Impacts of Different Types of ENSO on the Interannual Seesaw between the Somali and the Maritime Continent Cross-Equatorial Flows

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ABSTRACT

The impacts of different types of El Niño–Southern Oscillation (ENSO) on the interannual negative correlation (seesaw) between the Somali cross-equatorial flow (CEF) and the Maritime Continent (MC) CEF during boreal summer (June–August) are investigated using the ECMWF twentieth-century reanalysis (ERA-20C) dataset and numerical experiments with a global atmospheric model [the Met Office Unified Model global atmosphere, version 6 (UM-GA6)]. The results suggest that ENSO plays a prominent role in governing the CEF-seesaw relation. A high positive correlation (0.86) exists between the MC CEF and Niño-3.4 index and also in the case of eastern Pacific (EP) El Niño, central Pacific (CP) El Niño, EP La Niña, and CP La Niña events. In contrast, a negative correlation (−0.35) exists between the Somali CEF and Niño-3.4 index, and this negative relation is significant only in the EP El Niño years. Further, the variation of the MC CEF is highly correlated with the local north–south sea surface temperature (SST) gradient, while the variation of the Somali CEF displays little relation with the local SST gradient. The Somali CEF may be remotely influenced by ENSO. The model results confirm that the EP El Niño plays a major role in causing the weakened Somali CEF via modifying the Walker cell. However, the impact of the EP El Niño on the Somali CEF differs with different seasonal background. It is also found that the interannual CEF seesaw displays a multidecadal change before and after the 1950s, which is linked with the multidecadal strengthening of the intensity of the EP ENSO.

1. Introduction

The Asian–Australian monsoon is the most powerful monsoon system as a result of the strongest thermal contrast between the Eurasian continent and the Indo-Pacific Ocean. The seasonal evolution and the year-to-year variability of the Asian–Australian monsoon produce remarkable influences on the agriculture, economy, and society of the Eastern Hemisphere tropics and subtropics regions (e.g., Wang 2006). The tropospheric low-level cross-equatorial flows (CEFs) over the western Indian Ocean and western Pacific regions have been widely recognized as essential components of the Asian–Australian monsoon systems (e.g., Tao et al. 1962; Findlater 1966; Tao and Chen 1987). These CEFs are driven by the pressure gradient between the thermal low over the Asian continent and the Mascarene high and the Australian high in Southern Hemisphere (e.g., Wang and Li 1982; Zeng and Li 2002). The interannual variations of the CEFs play a key role in causing the variations in monsoon rainfall and interhemispheric transport of moisture and energy (e.g., Saha and Bavadekar 1973; Ramesh Kumar et al. 1999; Wang and Xue 2003). As the component of two distinct South Asian monsoon and East Asian–Australian monsoon

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systems, respectively, the Somali CEF\(^1\) and the CEF over the Maritime Continent (MC) region have often been viewed to be independent. However, a few recent studies have suggested that the interannual variations of the two CEFs may not be independent from each other (e.g., Wang and Yang 2008). An interannual negative relation (seesaw) between the Somali CEF and the MC CEF during boreal summer (June–August) has been recently noticed (e.g., Cong et al. 2007; Zhu 2012; Li and Li 2014).

The Somali CEF and the MC CEF have important influences on the Indian summer monsoon (ISM) and East Asian summer monsoon (EASM), respectively (e.g., Simmonds et al. 1999; Halpern and Woiceshyn 2001; Wang and Ho 2002). It has been found that more rainfall in the ISM and tropical EASM region is often related to an intensified Somali CEF and MC CEF, respectively (e.g., Mao et al. 1990; Liu et al. 2009). However, the ISM and tropical EASM usually do not experience either stronger or weaker rainfall simultaneously. Instead, a remarkable out-of-phase variation of rainfall anomalies in the ISM area and the tropical EASM region has been noticed by previous studies (e.g., Huang et al. 1998; Zhang 2001). This out-of-phase variation of the two tropical monsoonal precipitation anomalies may be partly caused by the negative relation between the Somali CEF and the MC CEF (Fig. 1). To represent the negative correlation between the two CEFs, Li and Li (2014) have proposed a CEF-seesaw index. It turns out that the CEF-seesaw index shows a better skill in capturing the out-of-phase relation of the ISM and EASM rainfall variations than the individual CEFs do (Li and Li 2014). Li and Li (2016) have also found that the CEF-seesaw index shows a significant correlation with a southwest–northeast-oriented rainfall anomaly pattern in China that is identified by the second leading empirical orthogonal function mode (EOF2). Thus, the CEF seesaw may provide a useful index for a better understanding of the summer rainfall anomaly pattern in China.

To understand the CEF seesaw, previous studies (e.g., Wang et al. 2001; Zhu and Chen 2002; Chen et al. 2005) have noticed that their relation with El Niño–Southern Oscillation (ENSO) is opposite. Generally, during a warm ENSO episode, the Somali CEF weakens, whereas the MC CEF intensifies. In contrast, a cold ENSO episode usually comes along with a strengthened Somali CEF but with a weakened MC CEF. This suggests that ENSO may play an important role in generating the CEF seesaw. However, the exact mechanisms have not yet been clearly examined. In addition, ENSO itself displays a large diversity. For instance, the amplitude of El Niño is often significantly larger than that of La Niña (e.g., Burgers and Stephenson 1999). This asymmetry represents an intrinsic nonlinear characteristic of the ENSO phenomenon (e.g., Jin et al. 2003; An and Jin 2004). Recent studies have also identified two different types of ENSO. Different from the canonical El Niño that display the major sea surface temperature (SST) anomalies in the equatorial eastern Pacific (EP), the central Pacific (CP), or Modoki, type of El Niño shows maximum warm SST anomalies in the central equatorial Pacific (e.g., Fu et al. 1986; Wang 1995; Ashok et al. 2007; Kao and Yu 2009). The EP and CP ENSO exhibit distinct impacts on the Asian–Australian monsoon systems. For instance, the Australian rainfall has been found to be more sensitive to the CP type of ENSO compared to the EP type of ENSO (e.g., Wang and Hendon 2007; Taschetto and England 2009). The rainfall anomalies in southern China are dramatically different during the two types of ENSO years (e.g., Weng et al. 2007; Feng and Li 2011; Zhang et al. 2011). The EP and CP ENSO also exhibit different influences on the Indian Ocean. The EP ENSO shows a strong influence on the tropical Indian Ocean, whereas the CP ENSO displays more influences on the southern Indian Ocean (Kao and Yu 2009). Whether the different types of El Niño and La Niña may have different impacts on the CEF seesaw is an intriguing issue.

\(^{1}\)The well-known Somali jet usually refers to the southwesterly low-level jet with a maximum-velocity core along the coast of Somalia north of the equator. Here, the Somali CEF refers to the southerly flow near the equator.
The present study aims to investigate the impacts of different types of ENSO on the Somali CEF and the MC CEF, as well as possible mechanisms that contribute to the CEF seesaw. The observational datasets and model experiments conducted in this study are described in section 2. The observational results for the relation between the different types of ENSO and the two CEFs are presented in section 3. In section 4, results based on a set of atmospheric model sensitivity experiments are presented to support the observational results. The possible mechanisms for the impact of ENSO on the Somali CEF, the multidecadal fluctuation of the CEF seesaw, and the possible role of the Indian Ocean dipole (IOD) in the CEF seesaw are discussed in section 5. A summary is given in section 6.

2. Observational data and model experiments

a. Observational data and methods

Monthly mean horizontal and vertical winds at multiple pressure levels, sea level pressure (SLP), precipitation, and SST data for the period 1900–2010 are derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) twentieth-century reanalysis (ERA-20C), with horizontal resolution of $1^{\circ}\times 1^{\circ}$ (Poli et al. 2013). The Global Precipitation Climatology Project (GPCP), version 2, during 1979–2014 is also used in this study (Adler et al. 2003). The present study focuses on the seasonal mean of boreal summer (June–August), unless stated otherwise. To obtain the interannual variability, a linear detrending process is first applied to the original seasonal mean data. Then the fast Fourier transform (FFT) method is used to filter out the decadal (greater than 10 years) components. The Student’s $t$ test is applied for estimating the statistical significance of the results.
speed and variability of the MC CEF occurs at 925 hPa. Thus, the velocity at the 850-hPa pressure level is used to measure the strength of the Somali CEF, whereas the velocity at 925 hPa is used to measure the MC CEF (Fig. 2a). Readers are referred to Table 2 of Li and Li (2014) for more details (note that their Australian CEF is renamed to be the MC CEF in this study).

Because of the large variety of ENSO evolution during the JJA season, we first use the Niño-3.4 index (the area-averaged SST anomaly in the 5°S–5°N, 170°W–120°W) to identify the El Niño (i.e., Niño-3.4 index greater than 0.5°C) and La Niña (i.e., Niño-3.4 index is lower than −0.5°C) events. The El Niño and La Niña events are then classified into the EP or CP type of El Niño and La Niña by comparing the amplitude of the Niño-3 index (5°S–5°N, 90°E–150°W) with that of the Niño-4 index (5°S–5°N, 160°E–150°W). Namely, the EP (CP) of ENSO event is identified if the magnitude of the Niño-3 index is greater (lower) than that of the Niño-4 index; meanwhile, the magnitude of the Niño-3 (Niño-4) index should be greater than 0.5°C. This classification of the EP and CP types of ENSO follows the method used in Yeh et al. (2009) and Kug et al. (2009), except that they applied it to DJF (i.e., ENSO onset/decay phase) while the present study focuses on JJA (2009), except that they applied it to DJF (i.e., ENSO onset/decay phase). The identified EP and CP ENSO events are listed in Table 1. Note that results based on the El Niño Modoki index (EMI) method (e.g., Ashok et al. 2007; Yu and Kim 2013) are similar (not shown). It is also worth noting that there are more EP La Niña events than the EP El Niño events in the boreal summer (JJA), particularly after the 1980s. This is probably related to the different evolution characteristics between El Niño and La Niña. It has been known that most La Niña events start from the eastern Pacific and then propagate and/or extend westward toward the central Pacific (e.g., McPhaden and Zhang 2009). In contrast, a number of El Niño events, particularly after the late 1970s, start from the central Pacific and then propagate and/or extend eastward. Therefore, it is reasonable that more EP La Niña events occur in the developing phase of the ENSO (JJA) compared to the EP El Niño case.

### Table 1. Classification of the different types of ENSO.

<table>
<thead>
<tr>
<th>Type</th>
<th>Year(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP type</td>
<td></td>
</tr>
<tr>
<td>CP type</td>
<td></td>
</tr>
<tr>
<td>Niño-3 and Niño-3 &gt; 0.5°C)</td>
<td></td>
</tr>
<tr>
<td>Niño-4 &gt; 0.5°C)</td>
<td>1909, 1917, 1950, 1956, and 1989</td>
</tr>
</tbody>
</table>

### b. Model experiments

The Met Office Unified Model global atmosphere, version 6 (UM-GA6; Walters et al. 2017), is used here to examine the impacts of different types of ENSO on the two CEFs. UM-GA6 is the atmospheric component of the Australian Community Climate and Earth-System Simulator. The dynamical core used by UM-GA6 is the even newer dynamics for general atmospheric modeling of the environment (ENDGame), which uses a semi-implicit semi-Lagrangian formulation to solve the nonhydrostatic, fully compressible deep-atmosphere equations of motion (Wood et al. 2014). The model runs at N96 (~135 km) horizontal resolution and 85 vertical levels (LS5), which has 50 levels below 18 km, 35 levels above, and a fixed model lid at 85 km above the surface. The radiation scheme of Edwards and Slingo (1996) is used with a configuration based on Cusack et al. (1999). The large-scale precipitation (or microphysics) scheme used in the model is based on Wilson and Ballard (1999), with a lot of modifications. The small-scale precipitating events are handled by the convection scheme. The model uses a mass flux convection scheme based on Gregory and Rowntree (1990) with various extensions to include downdrafts (Gregory and Allen 1991) and convective momentum transport. To depict the large-scale cloud, UM-GA6’s prognostic cloud fraction and prognostic condensate (PC2) scheme (Wilson et al. 2008a,b) along with the modifications to the cloud erosion parameterization described by Morcrette (2012) are used. The “boundary layer” parameterization scheme is based on that of Lock et al. (2000) with the modifications described in Lock (2001) and Brown et al. (2008). It is a first-order turbulence closure mixing adiabatically conserved heat and moisture variables, momentum, and tracers. For more details of the model physics, readers are referred to Walters et al. (2017).

We examine UM-GA6’s performance in the Atmospheric Model Intercomparison Project (AMIP) runs from 1982 to 2008 with observed SST forcing. The model shows a good ability to reproduce the climatological low-level CEFs in Asian–Australian summer monsoon regions (Figs. 2a,b). Furthermore, the interannual
seesaw relation (with a correlation coefficient of $-0.46$) between the Somali CEF and the MC CEF, the negative correlation ($-0.40$) between the Somali CEF and Niño-3.4 index, and the positive relation (0.76) between the MC CEF and the Niño-3.4 index are all reproduced realistically in the model’s AMIP runs (Figs. 2c,d). Thus, the UM-GA6 AGCM provides a reliable tool to examine the impacts of ENSO on the CEF seesaw. For this purpose, we conduct a few sets of model experiments in which the SST anomaly forcing of different types of ENSO is prescribed in the tropical Pacific. The detailed description of the model experiments is given in section 4.

3. Observation results

The scatterplot of the interannual anomalies of the Somali CEF and the MC CEF is shown in Fig. 3. A statistically significant negative correlation (with a correlation coefficient of $-0.30$) is seen for all years during 1900–2010. This negative correlation becomes stronger ($-0.47$) during ENSO years (red dots). In contrast, during the non-ENSO years (blue crosses), there is almost no correlation (0.05) between the two CEFs. This indicates the dominant role of ENSO in causing the interannual CEF seesaw. The magnitude of the anomalous MC CEF is generally larger than that of the Somali CEF during ENSO years, whereas this magnitude difference is less apparent during non-ENSO years.

To investigate the impacts of ENSO on individual CEFs, we plot the correlations between the different types of ENSO (including the EP El Niño, CP El Niño, EP La Niña, and CP La Niña) with the Somali CEF and the MC CEF separately (Fig. 4). The MC CEF has a strong linear correlation with the ENSO (0.86). This high positive correlation appears for all types of ENSO, and there are no clear differences among the different types of ENSO. However, the relation of the Somali CEF to ENSO is much weaker (with the correlation coefficient of $-0.35$), and the different types of ENSO appear to have distinct influences on the Somali CEF. The intensity of the Somali CEF is weaker than normal during most of the EP El Niño years (12 out of 13). During the other three types of ENSO (CP El Niño, EP La Niña, and CP La Niña) years, however, the variation of the Somali CEF is uncertain. The probability of the occurrence of a stronger or a weaker Somali CEF during each of the three different types of ENSO events is nearly equal. In summary, these results suggest that ENSO may play an important role in causing the seesaw relation between the Somali CEF and the MC CEF (Fig. 3). Further, since the MC CEF has a high positive relation with all different types of ENSO (recall Fig. 4b) but the Somali CEF has a significant negative relation with only the EP El Niño (recall Fig. 4a), the negative correlation between the Somali CEF and the MC CEF could be mainly forced by the EP El Niño.

To further examine the different relations between the different types of ENSO and the two CEFs, composite analyses are conducted. Figure 5 displays the composite 850-hPa horizontal winds during the different types of ENSO years (see Table 1 for the events of each type of ENSO selected for the composite analysis). Consistent with a previous study (e.g., Chen et al. 2005), during the El Niño years, the Somali CEF tends to be weakened, while the MC CEF is strengthened (Figs. 5a,c), and vice versa for La Niña years. However, the response of the two CEFs to the different types of ENSO depicts a large difference. All the types of ENSO show statistically significant and strong impacts on the MC CEF, although El Niño appears to exert a relatively stronger influence on the MC CEF than La Niña does. In contrast, the magnitudes of the Somali CEF anomalies during the different types of ENSO years are much
weaker. Only during the EP El Niño years, the Somali CEF is significantly weakened, in association with a basinwide counterclockwise anomalous circulation in the tropical Indian Ocean and easterly anomalies along the equatorial Indian Ocean (Fig. 5a). The basinwide anomalous circulations and equatorial wind anomalies are weaker during the other types of ENSO, inducing less significant anomalies of the Somali CEF (Figs. 5b–d).

Figure 6 shows the composite precipitation anomalies during the different types of ENSO. The Indian summer rainfall is below normal during the EP El Niño years, particularly in the eastern Arabian Sea along the west coast of India. The dry rainfall anomaly there is associated with anomalous descending flow over the South Asia and consistent with the weakened Somali CEF. In contrast, the rainfall anomalies during the other three types of ENSO are slightly positive (albeit not statistically significant) in the eastern Arabian Sea along the west coast of India. The results suggest that the Somali CEF anomalies are consistent with the Indian summer monsoon anomalies during the different types of ENSO. It is worth noting that the Indian summer monsoon during the EP El Niño events is drier than that during the CP El Niño events. This is different from the finding of Kumar et al. (2006); it may be partly due to different datasets, methodologies, and models that are used in the two studies. Future studies are warranted to explore this discrepancy.

The two CEFs are principally driven by the interhemispheric south–north pressure gradients, in association with the large-scale land–ocean surface thermal contrasts. To examine the possible role of the meridional pressure gradients in the interannual variations of the two CEFs, we plot the composite SLP anomalies during the different types of ENSO. As shown in Fig. 7, during both the EP and CP El Niño years, the Australian high is intensified and the SLP north of the equator is reduced, which gives a strong anomalous south–north pressure gradient over the MC region (Figs. 7a,c). This leads to a stronger-than-normal MC CEF during El Niño years, whereas during La Niña years, the MC CEF is weakened in association with the reduced south-minus-north cross-equatorial SLP gradient (Figs. 7b,d). In contrast, the cross-equatorial SLP gradients in the western tropical Indian Ocean are generally weak, consistent with the weak Somali CEF anomalies, during the different types of ENSO. However, the SLP anomalies in the tropical Indian Ocean during the EP ENSO years are generally stronger and more statistically significant than those during the CP
ENSO years. In particular, the anomalous south-minus-north cross-equatorial pressure gradient in the western Indian Ocean becomes the lowest during the EP El Niño years (Fig. 7a). The results suggest that the different SLP anomalies during the different types of ENSO may account for the different variations of the two CEFs.

Table 2 shows high correlations between the Somali (MC) CEF and the south-minus-north cross-equatorial pressure gradients in the western Indian Ocean (MC area). These correlations are statistically robust across the five different latitudinal boxes that are used to calculate the meridional SLP gradients. The results support the importance of the local meridional SLP gradients in driving the interannual variations of the two CEFs. To further examine whether these SLP anomalies are induced by local SST anomalies or remote forcing, we calculate the correlations between each of the two CEFs and south-minus-north cross-equatorial SST gradients along each of the CEF longitude bands (Table 2). The results show high negative correlations between the MC CEF anomaly and the anomalous cross-equatorial SST gradients in the MC region. This suggests that the local SST anomalies in the tropical western Pacific may play an important role in affecting the cross-equatorial SLP gradient and hence the MC CEF. This result is in agreement with that of Zhou and Kim (2015). They found that the meridional SST gradient in the western Pacific modulated by ENSO affects the pressure gradients in the boundary layer as a result of the Lindzen–Nigam mechanism (Lindzen and Nigam 1987) and subsequently the interannual variations of the CEFs in the western Pacific region. In addition, the IOD may also affect the meridional SST gradient in the MC region and hence the MC CEF (e.g., Weller and Cai 2014). In contrast to those in the MC region, the correlations between the Somali CEF anomaly and the anomalous cross-equatorial SST gradients in the western Indian Ocean are near zero (Table 2). This suggests that the local SLP anomalies responsible for the interannual variations of the Somali CEF are not caused by the local SST anomalies; instead remote forcing such as ENSO may have played an important role.

To investigate how ENSO remotely affects the Somali CEF, we calculate the composite Walker cell anomalies during different types of ENSO (Fig. 8). During the El Niño years, the Walker cell along the equatorial Pacific
is weakened owing to a weaker warm pool–cold tongue SST gradient in the Pacific. The resultant anomalous descent flows over the MC region induce low-level easterly anomalies along the equatorial Indian Ocean (e.g., Klein et al. 1999). In contrast, during the La Niña years, the Walker cell is intensified along with westerly anomalies over the equatorial Indian Ocean. It appears that the low-level easterly and westerly anomalies in the Indian Ocean are generally stronger in the EP ENSO years than those in the CP ENSO years. This indicates that the EP type of ENSO may exert a stronger influence on the tropical Indian Ocean than the CP ENSO does (e.g., Kao and Yu 2009). The results are consistent with the low-level wind anomalies (recall Fig. 5). It is suggested that the anomalous Walker cell in the Indian Ocean induced by the EP El Niño SST forcing in the Pacific may play an important role in modulating the intensity of the Somali CEF. We examine this issue further in the discussion section.

In summary, the observational analyses described above suggest that ENSO plays a dominant role in the interannual seesaw relation between the Somali CEF and the MC CEF. While the MC CEF exhibits high correlations with all the different types of ENSO, the Somali CEF displays a strong asymmetric relation with ENSO. That is, only the EP El Niño has a significant influence on the Somali CEF, and the other three types of ENSO show less influence. It is also found that the MC CEF and the Somali CEF may be governed by distinct mechanisms. The interannual variation of the MC CEF appears to be mainly caused by the local cross-equatorial SST and SLP gradient in association with ENSO. Meanwhile, the Somali CEF shows little correlation with the local cross-equatorial SST gradient in the western Indian Ocean. Instead, the anomalous Walker cell in the Indian Ocean due to the remote impact of EP El Niño may play a role.

4. Model results

To verify the observational findings, we perform several sets of model experiments based on the UM-GA6 AGCM. We first conduct five sets of experiments, including one control run and four sets of sensitivity experiments for the different types of ENSO. Each set of experiments contains 20 ensemble members (Table 3). The control run is integrated from 1 March to 30 August with the observed climatological SST forcing (note that the 360-day calendar is used in UM-GA6 as a default option). The initial conditions for the 20 control simulations are provided by the AMIP run during 1982–2001 (i.e., 1 March of each
The sensitivity runs are the same as the control run, except that the tropical Pacific SST anomalies from May to September (see the green boxes in Fig. 9) for each type of ENSO are superimposed upon the climatological SST forcing, respectively. Note that it is necessary to include the SST anomalies in May and September in order to have correct linearly interpolated June–August SST forcing. Boreal summer (June–August) seasonal means of the model’s outputs are then analyzed. The SST anomalies used in the sensitivity runs are obtained from the monthly composite SST anomalies of the four types of ENSO (Fig. 9). It is clear that the EP events are in average stronger than the CP events. The mean Niño-3.4 SSTA of EP (CP) El Niño events is 1.0°C (0.75°C), larger than −0.88°C (−0.60°C) of EP (CP) La Niña events. Thus, the stronger EP El Niño SSTA could be one of the possible reasons for its stronger influence on the two CEFs.

Table 2. Correlation coefficients between the two CEFs with their local south-minus-north SLP and SST differences across the equator. Correlations in boldface indicate statistical significance at the 5% level according to Student’s t test.

<table>
<thead>
<tr>
<th>Latitudinal boxes</th>
<th>Somali region (37.5°–62.5°E)</th>
<th>MC region (102.5°–152.5°E)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SLP differences</td>
<td>SST differences</td>
</tr>
<tr>
<td>15°S–0° minus 0°–15°N</td>
<td>0.73</td>
<td>0.01</td>
</tr>
<tr>
<td>20°S–0° minus 0°–20°N</td>
<td>0.77</td>
<td>0.01</td>
</tr>
<tr>
<td>25°S–0° minus 0°–25°N</td>
<td>0.77</td>
<td>0.04</td>
</tr>
<tr>
<td>30°S–0° minus 0°–30°N</td>
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<td>0.02</td>
</tr>
<tr>
<td>35°S–0° minus 0°–35°N</td>
<td>0.69</td>
<td>0.01</td>
</tr>
</tbody>
</table>
observational features (recall Fig. 5). The basinwide counterclockwise (clockwise) anomalous circulation in the tropical Indian Ocean and the easterly (westerly) anomalies in the northern Indian Ocean during the El Niño (La Niña) are realistically reproduced with the prescribed tropical Pacific SST forcing. In particular, the EP El Niño SSTA forcing exerts the strongest and most statistically significant impact on the Somali CEF (with the magnitude reaching $-0.51 \text{ m s}^{-1}$; Fig. 10a) compared to the other three types of ENSO SST forcing (with the magnitude being $-0.30$, $0.34$, and $0.23 \text{ m s}^{-1}$ for the CP El Niño, EP La Niña, and CP La Niña, respectively; Figs. 10b–d). This supports the observational finding of the strong asymmetric impact of different types of ENSO on the Somali CEF. Consistently, the EP El Niño SST forcing reproduces the strongest anomalous Walker cell in the equatorial Pacific and the strongest low-level zonal wind anomalies along the equatorial Indian Ocean compared to the other three types of ENSO SST forcing (Fig. 11). The model’s simulated Walker cell anomalies in the Indo-Pacific region during the different types of ENSO are also generally similar to the observations (recall Fig. 8), despite the fact that the model is deficient in reproducing the low-level easterly anomalies in the eastern equatorial Indian Ocean with the EP and CP El Niño SST forcing.

![Composite: Walker Cell anomalies (5°S-5°N)](image)

**FIG. 8.** As in Fig. 5, but for the composite Walker cell anomalies along 5°S–5°N during the different types of ENSO years. Here, the Walker cell is represented by the streamlines of zonal wind $u$ (m s$^{-1}$) and pressure vertical velocity $\Omega$ (Pa s$^{-1}$; scaled by $-100$). Color shading at surface–500-hPa layers indicates the intensity of the zonal wind anomalies.

**TABLE 3.** Model’s control and sensitivity experiments.

<table>
<thead>
<tr>
<th>Name</th>
<th>Ensemble members</th>
<th>Boundary condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control run</td>
<td>20</td>
<td>Climatological SST (1980–2009)</td>
</tr>
<tr>
<td>CP El Niño run</td>
<td>20</td>
<td>Climatological SST with CP El Niño SSTA (May–Sep)</td>
</tr>
<tr>
<td>EP La Niña run</td>
<td>20</td>
<td>Climatological SST with EP La Niña SSTA (May–Sep)</td>
</tr>
<tr>
<td>CP La Niña run</td>
<td>20</td>
<td>Climatological SST with CP La Niña SSTA (May–Sep)</td>
</tr>
</tbody>
</table>
It is interesting that the model’s simulated response of the Walker cell in the Indo-Pacific region to the El Niño SST forcing is much stronger than the response to the La Niña SST forcing. This asymmetry is visible in the observations (cf. Figs. 11 and 8). However, the simulated response to the La Niña SST forcing is much weaker than the observed composite anomalies. While the anomalous descent motion in the central-eastern Pacific is well simulated with the La Niña SST forcing, the anomalous ascent over the MC area is underestimated (Figs. 11b,d). This is probably partly because the SST anomalies in the tropical Indian Ocean and MC area (as well as other regions) are not included in the model sensitivity experiments.

5. Discussion

a. Possible mechanism for the impact of ENSO on the Somali CEF

As presented in the previous sections, the Pacific ENSO, particularly the EP El Niño, has important impacts on the interannual variations of the Somali CEF, possibly via modifying the Walker cell in the Indo-Pacific region. However, it is unclear how the ENSO-driven Walker cell anomalies in the Indian Ocean may impact on the Somali CEF. According to the Matsuno–Gill pattern (Matsuno 1966; Gill 1980) with a prescribed climatological annual mean state, the anomalous Walker cell, in response to the nearly equatorial symmetric SST anomaly forcing during the EP El Niño years, will induce equatorial symmetric easterly anomalies along the equatorial Indian Ocean (see the black lines in Fig. 12a for a schematic illustration). A pair of anticyclonic Rossby waves south and north of the equator in the Indian Ocean, in response to the suppressed convection over the MC area, will induce southerly anomalies in the Northern Hemisphere along the Somali coast and northerly anomalies in Southern Hemisphere. As a result, the intensity of the Somali CEF should not be affected by ENSO. However, both the observation and model experimental results indicate a significant strong impact of the EP El Niño SST forcing on the Somali CEF during June–August (recall Figs. 5a and 10a), in association with a strong equatorial asymmetric circulation in the tropical Indian Ocean (i.e., the basinwide counterclockwise anomalous circulation). And the low-level easterly anomalies mostly appear in the north Indian Ocean.

We speculate that the strong equatorial asymmetry in the Indian Ocean during the EP El Niño years may be
caused by the strong equatorial asymmetry of the seasonal climatological background in the boreal summer. During June–August, the convection centers migrate to the Northern Hemisphere in association with the establishment of Asian summer monsoon systems. Consequently, the anomalous Walker circulation and the easterly anomalies in the Indian Ocean may also be shifted to the north of the equator (red dashed lines in Fig. 12a). As a result, the southern anticyclonic Rossby wave response is also shifted northward, leading to the basinwide counterclockwise anomalous circulation in the tropical Indian Ocean. This acts to reduce the Somali CEF. If the above hypothesis is correct, we shall expect to see an overall opposite response in boreal winter (December–February) when the convection centers migrate to the Southern Hemisphere (blue dotted lines in Fig. 12a). 

To verify this hypothesis, we conduct another two sets of model experiments for the period of September–February. In the first set of experiments, global monthly climatological SST forcing is specified. In the second experiment, we add additional monthly SST anomalies from November to March into the climatological SST forcing. The monthly SST anomalies from November to March exactly correspond to the monthly EP El Niño SST anomalies from May to September, which are used in the previous experiment for the boreal summer. Similarly, 20 ensemble simulations are performed with their initial conditions on 1 September being provided by the AMIP runs during 1982–2001. The model results support our hypothesis. In boreal summer, in response to the EP El Niño SST anomaly forcing, wet anomalies appear in the central-eastern Pacific, the South China Sea, and east of the Philippines (Fig. 12b). In contrast, dry anomalies appear in the MC area and South Asia. This pattern is similar to the observed despite some local discrepancies (cf. Fig. 12b and Fig. 6a). The largest wind divergence appears along about 100°–110°E between the equator and 10°N. Consistently, anomalous easterlies (westerlies) occur in the northern Indian Ocean (western Pacific). However, in boreal winter, in response to the same EP El Niño SST anomaly forcing, the dry anomaly in the MC area is weak and shifted southward (Fig. 12c). Consistently, the largest wind divergence appears along about 150°–160°E between 10°S and the equator, with the most anomalous easterlies in the Indian Ocean being located at about 10°S. The results suggest that whether ENSO may induce anomalous southerlies or northerlies along the Somali coast is determined by the seasonal climate background.

b. Multidecadal variation of the CEF seesaw

Previous studies have found that the interannual CEF-seesaw relation displays large multidecadal fluctuations

FIG. 10. As in Fig. 5, but for simulated impacts of the (a) EP El Niño, (b) EP La Niña, (c) CP El Niño, and (d) CP La Niña on the 850-hPa wind anomalies (m s⁻¹). These are 20-member ensemble mean differences between individual sets of the UM-GA6 sensitivity experiments and the control run (Table 3). The average magnitude of the Somali CEF anomalies in the sensitivity runs in (a)–(d) reaches 0.51, 0.34, 0.30, and 0.23 m s⁻¹, respectively. Meanwhile, the average magnitude of the MC CEF anomalies in (a)–(d) is 0.75, 0.29, 0.83, and 0.41 m s⁻¹, respectively. Note that the magnitudes of the MC CEF anomalies are calculated based on the values at the 925-hPa level.
Figure 13a displays the multi-decadal fluctuation of the interannual relation between the Somali CEF and the MC CEF with the correlation being calculated in a 15-yr running window. The result indicates a regime shift around the mid-1950s. The significant interannual CEF-seesaw relation only appears in the late decades since the mid-1950s, and the CEF-seesaw correlation is insignificant before the mid-1950s. The weak correlation between the Somali and MC CEF in the early period (1900–50) can also be seen in the NOAA Twentieth Century Reanalysis datasets, versions 2 (r = −0.04) and 2c (r = 0.12) (Compo et al. 2006, 2011). The consistent results between the different reanalysis datasets may support the credibility of the weak CEF-seesaw correlation before 1950s. However, the robustness of this multidecadal change may also be subject to the poor quality of observations in the early decades.

What causes the multidecadal fluctuation of the interannual CEF seesaw is an interesting question but has not yet been addressed. The results presented in the previous sections illustrate that ENSO, especially the EP El Niño type, plays an important role in generating the seesaw between the Somali CEF and the MC CEF. We hypothesize that the multidecadal fluctuation of the CEF seesaw may also be linked with the multidecadal change of the ENSO. To examine this hypothesis, we plot in Fig. 13b the multidecadal change of the EP ENSO amplitude (represented by the Niño-3 SST anomaly index) calculated within a 15-yr running window. There is a coherence in the multidecadal fluctuations between the CEF-seesaw relation and the EP ENSO amplitude (cf. Figs. 13a and 13b), with a correlation coefficient of −0.73. We also investigate the relation between the multidecadal change of the CEF seesaw and that of the CP ENSO amplitude (represented by the Niño-4 SST anomaly index; Fig. 13c), but no clear relation between them is found (with a correlation coefficient of −0.03).

Since ENSO shows a strong asymmetric impact on the Somali CEF and the MC CEF, we further investigate the correlation between the Niño-3 SST index and individual CEFs in two epochs (i.e., 1900–50 vs 1955–2010). As shown in Table 4, the correlations of the MC CEF with the Niño-3 index in the two periods do not change much and are significantly positive. In contrast, the negative correlation between the Somali CEF and the Niño-3 index only appears during 1955–2010, when the amplitude of the EP ENSO is relatively strong. Meanwhile, the negative correlation between the Somali CEF and the Niño-3 index is very weak during 1900–50 when the EP ENSO variance is weak. The results suggest that the multidecadal fluctuation of the intensity of the EP ENSO may play a role in the multidecadal change of the interannual CEF seesaw.
To confirm the observational results, we conduct two additional sensitivity experiments in which the intensity of the EP El Niño SST anomaly forcing is increased to be 1.5 and 2 times of the original one (recall Table 3). Again, we perform 20 ensemble simulations for each
sensitivity experiment. The model results demonstrate that the stronger EP El Niño forcing has more significant influence on the Somali CEF (Fig. 14). With a forcing of 1.5 and 2 times the EP El Niño, the Somali CEF is weakened by −0.94 and −1.6 m s⁻¹, respectively. It is worth noting that the strength of the MC CEF is nearly unchanged with the stronger EP El Niño forcing, inconsistent with the observational result (recall Fig. 4b). This may be partly because the SST anomaly forcing is not specified in the entire MC region in the model (Fig. 9), yet the local SST gradient is crucial to the variation of the MC CEF. In summary, the multidecadal fluctuation of the CEF seesaw may be related to that of the EP ENSO’s amplitude, and the increased EP El Niño intensity since the mid-1950s might have exerted increased influence on the Somali CEF.

c. Connection with Indian Ocean dipole

It is well known that the IOD often co-occurred with the ENSO (e.g., Saji et al. 1999; Webster et al. 1999; Ashok et al. 2003) and that the IOD also has a significant influence on the Walker circulation (Tozuka et al. 2016). To investigate the possible influence of the IOD on the CEF seesaw, we identify IOD events (i.e., the DMI magnitude is greater than one standard deviation) without ENSO (i.e., the magnitude of the Niño-3.4 index is smaller than 0.5). The dipole mode index (DMI) is defined as the SST anomaly difference between the tropical western Indian Ocean (10°S–10°N, 50°–70°E) and the southeastern Indian Ocean (10°S–0°, 90°–110°E) (e.g., Saji et al. 1999). Both the DMI and ENSO indices are calculated based on the June–August seasonal mean. The identified pure IOD events are listed in Table 5, and the composite wind anomalies at 850 hPa during the pure positive and negative IOD events are shown in Figs. 15a,b. The result suggests a weak influence of the pure IOD on the two CEFs and the CEF-seesaw relation. In contrast, the result during the pure EP El Niño events without the IOD (Fig. 15c) shows that the Somali CEF is significantly weakened and the MC CEF is strengthened. These results suggest that the EP El Niño events have a strong influence on the CEFs and their seesaw relation, compared to the IOD.

6. Summary

The impact of ENSO on the interannual negative correlation between the Somali CEF and the MC CEF during boreal summer (June–August) is investigated using both the observational dataset (ERA-20C) and one global atmospheric model (UM-GA6). The results suggest that the ENSO plays a dominant role in generating the interannual seesaw relation between the Somali CEF and the MC CEF. We explore the distinct relationship between the different types of ENSO (i.e., the EP El Niño, CP El Niño, EP La Niña, and CP La Niña) and the individual CEF. The MC CEF exhibits a high positive correlation with ENSO and the impacts of the different types of ENSO on the MC CEF are nearly symmetric. In contrast, the Somali CEF shows a much weaker negative correlation with ENSO. The different types of ENSO have a strong asymmetric impact on the Somali CEF. In particular, the EP El Niño exerts the strongest and most significant influence on the Somali CEF. Our results suggest distinct mechanisms that may account for the interannual variation of the Somali CEF and the MC CEF. The interannual variation of the MC CEF highly coincides with the south–north
cross-equatorial SST gradient in the local MC regions, whereas the interannual variation of the Somali CEF displays no linkage with the local south–north cross-equatorial SST gradient in the western Indian Ocean. This indicates that the Somali CEF may be remotely influenced by ENSO via the Walker cell. The results of the model sensitivity experiments support the above observational findings.

We further explore the possible mechanism of ENSO’s remote impact on the Somali CEF. The results suggest that whether the EP El Niño SST forcing may induce anomalous southerlies or northerlies in the Somali CEF region is determined by the seasonal mean background. During the boreal summer (June–August), when the convection centers migrate to the Northern Hemisphere, the easterly anomalies prevail over the northern Indian Ocean as a result of the weakened Walker cell during the EP El Niño years. This induces a basinwide counter-clockwise anomalous circulation in the tropical Indian Ocean, which favors north–south wind anomalies along the Somali coast. In contrast, in boreal winter (December–February), the easterly anomalies driven by the EP El Niño forcing shift to Southern Hemisphere, which corresponds to the southward migration of the convection centers. Thus, south–north wind anomalies are generated in the Somali CEF region.

The interannual correlation between the Somali CEF and the MC CEF has undergone a large multidecadal variation in the past century. This appears to be related to the multidecadal amplitude change of the EP ENSO. Model experimental results suggest that a stronger EP El Niño SST anomaly forcing exerts a stronger influence on the Somali CEF. In contrast, the strength of the MC CEF changes little despite the stronger EP El Niño forcing. Therefore, the increased EP El Niño amplitude since the mid-1950s might have played an important role in generating the robust negative correlation between the Somali CEF and the MC CEF in recent decades.

The present study confirms the important role of ENSO in causing the interannual CEF seesaw. It is worth noting that not every significant CEF-seesaw year co-occurs with an ENSO event. We investigate the co-occurrence probability of the CEF seesaw with the ENSO events. The results reveal that all low CEF-seesaw events (i.e., with a weakened Somali CEF but an intensified MC CEF) co-occur with El Niño events. However, four high CEF-seesaw events (i.e., with a strengthened Somali CEF but a weakened MC CEF), accounting for nearly 29% of the high CEF-seesaw events over the past century, appear in the absence of the ENSO events. This suggests that other processes may also play a role in causing the interannual CEF seesaw, especially for the high CEF-seesaw events. Examining exact influences of the SST forcing in other ocean basins, land surface processes, and possibly atmospheric internal processes on the interannual CEF seesaw warrants further studies.

<table>
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<tr>
<th>Years</th>
<th>Positive IOD without ENSO</th>
<th>Negative IOD without ENSO</th>
<th>EP El Niño without IOD</th>
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**TABLE 5. List of the pure IOD events that occurred without ENSO and the pure EP El Niño events without IOD.**
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