The negative feedback effects of sea surface temperatures on El Niño Events in the West Indian Ocean

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Abstract
In this study, multiple sets of atmospheric and oceanic observational data were used in combination with composite analysis and correlation analysis methods, in order to analyze the anomalous eastward spread phenomena of the equatorial Indian Ocean during the autumn and winter seasons when El Niño events have previously occurred. The analysis results showed that anomalous increases in the SSTs (sea surface temperatures) in the West Indian Ocean during the early autumn seasons had triggered the responses of anomalous easterlies. Meanwhile, anomalous anticyclonic circulation was observed to have existed on the north side of the easterlies. It was found that with the maximum center of the specific humidity retreating toward the vicinity of the equator during the processes of the seasonal conversion, the asymmetry of moisture advection on the eastern and western sides of the anomalous anticyclonic circulations tended to lead to the circulation systems to move in an eastward direction until reaching the Northwest Pacific region. During the winter seasons with peak periods of El Niño events, the easterly anomalies in the equatorial West Pacific Ocean were found to stimulate the upturning Kelvin fluctuations in the ocean. This resulted in eastward spreading actions which eventually helped the El Niño events to transform into La Niña events.

KEYWORDS
air–sea interactions, anomalous eastward spread of the easterlies, correlation analyses, negative feedback of the El Niño events, sea surface temperatures in the West Indian Ocean

1 | INTRODUCTION

ENSO (El Niño–Southern Oscillation) is the main mode of the climate variabilities in the tropical Pacific Ocean. ENSO is formed by the dynamic coupling of the ocean and atmosphere in the tropical Pacific Ocean (Trenberth et al., 1998). El Niño refers to the anomaly of the heating of equatorial East Pacific SSTs, and the Southern Oscillation (SO) refers to the reverse change phenomena of the pressure between the Indian and South Pacific Oceans. Since both display a very highly corresponding relationship, they are generally collectively referred to as ENSO, of which the warm and cold phase correspond to the El Niño (warm) and La Niña (cold) events, respectively. The results of recent studies have shown that ENSO events can be divided into two categories according to the locations of the SST anomaly centers. For example, traditional and central-type ENSO events with SST anomaly centers located in the tropical Eastern and Central Pacific Oceans (Ashok et al., 2007; Kao and Yu, 2009; Kug et al., 2009). ENSO events are known to be closely related...
to global climate anomalies (Zhang et al., 1996; Wang et al., 2000, 2003; Wu and Wang, 2002; Wu et al., 2009; Jin et al., 2016; Okumura et al., 2017). The identification of the generation mechanism of ENSO events is of great significance for deepening the understanding and establishing effective prediction method for ENSO events and associated climate anomalies.

At the present time, the following mainstream theories mainly exist for the formation and maintenance of ENSO events: When El Niño events occur (eg, positive SST anomalies occur in the tropical middle and central East Pacific Ocean, accompanied by westerly anomalies in the region), the trade winds weaken causing the Walker circulation to be abated. The abating of Walker circulation is known to be conducive to the eastward accumulation of warm water in the West Pacific Ocean, which subsequently leads to anomalous increases of the SST. These increases in the SST have been observed to enhance and maintain El Niño events, including the Bjerknes positive feedback mechanism (Bjerknes, 1969). In accordance with the trade wind relaxation theory presented by Wyrtki (1975), the trade winds in the tropical Pacific Ocean (easterlies) drive the ocean flow to the Western Pacific Ocean along the equator. The resulting accumulations on the ocean's westerly boundary raise the sea surface height, and cause increases in the thermocline. Meanwhile, the sea levels in the Eastern Pacific Ocean decrease, and the thermocline becomes shallow. These types of situations result in increases in the sea surface slope between the equatorial Western and Eastern Pacific Ocean regions, in which considerable potential energy becomes preserved. The weakening of trade winds leads to the release of the marine potential energy, and the warm surface water is transported to the tropical Eastern Pacific Ocean. Then, as the sea surface height increases, the thermocline thickens, and the sea surface temperatures increase, resulting in the occurrences of El Niño events. In accordance with the unified oscillator theory presented by Wang (2001), four negative feedback mechanisms may jointly terminate El Niño events. These include delayed oscillator mechanisms (Zebiak and Cane, 1987; Suarez and Schopf, 1988); charge-discharge oscillator mechanisms (Jin, 1997; Li, 1997); Western Pacific Ocean oscillator mechanisms (Weisberg and Wang, 1997); and advection-reflection oscillator mechanisms (Picaut et al., 1997).

It has been well documented that the anomalous warming of the tropical Pacific SST during El Niño events has a significant teleconnection effect on the climate variabilities of the Indian and Atlantic Oceans (Enfield and Mayer, 1997; Chang et al., 2000; Alexander and Scott, 2002; Chiang and Sobel, 2002; Kug and Kang, 2006; Chowdary and Gnanaseelan, 2007; Xie et al., 2009; Sayantani et al., 2014). However, a growing number of related research results have also shown that SST anomalies in the tropical Indian and Atlantic Ocean regions also have remote influences on the variabilities of the ENSO events (Xie et al., 2002; Annamalai et al., 2005; Schott et al., 2009; Luo et al., 2012; Ham et al., 2013; McGregor et al., 2014; Sasaki et al., 2014; Chen and Li, 2017; Saji et al., 2018). It was observed in this study that the link between the SST anomalies and the ENSO events in the Southwestern Indian Ocean has so far received less attention from meteorologists. Therefore, the relationship between the SST anomalies and the ENSO events in the Southwestern Indian Ocean was analyzed in this study, for the purpose of identifying the possible influences of a physical mechanism on the Southwestern Indian Ocean ENSO events, and thereby provide a scientific basis and clues for a deeper understanding of ENSO events.

2 | DATA AND METHODS

The atmospheric low-level wind field and specific humidity datasets which were used in this study were obtained from the NCEP reanalysis data (National Centers for Environmental Prediction Reanalysis Version 2, NCEPv2 Kanamitsu et al., 2002). The extensions and reconstructions of the SST data (Extended Reconstructed Sea Surface Temperature Version 5, ERSSTv5; Huang et al., 2017); OLR data (Outgoing Longwave Radiation; Liebmann and Smith, 1996); and GPCP data (Global Precipitation Climatology Project) were provided by NOAA (National Oceanic and Atmospheric Administration). In the tropical ocean areas, the propagation of the fluctuations in the thermocline is a key factor in maintaining the ENSO and Indian Ocean Dipole (IOD) cycles. The changes in the thermocline depths can be represented by the changes in the depths of a 20°C isotherm (Z20) or sea surface heights (SSH). In this research study, the depth data of the oceanic thermocline was derived from GODAS (Global Ocean Data Assimilation System; Saha et al., 2006), which was provided by the NCEP, and the ORAS data (Ocean Reanalysis System 4, ORAS4; Baldwin et al., 2013) was provided by the European Centre for Medium-Range Weather Forecasts.

The selection criterion of the El Niño events in the current study were consistent with NOAA ONI (Oceanic Niño Index). When the 3-month sliding average SST anomalies (sea surface temperature) in the Niño3.4 area were greater than 0.5 K for five consecutive months, they were defined as El Niño events. Therefore, in accordance to this criterion, a total of 11 El Niño events (1982, 1986, 1987, 1991, 1994, 1997, 2002, 2004, 2006, 2009, and 2015) were selected for this study’s analysis of the period ranging from 1979 to 2017.

In order to determine the previous signals of the atmospheric and oceanic fields in the Indian Ocean which had
affected the ENSO cycles, the inter-annual change anomalies were obtained after removing the climate mean state. Then, a synthetic analysis method was first used to investigate the spread situations of the easterly anomalies in the equatorial Indian Ocean; determine the Indian Ocean SSTs which were associated with the ENSO cycles; and identify the key areas with changes in convective activities. On this basis, a correlation analysis method was applied to further investigate the effects of the anomalous heating fields in the identified key areas on the latitudinal wind fields and oceanic waves of the equatorial Pacific Ocean. The specific processes used in this study are shown in the following content.

3 | RESULTS

3.1 | Anomalous eastward spread of the equatorial Indian Ocean easterlies

The observational results showed that during the autumn and winter periods of the El Niño events, the easterly anomalies of the equatorial Indian and Pacific Ocean regions had displayed obvious eastward spread characteristics. Figure 1 details the time series of the equatorial low level (925–700hPa) zonal wind anomalies in all of the El Niño events since 1979. It can be seen that the majority of El Niño events had the eastward spread characteristics of anomalous easterlies. The composite results of the El Niño events clearly showed that during the early autumn seasons in the northern hemisphere, there were strong anomalous easterlies in the equatorial Indian Ocean (60°–90°E), when the equatorial Pacific Ocean was dominated by anomalous westerlies. In the following autumn and winter periods, the easterly anomalies of the equatorial Indian Ocean had constantly spread eastward to the equatorial Eastern Pacific Ocean region. Meanwhile, the westerly anomalies over the equatorial Pacific Ocean had gradually retreated in an eastward direction. Subsequently, the easterly anomalies continued to spread further eastward to the equatorial Eastern Pacific Ocean region and were transformed into westerly anomalies over the Indian Ocean. It was suggested that in the cases where the Walker Circulation was strengthened, El Niño events had been transformed into La Niña events at the end of the following year.

The results revealed that eight of the 11 El Niño events since 1979 had displayed the relatively obvious easterly spread characteristics of the equatorial Indian Ocean. The observational results also indicated that La Niña events had occurred at the end of the next year for eight of the El Niño events. Meanwhile, it was also noted that during the three El Niño events which had occurred in 1986, 1991, and 2002, the anomalous easterlies of the Indian Ocean had presented no obvious eastward spread and were instead dominated by local oscillation characteristics (Figure 1 b, d, g). The observational results also revealed that there were no La Niña events in the following year for those three El Niño events. The absence of eastward spread during 1986, 1991, and 2002 El Niños may be attributed to (a) reversed zonal dipole mode of convective heating in northern fall of 1986 and 1991, and (b) anomalous descending motion along the equatorial Indian Ocean and western Pacific during the mature winter of 1986, 1991, and 2002 El Niños (figures not shown).

The above statistical results suggested that if the easterly anomalies over the equatorial Indian Ocean during the autumn and winter seasons of the El Niño events had or had not displayed eastward spread characteristics played an important indicative role in determining the phases of the El Niño events. Therefore, the future generation of eastward spreading may provide major assistance in understanding the ENSO cycles. In the subsequent research studies, synthesis analyses will be conducted on the eight El Niño events with the characteristics of eastward spreading of the easterly anomalies, with the expectations of determining the causes of the easterly anomalies and eastward spreading and analyzing the possible influences on the ENSO cycles.

3.2 | Trigger mechanism of the easterly anomalies in the equatorial Indian Ocean

In the early autumn months of the synthetic El Niño event (September), the SST anomaly field in the tropical Indian Ocean showed a zonal dipole distribution pattern, with positive anomalies dominant in the Western Indian Ocean, and negative anomalies dominating the Eastern Indian Ocean (Figure 2a). This zonal dipole distribution pattern was observed to be maintained in the autumn months of the El Niño years (Figure 2a, d, g). Meanwhile, during the winter periods, the entire Indian Ocean region had been transformed into a uniform positive anomaly distribution (Figure 2j, m). In the tropical Western Pacific Ocean region during the same period, the SST distribution pattern mainly consisted of the warm SST anomalies related to the El Niño events at the equator, and the cold SST anomalies outside the equatorial region. This SST anomaly distribution pattern was observed to be relatively stable, without significant changes observed over time.

With consideration given to the fact that the propagation processes of the fluctuations on the thermocline were key factors in maintaining the ENSO cycles, the variations in the thermocline depth anomalies over time in the tropical Indo-Pacific region were examined in this study (Figure 2b, e, h, k, n). The time series of the thermocline depths in the tropical seas could be approximately represented by the changes...
of the depths of the ocean $20^\circ$ isotherm or sea surface heights. It could be seen that from the autumn to the winter periods, the tropical Indian Ocean region was always dominated by a zonal dipole distribution with positive anomalies in the Western Indian Ocean, and negative anomalies in the Eastern Indian Ocean. It could also be seen that in the Western Indian Ocean region, the SST anomalies and thermocline depth anomalies were in the same phase, and dynamic ocean
processes had dominated the SST changes. Moreover, the oceanic changes played leading roles in the processes of the atmospheric and oceanic feedback. In accordance with the theory presented by Gill (1980) regarding the responses of tropical atmosphere to anomalous heat source forcing actions, the rises in temperature in the Western Indian Ocean would trigger the eastward spread of the Kelvin waves in the atmosphere, which would subsequently, induce anomalous easterly responses along the equatorial Indian Ocean.

The above views were further confirmed by the variations in the convective activities. Figure 2c details the spatial distributions of the OLR anomaly fields in the tropical Indian and Pacific Ocean regions during the early autumn periods of the El Niño years. It was observed that in the equatorial Western Indian Ocean region, weak convection activities (OLR negative anomalies) had been generated. The Eastern Indian Ocean-marine continent-Western Pacific region (80°-150°E) was found to be dominated by suppressing phase convective activities (OLR positive anomalies). In the equatorial Central Pacific Ocean region (150°E-150°W), the strong convection activities were mainly related to the warm SST anomalies during the El Niño events. In the following autumn and winter periods (Figure 2f, i, l, o), due to the warm SST anomalies in the equatorial Western Indian Ocean region (40°-80°E, 10°S-10°N), the convective activities had been gradually

FIGURE 2 Time series of the SST (unit: 2 × 10^{-2} K); thermocline depth (Z 20; unit: m); and outgoing longwave radiation field (OLR; unit: W/m^2) anomalies in the tropical Indo-Pacific region during the autumn and winter periods of the composite El Niño events (including eight El Niño events which had occurred in 1982, 1987, 1994, 1997, 2004, 2006, 2009, and 2015)
enhanced. Therefore, the easterly anomalies over the equatorial Indian Ocean had become gradually increased (Figure 1).

3.3 | Eastward spread mechanism of the easterly anomalies in the equatorial Indian Ocean

The observational results confirmed that in the majority of the El Niño events, the easterly anomalies of the equatorial Indian Ocean region displayed eastward spread characteristics, and had mainly occurred during the autumn and winter seasons (Figure 1). However, what caused the eastward spread of the easterly anomalies still remains to be clarified. Also, whether or not the eastward spread phenomena were only phase-locked during the autumn and winter seasons remained unclear. In order to examine the aforementioned problems, the time series of the average specific humidity in the tropical Indian and Pacific Ocean regions, along with the low-level anomalous wind field during the autumn and winter seasons for the composite El Niño events, were reviewed (Figure 3, left). In order to highlight the comparison of the intensities of specific humidity between the equatorial region and the outer equatorial region, the field of the climatic average state was subtracted from the mean value of the tropical region (30°S–30°N), for the purpose of obtaining the spatial anomaly value of the climatic specific humidity. It could be seen that during the early autumn periods, easterly anomalies had occurred in the equatorial Indian Ocean in response to the positive anomaly fields of the SST and convective activities in the Western Indian Ocean region (Figure 3a). As time progressed, the easterly anomalies were constantly enhanced and extended in an eastward direction. Anomalous anticyclonic circulations were generated on the northern and southern sides of the easterly anomalies (Figure 3c). Meanwhile, during the transition from autumn to winter, the maximum center of the climate state specific humidity, which was originally located north of the equator, had gradually retreated to the vicinity of the equator. Therefore, the anomalous northerlies on the eastern side of the anomalous anticyclonic circulations (taking the northern hemisphere as an example) had advected the drier and colder air to the equator (negative moisture advection), and the anomalous southerlies on the west side had advected the warmer and wetter air at the equator (positive moisture advection). Due to the fact that the anomalous anticyclonic circulations were a dry cooling system, the asymmetry of the moisture advection on the eastern and western sides of such a circulation caused the anomalous anticyclone to move gradually eastward (Chen et al., 2007). Correspondingly, the easterly anomalies of the equatorial Indian Ocean on the southern side of the anticyclone had also spread in an eastward direction. It is noted that eastward propagation of anomalous easterly can also be clearly seen in the individual El Niño events (figures not shown).

The aforementioned process was also clearly indicated by time series of the anomalous precipitation fields and stream function fields (Figure 3, right). During the months of October of the examined years, strong anomalous anticyclonic circulations were generated (positive stream function anomalies) in the Northern Indian Ocean, and strong suppressed convection activities (negative precipitation anomalies) were observed to have existed on the eastern sides of the anticyclonic circulations. Over time, the anomalous anticyclone and negative convection center had gradually moved eastward to the Northwestern Pacific Ocean region and had then merged with the local suppressed phase-convection activities (Chen and Li, 2017). Therefore, during the winter periods of the El Niño years, the Northwestern Pacific Ocean region was dominated by negative precipitation anomalies and anticyclonic circulation activities (Figure 3j). The presence of anomalous anticyclonic circulations caused the El Niño events to decay rapidly and transform into La Niña events at the end of the following year.

4 | CONCLUSIONS AND DISCUSSION

In this study, multiple sets of atmospheric and marine observations and reanalysis data were analyzed, and the obtained data were used in a composite analysis method. It was confirmed that during the autumn and winter periods of the majority of the examined El Niño events, easterly anomalies had been generated in the equatorial Indian Ocean, which had spread in an eastward direction towards the Western Pacific Ocean region. During these periods, the SST anomalies in the Western Indian Ocean region were in the same phases as the anomalies of the thermocline depths. Therefore, it was concluded that the oceanic changes had played a leading role. The temperature rises in the West Indian Ocean had triggered the responses of anomalous easterlies, and there were anomalous anticyclonic circulations observed on the northern sides of the anomalous easterlies. During the seasonal conversion processes, along with the maximum center of climate state specific humidity gradually retreating to the equator, the asymmetry of moisture advection on the eastern and western sides of anomalous anticyclonic circulations had led to drier and colder atmospheric conditions on the eastern side, and warmer and moister conditions on the western side. Therefore, the anomalous anticyclonic systems were observed to gradually move eastward towards the Northwestern Pacific Ocean region, which helped the El Niño events transitions to La Niña events.
In this research study, based on the observational data and the composite analyses results, the regional mean values of the precipitation and SST anomalies in the equatorial West Indian Ocean (40°W–80°E, 10°S–10°N) were selected as the inter-annual variation index. Then, the leading–lagging correlations between these values and the anomalous zonal wind fields and oceanic wave processes in the equatorial Indo-Pacific region (5°S–5°N) were investigated. The results showed that during the autumn and winter periods of the El Niño years, the positive precipitation anomalies in the West Indian Ocean had stimulated the anomalous easterlies (negative correlation) in the equatorial Indian Ocean. Furthermore, during the year following each of the El Niño events, the easterly anomalies had extended eastward towards the

**FIGURE 3** Time series of (left) the average specific humidity (shading; unit: $3 \times 10^{-2}$; regional mean value removed to facilitate the projection of the relative intensities of the equator and the outer equator areas); horizontal wind field anomalies at 850 hPa (vector; unit: m/s); (right) precipitation rates (shading; unit: $10^{-3}$ mm/day); and wind stream functions (contour line; unit: $10^6$ m$^2$/s) in the tropical Indian and Pacific Ocean regions during the autumn and winter seasons for the composite El Niño events. Pink dashed lines denote the latitude of maximum specific humidity.
Meanwhile, during the autumn and winter periods of the El Niño occurring years, the warm SST anomalies and local thermocline depth (Z20) anomalies over the West Indian Ocean had displayed high positive correlations. At the same time, on the eastern side, negative correlations were dominant in the East Indian Ocean—maritime continent—Western Pacific Ocean region. In the second year of the El Niño events, the anomaly centers of the negative thermocline depths were observed to have moved eastward, and at the end of the second year, the thermocline anomalies of the equatorial Indo-Pacific region presented negative—positive—negative distribution characteristics, which reflected the eastward spread of the fluctuations on the thermocline. Due to the fact that the Indian Ocean is separated from the Pacific Ocean by a maritime continent, the oceanic processes in the Indian Ocean cannot directly affect those in the Pacific Ocean, except via an atmospheric bridge. Therefore, at the end of the second year of the El Niño events, it was found that the Walker Circulation was strengthened, and El Niño events had been completely transformed into La Niña events (Figure 4b).

The results of the leading–lagging correlation analysis indicated that the inter-annual variation anomaly index of the SST and convection activities in the West Indian Ocean could better represent the changes in the SST and ocean fluctuations in the equatorial Pacific Ocean in the year following an El Niño event. The anomalous anticyclonic circulations from the Indian Ocean had converged with the anomalous convective activities in the Northwest Pacific Ocean, which played a crucial role in the ENSO cycles. Meanwhile, during positive IOD years, the low level of tropical Indian ocean is controlled by anomalous easterlies. The results show that seven out of the eleven El Niño years (since 1979) co-occurrence with positive IOD years. And most IOD co-occurrence with El Niño years have easterly propagation. The anomalous easterlies associated with positive IOD events can persist from autumn to following early winter which is the mature phase of El Niño (Saji et al., 2018). The easterly propagation facilitates the decay of El Niño. It should be pointed out that the formations of the Northwest Pacific anticyclonic circulations during the winter peak periods of the El Niño events were complex and multi-participatory processes. Meanwhile, the SST changes in the southwestern Indian Ocean region were found to only explain part of the wind field changes in the far West Pacific Ocean and the fluctuations in the equatorial Pacific Ocean thermocline. Therefore, the formations of the ENSO cycles were concluded to be the results of multiple processes with joint actions. The negative feedback mechanism of the easterly anomalies of the equatorial Indian Ocean to the decline of the El Niño events will be a potentially useful complement to the existing negative feedback theory.

ACKNOWLEDGEMENTS

This study was supported by the Natural Science Foundation of China (41575133, 41305079).

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How to cite this article: Zhang F, Zhang G, Liu L, Dong L. The negative feedback effects of sea surface temperatures on El Niño Events in the West Indian Ocean. *Atmos Sci Lett*. 2019;20:e924. [https://doi.org/10.1002/asl.924](https://doi.org/10.1002/asl.924)