following spring (a), summer (b), autumn (c) and the concurrent winter (d), respectively.

Figure 3 illustrates the pattern correlation between PC2 of the EOF2 SSTA mode for summer in the tropical Pacific and SSTA during four seasons in China's offshore, as El Niño Modoki often occurs in summer. The SST during spring (MAM) used in the correlation analysis, as shown in Fig. 3a, is prior to the summer when El Niño Modoki happens and summer (JJA) means the same time as El Niño Modoki, while autumn (SON) and winter (DJF) associated with El Niño Modoki during boreal summer are the following seasons. In contrast to Fig. 2, El Niño Modoki is obviously related to SST during four seasons in China's offshore. In particular, it shows that there is remarkably negative correlation between PC2 and SST during autumn in China's offshore, which is located in the northeast part of South China Sea and east of the Taiwan Island. The maximum correlation coefficient that exceeds -0.55 is statistically significant at the 0.01 confidence level. It seems that the significantly related regions are closely linked to the east of Taiwan Island and the Kuroshio, extending to the northeast till the offshore area of southern Japan. In consequence, it is suggested that the northeastern South China Sea and east of Taiwan Island through the south of Japan are more easily affected by El Niño Modoki than that in the other marine areas, and the Kuroshio may be one of the most important ways of transporting the impact signal from El Niño Modoki in the central tropical ocean.

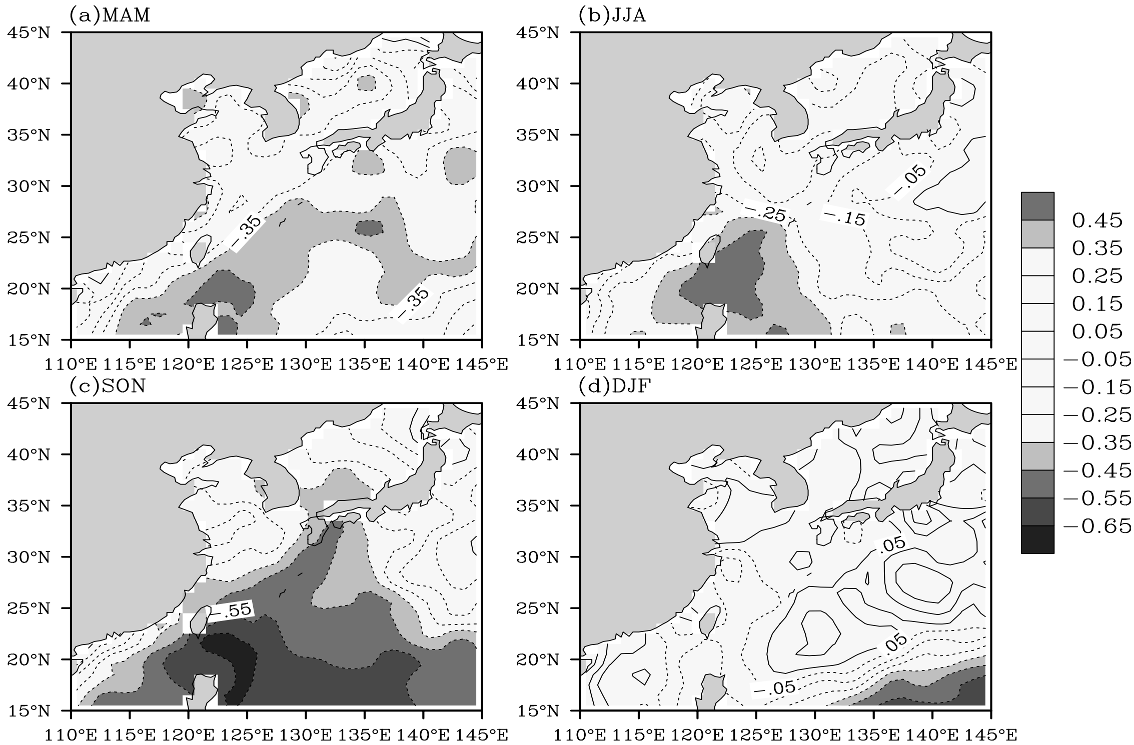

Figure 3. Relationships between El Niño Modoki during boreal summer and SST in China's offshore during the preceding spring (a), concurrent summer (b), the following autumn (c) and winter (d), respectively.

The above analysis indicates that the impacts of El Niño Modoki on SST in China's offshore are obviously different from that of canonical El Niño. As we know, the correlation coefficient between PC1 and PC2 is zero by definition. Hence, the potential impacts of El Niño and El Niño Modoki on SSTA during four seasons in China's offshore should be identified as relatively independent of each other. The relationship between SST in China's offshore and canonical El Niño is positive in lag-correlation by about six months, while the relationship of SST in China's offshore to El Niño Modoki is obviously negative and shows that SST in China's offshore responds in shorter lag-correlation by three months. In addition, SST in the most of continental shelf of the Yellow and East China Seas is weakly correlated with El Niño Modoki. This is probably because that most of continental shelf waters are easily influenced by the East Asian monsoon[16] and the meridional heat transport by the Kuroshio from the tropical Pacific becomes weaker during an El Niño Modoki period, while warm waters move to the central tropical Pacific. However, El Niño Modoki probably has also impacts on the SST of China's offshore by influencing the East Asian atmospheric circulation.

In order to further examine the internal causal relationship between SST during autumn in China's offshore and El Niño Modoki in summer, an index, referred to as EMI[6], is introduced, which describes the intensity of El Niño Modoki, and it is defined based on realistic SST in the tropical Pacific as follows:

$$EMI=[SSTA]_A-0.5\times[SSTA]_B-0.5\times[SSTA]_C \quad (1)$$

The brackets in Eq. (1) represent the area-averaged SSTA over each of the regions of A (165°E to 140°W, 10°S to 10°N), B (110°W to 70°W, 15°S to 5°N), and C (125°E to 145°E, 10°S to 20°N), respectively. The EMI deriving from SST could reflect the main characteristics of El Niño Modoki, which is somewhat different from PC2. Moreover, the correlation between EMI and the PC2 is 0.97, statistically significant at the 0.01 confidence level, which indicates that the EMI could appropriately describe the El Niño Modoki event.

Using the method of regression, the relationship between the EMI and SST during autumn in China's offshore is analyzed and results (Fig. 4) similar to Fig. 3c are obtained. The results indicate that SST during autumn in China's offshore, especially in the South China Sea and waters east of Taiwan Island as well as the northeast of the Kuroshio's adjacent waters, is negative to the summer EMI (Fig. 4). The correlation between the summer EMI and the PC1 of the EOF1 SSTA mode for fall in China's offshore is -0.38 (Fig. 5), above the 0.05 confidence level. A power spectrum analysis of summer EMI indicates that El Niño Modoki has a two-year interannual variability that is similar to the result of YU et al.[9]. Thus, it is suggested that the interannual variability of El Niño Modoki may influence SST during autumn in China's offshore.

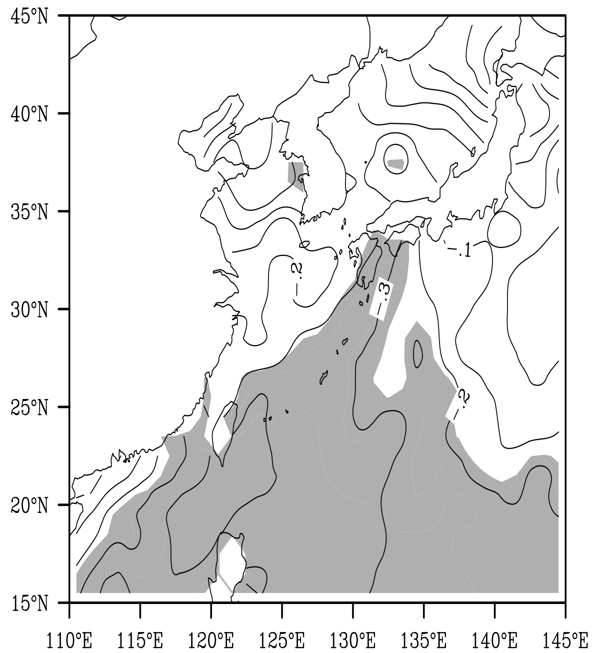

Figure 4. Regression of summer EMI on SSTA during fall in China's offshore.

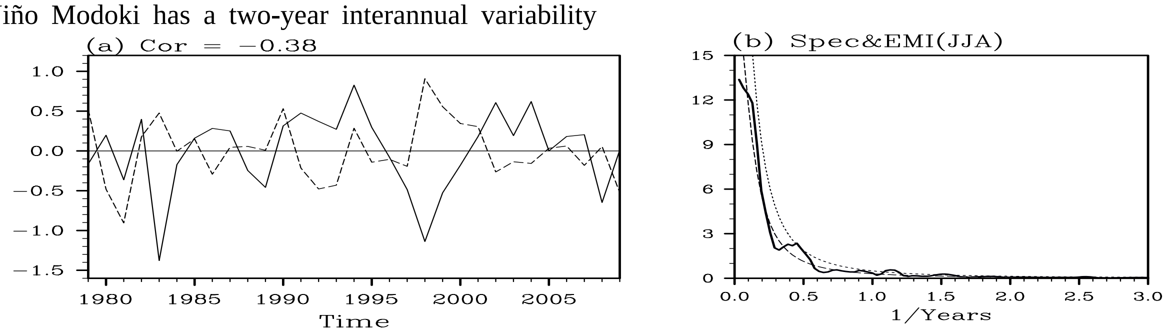

Figure 5. Summer EMI (solid line) and PC1 (dashed line) of SST during autumn in China's offshore (a) and power spectrum of summer EMI (b). Dashed line (dotted line) denotes the 90% (95%) confidence level.

4 POSSIBLE CAUSES FOR INFLUENCE OF EL NIÑO MODOKI ON SST DURING AUTUMN IN CHINA'S OFFSHORE

The above analysis shows that the Kuroshio may play a vital role in El Niño Modoki affecting the SST during fall in China's offshore. Is there any other mechanism which is associated with El Niño Modoki that influences the SST in China's offshore? Recent studies show that local SST in tropical oceans may exert important influences on the remote climate change all over the world through "atmosphere bridge" [27, 28], just like the canonical El Niño and its teleconnection. For El Niño Modoki, zonal SST gradients in the tropical Pacific result in anomalous two-cell Walker Circulation over the tropical Pacific [29], i.e., joint ascending branches cover extensive areas of the central tropical Pacific and the descending branches of the two cells are over the western and eastern tropical Pacific. The anomalous circulation over tropical oceans will further modulate circulations over the mid- and higher-latitudes and reflect strong air-sea interactions over extratropical oceans, including China's offshore.

Figure 6 shows composite SSTA and wind field anomalies at 925 hPa during some typical El Niño Modoki events averaged over seven boreal summers, namely, JJA seasons of 1986, 1990, 1991, 1992, 1994, 2002, and 2004. The composite result indicates that the anomalous westerly and easterly during summer El Niño Modoki will prevail over the western and eastern tropical Pacific, resulting in the movement of surface warm waters to the central tropical Pacific. The western and eastern tropical Pacific will be cooling because of upwelling of subsurface cold water. On the one hand, relatively cold waters are sustained by the presence of anomalous westerly over the western tropical Pacific that weakens meridional heat transport of source areas of the Kuroshio and results in cooling in the East China Sea, but on the other hand, the anomalous northerlies prevailing from the northern part of the Philippines to the offshore area of China induced by El Niño Modoki make conditions unfavorable for transport of warm waters from tropical oceans to midlatitudes. Cai et al.[16] once reported that SST of China's offshore, especially the East China Sea, is much negatively correlated with East Asian winter monsoon. Furthermore, the lagged response of the ocean to change in the atmosphere circulation is about three months according to Mei et al.[30]. Therefore, it is easy to understand that SST during autumn in China's offshore is negatively to summer El Niño Modoki.

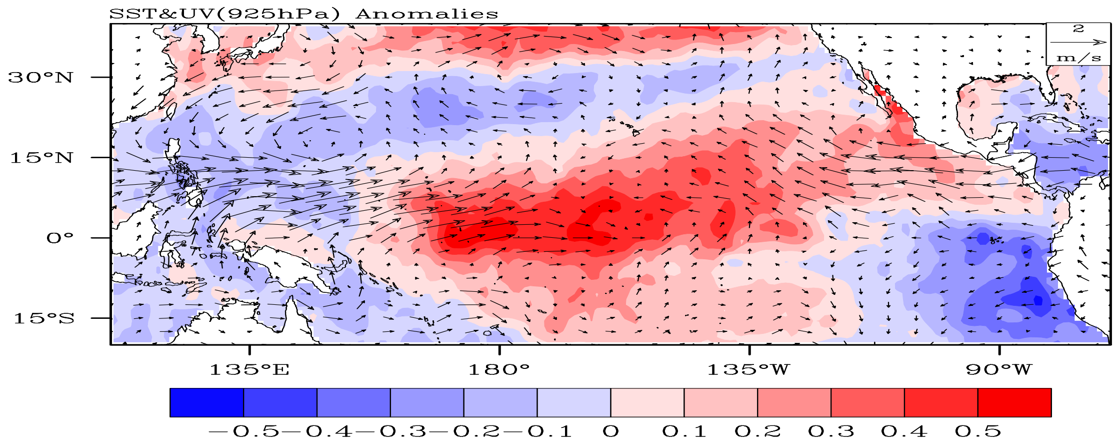

Figure 6. Composite mean summer winds at 925 hPa (arrows) and SSTA (color shading) in the tropical Pacific.

Generally, El Niño Modoki reaches its peak in summer and sometimes persists to autumn and winter. We also analyze the relationship between the autumn El Niño Modoki and SST during winter in China's offshore. However, there is no obvious relationship between them. Perhaps, the East Asian winter monsoon plays a leading role in the change of SST during winter in China's offshore[16].

5 CONCLUSIONS AND DISCUSSION

Recent studies indicated that the properties of El Niño exhibits changes in frequency and amplitude since the late 1970s and a new type of tropical Pacific phenomenon, with increased SST in the central Pacific and sandwiched by anomalous cooling in the east and west, has been observed. The events, namely El Niño Modoki, emerge with increasing frequency probably due to anthropogenic climate warming[29]. The modification in the structure of general circulation has implications for its teleconnection pattern in many terrestrial and oceanic climates all over the world. In this work, we investigate possible links between SST in China's offshore and El Niño Modoki. The main results are summarized as follows.

(1) The summer El Niño Modoki has some relations to SST during four seasons in China's offshore. In particular, there is remarkably negative correlation between El Niño Modoki and SST during fall over the northeast part of South China Sea and the Kuroshio areas from east of the Taiwan Island to the southern waters of Japan. The maximum correlation coefficient exceeds -0.55, above the 0.01 confidence level.

(2) SST in the west of the Kuroshio, including most of the Yellow Sea and East China Sea, is weakly correlated with El Niño Modoki, probably because SST of China's offshore is easily influenced by the East Asian monsoon. Furthermore, SST in the continental shelf may be also indirectly affected by the atmospheric circulation anomalies over China's offshore associated with El Niño Modoki, although the heat transports by ocean circulation associated with El Niño Modoki are weakened due to the mixing effect of the shallow sea.

(3) When El Niño Modoki occurs, the surface warm water in the western tropical Pacific moves to the central equatorial Pacific, resulting in the weakening of meridional heat transport of the Kuroshio. Meanwhile, anomalous northerlies prevailing over the regions from the northern part of the Philippines to the offshore area of China are also unfavorable for the transport of warm water from the western tropical Pacific to the mid-latitude area. Consequently, El Niño Modoki in summer may greatly contribute to cold SST during autumn in China's offshore by changing the meridional heat transport from Kuroshio, with a lagged response of the ocean to the atmospheric wind field.

The primary results presented here partially document the possible impacts of El Niño Modoki on the SST in China's offshore. However, it should be pointed out that there are still many other factors that could exert important influences on it, such as meridional heat transport by the Kuroshio, East Asian monsoon, and land-sea interaction. Hence, possible mechanisms for the variations of SST in China's offshore need further exploration in the future. Furthermore, the influences of El Niño Modoki on the SST of the above-mentioned areas also need to be verified by much more observation, dynamics theory and numerical modeling. Last but not least, the thermal anomalies of China's offshore and relevant energy and water cycle over East Asia associated with El Niño Modoki may further influence China's regional climate, which also needs further investigation.

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