Genesis of westerly wind bursts over the equatorial western Pacific during the onset of the strong 2015–2016 El Niño

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Abstract
The strong 2015–2016 El Niño was initiated by several strong westerly wind bursts over the equatorial western Pacific in March and May 2015. These westerly wind bursts trigger eastward propagating warm Kelvin waves and lead to large sea surface temperature (SST) warming in the equatorial eastern Pacific. The first burst of westerly winds in early March was mainly induced by the Arctic Oscillation (AO) event. These westerly wind anomalies were enhanced subsequently due to the Madden-Julian Oscillation activity and northerly cold surges from East Asia-western Pacific in mid-March. Another westerly wind burst in May, induced by anomalous southerly winds from the Australian continent, further increased the SST anomaly in the equatorial eastern Pacific. This study provides an evidence of the AO influence on this strong El Niño-Southern Oscillation (ENSO) event and demonstrates the complexity in the genesis of westerly wind bursts during the El Niño outbreak, which may help improve the prediction of ENSO.

Keywords: 2015–2016 El Niño; westerly wind bursts; Arctic Oscillation; MJO

I. Introduction

The El Niño-Southern Oscillation (ENSO) is the strongest ocean-atmosphere coupled mode in the tropical Pacific on the interannual timescale. It exerts pronounced influences on weather and climate over many parts of the globe (e.g. Trenberth et al., 1998; Wang et al., 2000; Alexander et al., 2002). Thus, a better understanding of the variability and mechanism of the formation of ENSO is of great importance for improving the ENSO prediction.

Observations show that a strong El Niño event occurred in the tropical central-eastern Pacific, with the maximum sea surface temperature (SST) anomalies reaching over 2.5°C after May 2015 (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml). The World Meteorological Organization reported that the current El Niño event is one of the strongest events since 1950 (http://www.wmo.int/pages/index_en.html). This ongoing strong El Niño has already been found to play an important role in a number of extreme weather and climate events. For instance, there have been a total of 21 storms in 2015 over the North Pacific, exceeding the record of 17 set in 1997, which was attributed to the effect of El Niño (Chu, 2004). The National Oceanic and Atmospheric Administration (NOAA) reported that, by the end of 2015, ocean conditions resulted largely from the ongoing El Niño event in the tropical central-eastern Pacific would cause almost 95% of the

US corals to bleach (http://coralreefwatch.noaa.gov/). The India Meteorological Department reported that the strong 2015–2016 El Niño contributes largely to the rainfall deficit in India during June–September 2015 (http://www.imd.gov.in/). In view of the pronounced influences, it is an important issue to characterize and understand the outbreak of this strong El Niño event.

Previous studies demonstrated that westerly wind anomalies over the equatorial western-central Pacific play a key role in the outbreak of El Niño events (Yu and Rienecker, 1998; Huang et al., 2001; Lengaigne et al., 2004). The anomalous westerly winds trigger an eastward propagating and downwelling Kelvin wave, which results in SST warming in the equatorial central-eastern Pacific. The SST warming may further develop into an El Niño event via the Bjerknes positive feedback mechanism (Bjerknes, 1969). Hence, a key issue to understand the outbreak of the 2015–2016 El Niño is to identify the origin of equatorial Pacific wind anomalies.

Westerly wind anomalies over the equatorial western-central Pacific are influenced by several factors, such as the Madden-Julian Oscillation (MJO; Madden and Julian, 1972; Hendon et al., 2007), northerly cold surges from East Asia (Li, 1990), southerly wind anomalies from the Australian continent (Chen and Wu, 2000; Xu and Chan, 2001) and the North Pacific Oscillation (NPO; Vimont et al., 2003). For example, Li (1990) indicated that northerly cold surges originated from East Asian land may induce westerly wind anomalies over the tropical western
Pacific via modulating the local atmospheric convection. Vimont et al. (2003) demonstrated that the boreal winter NPO influences El Niño events in the subsequent winter via the seasonal footprinting mechanism (SFM). Nakamura et al. (2006) found that the spring Arctic Oscillation (AO) is an important trigger for the outbreak of an El Niño in the following winter via modulating westerly wind anomalies over the equatorial western Pacific. A recent study reported that the AO can induce westerly wind anomalies in spring over the equatorial western Pacific via modulating the local atmospheric convection (Chen et al., 2014). In addition, Chen et al. (2013) found that only when the spring AO is in its positive phase, the preceding winter positive NPO may lead to an El Niño event in the following winter via the SFM. In this study, we will examine which factor(s) contribute to the generation of westerly wind anomalies in the equatorial western Pacific during the onset of the strong 2015–2016 El Niño.

2. Data and methods

This study uses daily mean 850 hPa winds from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis (Kalnay et al., 1996) with a horizontal resolution of 2.5° × 2.5°. The daily mean SST data were derived from the NOAA Optimum Interpolation 1/4 Degree Daily Sea Surface Temperature analysis (Reynolds et al., 2007), with a resolution of 0.25° × 0.25°. The pentad mean ocean temperature data were obtained from the NCEP Global Ocean Data Assimilation System reanalysis (Xue et al., 2012). This oceanic reanalysis has a 1° × 0.33° horizontal resolution and 40 levels in the vertical direction. The ocean temperature is used to calculate the ocean heat content (OHC) in the upper 300 m.

The normalized daily mean AO index was derived from the website of NOAA Climate Prediction Center (http://www.cpc.ncep.noaa.gov/). We employ a real-time multivariate (RMM) MJO index developed by Wheeler and Hendon (2004) to examine the MJO activity (http://www.bom.gov.au/climate/mjo). This RMM index monitors well the real-time MJO activity (Wheeler and Hendon, 2004).

3. Results

3.1. Formation of the 2015 El Niño

Before late March 2015, negative and positive SST anomalies appeared in the equatorial eastern and western Pacific, respectively (Figure 1(a)). Correspondingly, negative and positive anomalies of OHC are observed in the equatorial eastern and western-central Pacific, respectively (Figure 1(b)). This zonal distribution of SST and OHC anomalies in the equatorial Pacific provides a favorable condition for the outbreak of an El Niño (Jin, 1997). In mid-April 2015, large positive SST anomalies, with the magnitude reaching 2.1 °C, occurred abruptly in the equatorial eastern Pacific.
around 90°W (Figure 1(a)). This was preceded by a strong warm Kelvin wave that was formed in the equatorial central Pacific in early March 2015 (Figure 1(b)). This eastward propagating warm Kelvin wave can be captured by the OHC anomalies (Figure 1(b)). As shown in Figure 1(b), positive OHC anomalies propagated eastward and reached the equatorial eastern Pacific in April 2015. Note that the above-mentioned warm Kelvin wave can also be detected by the sea surface height anomalies (not shown). The large positive SST anomalies in the equatorial eastern Pacific after the early April tend to be related to this eastward propagating warm Kelvin wave. The magnitude of SST anomalies in the equatorial eastern Pacific increases and reaches above 2.5°C after the mid-June. As shown in Figure 1(b), another OHC anomaly with a smaller magnitude formed over the equatorial central Pacific in the mid-May and subsequently propagated eastward. This implies that the enhancement of SST anomalies after the mid-June is related to this latter eastward propagating Kelvin wave. The results hence suggest that the two eastward propagating warm Kelvin waves formed in March and May, respectively, play a key role in the outbreak of the 2015 El Niño.

Previous studies have demonstrated that an equatorial eastward propagating Kelvin wave can be resulted from tropical zonal wind stress anomalies or generated by the reflection of a Rossby wave at the western boundary (e.g., Matsumo, 1966; Huang et al., 2001). A comparison of Figure 1(b) and (c) indicates that the two above mentioned warm Kelvin waves were formed at a time of strong westerly wind anomalies over the equatorial western-central Pacific. Hence, the generation of these two eastward propagating Kelvin waves may be mainly attributed to the corresponding strong westerly wind anomalies in the early March and May. The westerly wind anomalies in the early March (>16 m s⁻¹) are larger than those in the early May (>13 m s⁻¹). Note that strong westerly wind anomalies are also observed in the equatorial western-central Pacific in the early July 2015, and propagate eastward to the tropical central-eastern Pacific in mid-July. This eastward propagating Kelvin wave may largely contribute to the strengthening of the current El Niño. As this study is focused on the onset phase of the 2015–2016 El Niño, we only investigate the factors that contributed to the formation of the westerly wind bursts in the early March and May.

3.2. Factors for the westerly wind burst in March 2015

Figure 2 displays the evolution of daily-averaged 850 hPa winds anomalies in March 2015. To help understand the formation of westerly wind anomalies over the equatorial western-central Pacific, we also show in Figure 3(a) the normalized time series of daily-averaged AO index from 15 February to 24 April, and the daily RMM index in Figure 3(b).

On 1 March, a strong anomalous anticyclone formed over the midlatitude of North Pacific, together with a weak anomalous cyclone over the subtropical central North Pacific (Figure 2(a)). Note that westerly wind anomalies are present over the equatorial central Pacific associated with an anomalous cyclone over the tropical South Pacific. This anomalous cyclone weakened in the following 2 days (Figure 2(b)). As such, the associated westerly wind anomalies over the equatorial central Pacific decayed. On 3 March, a clear dipole wind anomaly pattern is observed over the North Pacific, with a strong anomalous anticyclone in the midlatitude and a weak anomalous cyclone in the Tropics (Figure 2(b)). Correspondingly, weak westerly wind anomalies develop over the equatorial Pacific between 150°W and 180°E. The dipole wind anomaly pattern maintains and enhances in the next 4 days (Figure 2(b)–(e)). On 7 March, the maximum wind speed over the equatorial western-central Pacific reaches 17 m s⁻¹ (Figure 2(e)). The dipole pattern over the North Pacific bears a close resemblance to that associated with the spring AO (Gong et al., 2011; Chen et al., 2014). This indicates a possible contribution of AO to the formation of the anomalous cyclone over the tropical central North Pacific.

Chen et al. (2014) showed that the spring AO can exert a significant influence on the outbreak of an El Niño via modulating the westerly wind anomalies over the tropical western-central Pacific. Specifically, a significant anticyclonic circulation anomaly is observed over the midlatitude North Pacific and a pronounced cyclonic circulation anomaly is seen over the tropical central North Pacific in the positive phase of spring AO (please see their Figure 3). As such, westerly wind anomalies formed over the equatorial western-central Pacific to the south of the anomalous cyclone. The interaction between the synoptic scale eddy and low frequency mean flow plays a key role in the formation of the anomalous cyclone over the tropical central North Pacific in association with the spring AO. The normalized daily AO index shows values larger than 2 from 1 to 7 March (Figure 3(a)). In particular, the normalized AO index is larger than 5 on 7 March (Figure 3(a)). An enhancement of anomalous cyclone over the tropical central North Pacific and the associated westerly wind anomalies from 5 to 7 March (Figure 2(d)) is accompanied by an increase of the AO value (Figure 3(a)). Hence, AO plays a key role in the formation of the anomalous cyclone over the tropical central North Pacific and the anomalous westerly wind to its south over the equatorial western-central Pacific.

On 8 March, the anomalous cyclone over the tropical central North Pacific enhances, with the maximum wind speed reaching 20 m s⁻¹ (Figure 2(f)). In addition, an anomalous equatorial twin cyclones pattern is clearly seen. The enhancement of this anomalous cyclone over tropical central Pacific is also related to a northerly cold surge penetrating into the tropical western-central Pacific from East Asia. Previous studies demonstrated that the northerly cold surge from higher latitudes could...
result in deep convections in the Tropics and induce equatorial twin cyclonic anomalies (e.g., Li, 1990). Formation of the northerly cold surge over East Asia and western Pacific may be partly related to the spring AO (Nakamura et al., 2007). Nakamura et al. (2007) indicated that spring AO could impact the westerly wind anomalies over the tropical western Pacific via modulating the Asian cold surge. Nevertheless, the physical process responsible for the influence of spring AO on the Asian cold surge is still unclear and remains to be explored. The northerly cold surge from East Asia is observed in the next 3 days (Figure 2(g)–(i)). This indicates a contribution of the cold surge to the enhancement of westerly wind anomalies over the equatorial western-central Pacific.

The anomalous equatorial twin cyclones are stronger and their spatial scales are larger on 10 and 11 March compared to those on 8 and 9 March (Figure 2(g)–(i)). This enhancement may be related to the arrival of MJO into the tropical western Pacific. From 7 to 9 March, the RMM index enters phase 5 over the Maritime continent (Figure 3(b)). The anomalous cyclone to the northwest of Australia on 8 March may be related to the MJO activity (Figure 2(f)). After 10 March, the RMM index enters into phase 6 (Figure 2(h) and (i)). This indicates that the westerly wind anomalies associated with the

Figure 2. Anomalies of the daily mean 850 hPa wind (vector, m s\(^{-1}\)) and wind speed (shading, m s\(^{-1}\)) from 1 to 17 March in 2015. Anomalies are calculated by removing the daily mean climatology over 1982–2011.
MJO would enhance the westerly wind anomalous initiated by the AO and northerly cold surge. Thus, the further enhancement of westerly wind anomalies over the equatorial western-central Pacific on 10 and 11 March may be attributed to the MJO. After 13 March, the anomalous cyclone over the North Pacific propagates northward into subtropical western North Pacific, and the associated westerly wind anomalies are weakened and move away from the equator to around 10°N (Figure 2(j)–(l)). In comparison, the anomalous cyclone over the tropical South Pacific propagates southeastward into the subtropical southeastern Pacific (Figure 2(j)–(l)).

The earlier results indicate that the first appearance of westerly wind anomalies over the western Pacific is attributed to the AO. Subsequently, the enhancements of westerly wind anomalies are related to both the northerly cold surge originated from East Asia and an eastward propagating MJO. It should be noted that interactions may exist among AO, MJO and northerly cold surge. For example, Zhou and Miller (2005) indicated that a positive (negative) AO phase is more likely connected with a positive (negative) MJO phase in the boreal winter season. L’Heureux and Higgins (2008) found that the global circulation anomalies in association with AO bear a close resemblance to those related to MJO during boreal winter. Murakami (1988) reported that the northerly surge from extratropics could excite pronounced convection related to MJO. In addition, the occurrence frequency of the East Asian cold surge during boreal winter is found to be below normal when AO is in its positive phase (e.g. Jeong and Ho, 2005). Further investigation is needed to clarify whether spring AO plays a role in the formation of the northerly cold surge and MJO over the tropical western Pacific in March 2015 and to understand the related physical processes.

3.3. Factors for the westerly wind burst in May 2015

In the following, we further analyze the generation of westerly wind bursts over the tropical western-central Pacific in May 2015. Figure 4 displays the evolution of daily-averaged 850 hPa winds anomalies in May 2015. On 2 May, the wind anomalies over the tropical western-central Pacific are weak (Figure 4(a)). A strong anomalous cyclone (anticyclone) is observed over the midlatitudes of North (South) Pacific (Figure 4(a)). In addition, weak westerly wind anomalies are present over the equatorial western-central Pacific. An anomalous cyclone appears in the tropical South Pacific, but it is weakened and then disappears in the next 2 days (Figure 4(a) and (b)). On 4 May, the westerly wind anomalies are observed over the equatorial western Pacific extending eastward to the eastern Pacific, together with a weak anomalous cyclone seen in the tropical South Pacific (Figure 4(a)). In addition, weak westerly wind anomalies are present over the equatorial western-central Pacific. 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Figure 4. Anomalies of the daily mean 850 hPa wind (vector, m s\(^{-1}\)) and wind speed (shading, m s\(^{-1}\)) anomalies from 2 to 19 May in 2015. Anomalies are calculated by removing the daily mean climatology over 1982–2011.

region on 5 May (Figure 4(c)). As this southerly surge associated with the Australian monsoon continues for the next 4 days, a clear and strong anomalous cyclone forms over the tropical western Pacific between 150° and 170°E (Figure 4(d)–(g)). Xu and Chan (2001) have reported that anomalous southerly winds associated with the Australian monsoon could produce strong convergence over the equatorial western-central Pacific, which would subsequently lead to the intensification of tropical westerly wind anomalies. Correspondingly, the westerly wind anomalies around 160°E significantly increase (Figure 4(d)–(g)). On 11 May, a northerly surge originating from the midlatitude North Pacific penetrates deep into the equator and converges with the southerly surge from the Australian continent. This convergence leads to the generation of the anomalous equatorial twin cyclones and enhancement of the westerly wind anomalies between 150° and 170°E (Figure 4(h)). The southerly surge from Australia and the anomalous northerly wind weaken on 13 May and disappear on 15 May (Figure 4(i) and (j)). Subsequently, the anomalous cyclone over the tropical western-central Pacific weakens and propagates poleward, and the westerly wind anomalies over the tropical western-central Pacific decay (Figure 4(k) and (l)). An examination of the RMM index in May shows that the
MJO is inactive in May (Figure 3(b)). This implies that MJO may not play a significant role in the generation of westerly wind bursts over the tropical western-central Pacific in May 2015.

The results suggest that the southerly surge from the Australian continent plays a key role in the generation of the westerly wind anomalies over the equatorial western-central Pacific in May. This confirms the finding of previous studies that the southerly surge from East Australia can contribute to the development of the ENSO (Chen and Wu, 2000; Xu and Chan, 2001).

4. Summary and discussion

A strong El Niño event occurred in the tropical central-eastern Pacific in 2015. Our study indicates that the onset of this strong El Niño is closely related to two eastward propagating warm Kelvin waves induced by strong westerly wind anomalies in early March and May. The first appearance of westerly wind anomalies over the tropical western-central Pacific in March is found to be induced by the AO. The westerly wind anomalies are further enhanced by the MJO activity and the northerly cold surge from East Asia. Thus, the strong westerly wind anomalies generated jointly by the AO, MJO and northerly cold surge trigger eastward propagating warm Kelvin wave to initiate the SST warming in the equatorial eastern Pacific. In May, the generation of the westerly wind anomalies is mainly related to the southerly surge associated with the Australian monsoon activity. This study provides another evidence confirming that the AO can exert significant influences on the outbreak of an El Niño via modulating westerly wind anomalies over the equatorial western-central Pacific. Yet, it also indicates a combined role of other factors that provides a more favorable condition for the El Niño occurrence.

AO, MJO and cold surges from extratropics are important for the outbreak of the strong 2015–2016 El Niño. Nevertheless, it should be noted that other factors may also play a role in influencing this El Niño event. For example, previous studies indicated that the preceding NPO (Vimont et al., 2003), North Atlantic Oscillation (Oshika et al., 2015), North Atlantic SST (Wang et al., 2011; Ham et al., 2013) and warm water in the tropical Pacific (Anderson et al., 2013) may also influence the subsequent winter ENSO variability. In addition, preliminary results indicate that the preceding AO also plays an important role in the formation of westerly wind bursts over the equatorial western-central Pacific in the outbreak of the 1997–1998 El Niño (not shown). A comparison of the AO–ENSO connection between these two strong El Niño cases is ongoing.

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