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ENSO Remote Forcing: Influence of Climate Variability Outside the Tropical Pacific

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ABSTRACT

Climate variabilities in the Pacific, Indian and Atlantic Oceans are tightly connected. The influence of El Niño–Southern Oscillation (ENSO) on the Atlantic and Indian oceans has been documented for long. There are recent lines of evidence that regions outside the tropical Pacific feed back onto ENSO characteristics, such as its amplitude, periodicity, and time-sequence and spatial patterns, suggesting that basin interactions play a significant role for ENSO diversity and complexity. The climate variability that may influence ENSO includes the Pacific Meridional Mode, the Indian Ocean basin mode, the Indian Ocean Dipole, the Atlantic Niño and surface temperature variations in the North Tropical Atlantic, and the western hemisphere warm pool. The tendency of these climate modes to lead ENSO variability by several seasons could in particular provide an opportunity for improved long-lead predictions of ENSO. This chapter will provide a comprehensive review of our current understanding of the influence of climate variability outside the tropical Pacific on ENSO.

11.1. INTRODUCTION

The El Niño–Southern Oscillation (ENSO) is the dominant mode of Earth's climate variability on interannual timescales (chapters 1 and 2). ENSO is a climate mode that emerges from internal dynamics of the ocean-atmosphere coupled system in the tropical Pacific (chapters 6–8). Positive El Niño sea surface temperature anomalies (SSTA) usually appear in spring and amplify through the Bjerknes feedback (Bjerknes, 1969), which is a positive air-sea feedback loop in the tropical Pacific. This positive feedback mechanism is offset by several negative feedbacks, including the instantaneous negative feedback from air to sea fluxes (e.g. Lloyd et al., 2009), nonlinear interactions of convective anomalies with the seasonal cycle (e.g. Lengaigne et al., 2006) and delayed negative feedbacks from oceanic dynamics (e.g. Suarez & Schopf, 1988; Jin, 1997). This eventually leads to an El Niño event that peaks towards the end of the calendar year and then decays rapidly.

While rooted in the tropical Pacific, ENSO influences climate and weather phenomena worldwide through atmospheric and oceanic teleconnections (chapters 14 and 15). Within the tropics, ENSO teleconnections can be conceptualized as zonal shifts of the Walker Circulation. For example, the eastward shift of the Walker Circulation during an El Niño induces a warming over the entire Indian Ocean (e.g. Klein et al., 1999; Xie et al., 2009) and the North Tropical Atlantic (e.g. Enfield & Mayer, 1997; Huang, 2004) in response to atmospheric subsidence. The wind speed and latent heat flux anomalies associated with

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the circulation responses to convective anomalies also contribute to generating remote SSTA. In addition to those tropical teleconnections, El Niño–induced convective anomalies in the central Pacific also induce a stationary Rossby wave response that extends into the subtropics and midlatitudes (Hoskins & Karoly, 1981). Such a response alters the occurrence probability of extratropical weather patterns such as the Pacific North American and North Atlantic Oscillation (e.g. Trenberth & Hurrell, 1994; Alexander et al., 2002), with impacts on the underlying SST through changes in air-sea fluxes and Ekman currents (e.g. Alexander & Scott, 2008; Deser et al., 2010).

In addition to the above studies focusing on the influence of ENSO on the other basins, it was suggested early that the Indian Ocean and Pacific basin interannual variability are interactive and better understood as an integrated climate mode designated as the Tropospheric Biennial Oscillation (Barnett, 1983; Meehl, 1987; Meehl et al., 2003). Some studies also discovered precursor signals to ENSO in other basins, such as the Indian Ocean (e.g. Clarke & Van Gorder, 2003; Kug et al., 2005) or in the North Pacific (Vimont et al., 2001, 2003a, 2003b). There has been recently a growing number of studies supporting potential influences of other oceanic basins on ENSO. The regions that may influence ENSO through teleconnections include the north (e.g. Vimont et al., 2001, 2003a, 2003b, 2009) and south (Zhang et al., 2014) extratropical Pacific, the Southern Ocean (White et al., 2002; White & Annis, 2004; Terray, 2011; Boschat et al., 2013), the equatorial (e.g. Rodríguez-Fonseca et al., 2009; Martin-Rey et al., 2012; Ding et al., 2012) and northern subtropical (e.g. Ham et al., 2013a) Atlantic, and the tropical Indian Ocean (e.g. Kug & Kang, 2006; Ohba & Ueda, 2007; Luo et al., 2010; Izumo et al., 2010). These studies suggest that SSTA in a given region outside the tropical Pacific can induce wind changes over the equatorial Pacific. These wind changes induce an equatorial Pacific SSTA response, which can further be amplified by the Bjerknes feedback and interfere with the ENSO cycle.

In the tropics, where high ambient SSTs favor an impact of SSTA on deep atmospheric convection (e.g. Gadgil et al., 1984), these wind changes in the Pacific are usually explained by a steady atmospheric response, i.e. Gill-type response, to anomalous convective forcing in response to SST anomalies. Known modes of interannual SST variability in the other tropical oceans are thus potentially able to influence the El Niño evolution through this mechanism, which leads to wind changes over the tropical Pacific. The modes of tropical SST variability that have been most studied as precursors of ENSO (and will be briefly described later in the chapter) more specifically include the North Atlantic warming/cooling (Ham et al., 2013a), Atlantic Niño (Zebiak, 1993), Indian Ocean basinwide warming/cooling, and Indian Ocean Dipole (Saji et al., 1999).

Unlike in the tropics, midlatitudes SSTAs hardly trigger deep atmospheric convective anomalies, so that different mechanisms must operate to trigger remote wind anomalies in the equatorial Pacific. For instance, Vimont et al. (2001, 2003a) emphasized the potential influence of the North Pacific Oscillation, one of the dominant internal atmospheric modes in the North Pacific, on ENSO through the so-called "footprinting mechanism." In this mechanism, midlatitude Pacific stochastic atmospheric fluctuations drive SSTAs in winter through latent heat fluxes (see e.g. Chiang & Vimont, 2004). Off-equatorial air-sea interactions favor the propagation of these SSTAs into the equatorial Pacific by the following boreal spring and summer (Vimont et al., 2003a). Once reaching the tropical region, those SSTAs can trigger convective anomalies and equatorial zonal wind anomalies, which influence ENSO development (Alexander et al., 2010). A similar influence of the Southern Hemisphere subtropical Pacific has also been proposed (e.g. Zhang et al., 2014).

In addition to acting as an ENSO precursor, SSTA variations in other basins or in the extratropical Pacific may alter ENSO characteristics such as its magnitude, periodicity, diversity, and predictability (Timmermann et al., 2018; Cai et al., 2019). For instance, climate model experiments where the Atlantic or the Indian Ocean are decoupled from the Pacific suggest that the interannual variability in these two basins damps ENSO and shortens its periodicity (e.g. Dommenget al., 2006; Terray et al., 2015). While many studies have suggested that SSTA patterns in various regions may influence ENSO, the relative importance of each region, the detailed mechanisms through which this influence operates, and their consequences for ENSO predictability are still unclear (e.g. Dayan et al., 2014, 2015). There have been significant scientific advances in our understanding of the two-way interactions between the tropical Pacific and other basins in recent years (Cai et al., 2019), emphasizing that the influence of regions outside the tropical Pacific on the Pacific ENSO system is more vigorous than previously thought. The potential consequences of the influence of other basins on the El Niño phase transition (e.g. Kug & Kang 2006; Ohba & Ueda, 2007), diversity (Ham et al., 2013b; Capotondi et al., 2015; Dommenget & Yu, 2017; Timmermann et al., 2018), and for predicting El Niño and La Niña events at long leads (Park et al., 2018) thus call for a better understanding of these remote influences. The purpose of this chapter is to provide a comprehensive review of our current understanding of the influence of various regions on ENSO. In particular, we review the influence of the Indian Ocean in section 11.2, the Atlantic Ocean in section 11.3, and the extratropical Pacific in section 11.4. In section 11.5, we will summarize and compare the influence of various regions, and a further research direction will be discussed.

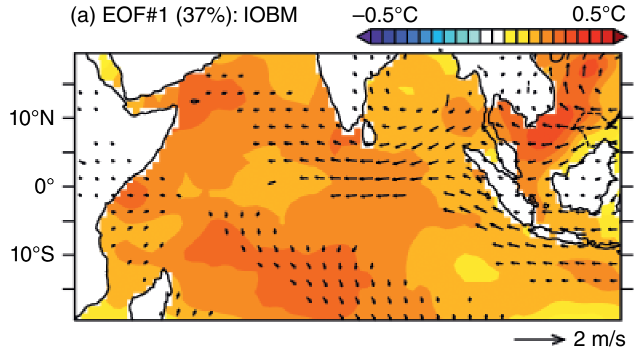
11.2. INDIAN OCEAN

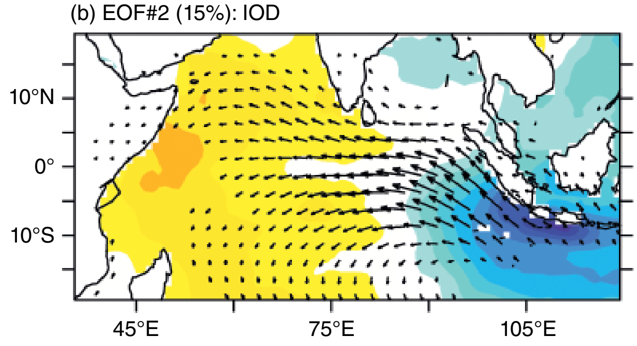
Despite the evident geographical separation between the Indian and the Pacific Oceans by the maritime continent, they share the Indo-Pacific warm pool, the biggest span of SST in excess of 27.5°C, a necessary condition for deep atmospheric convection to develop (Gadgil et al., 1984; Graham & Barnett, 1987). This Indo-Pacific warm pool hence maintains an intense deep atmospheric convective activity whose midtropospheric heating drives the ascending branch of the Walker Circulation and bridges these two oceans together. In addition to this, the western Pacific and the eastern equatorial Indian Ocean are connected through a gateway of narrow deep sills in the Indonesian Archipelago called the Indonesian Throughflow. The Indian and Pacific oceans mutually interact through these atmospheric and oceanic bridges, with potential influences on ENSO in the Pacific.

The tropical Indian Ocean has two dominant modes of variability at the interannual timescale, both influenced by ENSO but also thought to influence ENSO: the Indian Ocean Basin Mode and the Indian Ocean Dipole. The Indian Ocean Basin Mode (IOBM) is the leading mode of Indian Ocean interannual variability (~40% of the total variance of interannual SST anomalies) and is associated with a uniform warming of the entire Indian Ocean (Figure 11.1a). The IOBM is mostly explained by a delayed response to the zonal shifts in the Walker Circulation associated with the ENSO cycle (lag correlation with ENSO > 0.8 up to ~7 months after the ENSO peak; Figure 11.1c; Klein et al., 1999; Lau & Nath, 2003; chapter 14). During El Niños, the eastward shift of the Walker Cell induces subsidence over the Indian Ocean, reducing cloudiness and inducing anticyclonic anomalies, which contribute to increasing SST through both enhanced downward solar and reduced latent upward heat fluxes (Klein et al., 1999; Lau & Nath, 2003; Tokinaga & Tanimoto, 2004). The anticyclonic wind anomalies also force downwelling oceanic waves in the southern Indian Ocean, which also contribute to the sea surface warming in the southwestern Indian Ocean, the "thermocline ridge" region (Xie et al., 2002; Huang & Kinter, 2002; Vialard et al., 2009). The IOBM exhibits a clear amplitude asymmetry, with a larger basinwide warming than the corresponding cooling (Hong et al., 2010). It peaks in boreal spring, one season after the ENSO peak (Figure 11.1c), because local air-sea interactions maintain Indian Ocean SST anomalies beyond the end of the El Niño event, through boreal spring and summer. The southwestern Indian Ocean warming indeed forces antisymmetric wind anomalies that weaken the summer monsoon flow, hence reducing latent heat losses and maintaining the warming through summer, in particular in the northern Indian Ocean (Wu et al., 2008; Du et al., 2009; Xie et al., 2009).

Several studies have proposed that the IOBM affects the Pacific ENSO by modulating western Pacific wind anomalies (Kug & Kang 2006; Kug et al., 2006; Ohba & Ueda 2007, 2009, Okumura et al., 2011). This western Pacific wind response to the IOBM can either be isolated statistically from observations (Figure 11.2c and e.g. Kug & Kang, 2006; Dayan et al., 2015; Izumo et al., 2016) or from atmospheric model simulations forced by anomalous warming in the Indian Ocean (Figure 11.2d and e.g. Annamalai et al., 2005; Kug & Kang, 2006; Ohba & Ueda, 2007; Dayan et al., 2015). The Indian Ocean warming leads to enhanced convection, which influences the western North Pacific anticyclone anomaly (Watanabe & Jin, 2002; Kug & Kang, 2006; Xie et al., 2009, 2016) through atmospheric Kelvin waves, yielding easterly wind anomalies in the equatorial western Pacific in boreal winter (Figure 11.2c,d). Even though a controversial argument still exists on the seasonal dependency of the IOBM's effect on the western Pacific easterlies (Chen et al., 2016), these boreal winter western Pacific easterly anomalies last until the following summer, favoring a fast transition from El Niño to La Niña via the Bjerknes feedback in the Pacific basin (Kug & Kang, 2006; Kug et al., 2006; Ohba & Ueda, 2007, 2009, Okumura et al., 2011). Both observations (Kug & Kang, 2006) and model simulations (Okumura et al., 2011; Ohba & Watanabe, 2012) suggested that this IOBM feedback is larger for the warm phase than the cold phase; this asymmetry hence potentially contributes to the more systematic phase transition from El Niño to La Niña and a shorter duration of El Niños (e.g. Ohba & Ueda 2009; Okumura et al., 2011; Ohba & Watanabe, 2012). This feature could be attributable to the asymmetric IOBM amplitude and the zonal extension of the IOBM-induced wind anomalies in the western Pacific (Ohba & Watanabe, 2012).

The Indian Ocean also hosts a second prominent mode of interannual variability: the Indian Ocean Dipole (IOD; Reverdin et al., 1986; Saji et al., 1999; Webster et al., 1999; Murtugudde et al., 2000). Positive IOD events are characterized by cold sea surface anomalies near Java and Sumatra and weaker and broader warm surface anomalies in the western tropical Indian Ocean (Figure 11.1b). IOD events tend to peak in boreal fall and to decay rapidly during the following winter (e.g. Saji et al., 1999; Figure 11.1c). Similar to the Bjerknes feedback, positive air-sea interaction also operates during IOD events, giving rise to wind anomalies in the central equatorial Indian Ocean (Figure 11.1b), which in turn enhance the SST anomalies.


(a) EOF#1 (37%): IOBM


(b) EOF#2 (15%): IOD

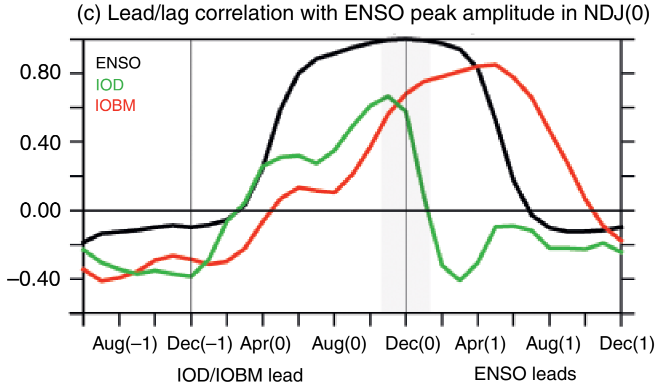

(c) Lead/lag correlation with ENSO peak amplitude in NDJ(0)

Figure 11.1 (a) First and (b) second EOF of detrended SST anomalies in the tropical Indian Ocean, an associated wind signal obtained through regression of the corresponding normalized PC. (c) Lead-lag correlation of the Niño-3 (a proxy of ENSO, black), average Indian Ocean (a proxy of the IOB, red) and dipole mode index (DMI; a proxy of the IOD, green) SST anomalies to the NDJ Niño-3 index.

While some IOD events can occur independently from ENSO (e.g. Yamagata et al., 2004; Fischer et al; 2005; Crétat et al., 2017; H. Wang et al., 2016), the anticyclonic wind anomalies in the southeastern Indian Ocean during El Niños tend to induce cold anomalies along Java and Sumatra that can grow into a positive IOD through the Bjerknes feedback (e.g. Xie et al., 2002; Annamalai et al., 2003). As a result, IOD events tend to peak in the boreal fall before the ENSO peak (r ~ 0.6; Figure 11.1c), to dissipate quickly during winter while the IOBM settles through winter to summer (r ~ 0.8; Figure 11.1c). This tendency of the IOD to phase-lock to ENSO results in a r ~ 0.6 synchronous correlation between the two climate modes. Recent studies suggest that positive IOD events that co-occur with El Niño tend to strengthen the *ongoing* El Niño (Luo et al., 2010) and foster the occurrence of extreme El Niño events (Saji et al., 2018). Those studies suggest that the eastern Indian Ocean cold SST anomalies during a positive IOD supress convective activity, inducing westerly anomalies over the equatorial western Pacific, that strengthen the El Niño development.

Observations, however, also indicate a tendency for the IOD to lead ENSO events by ~14 months (r ~ –0.4, Figure 11.1c). Some argue that this lead correlation is simply a consequence of the IOD being a purely passive response to ENSO and its biennial tendency (Stuecker

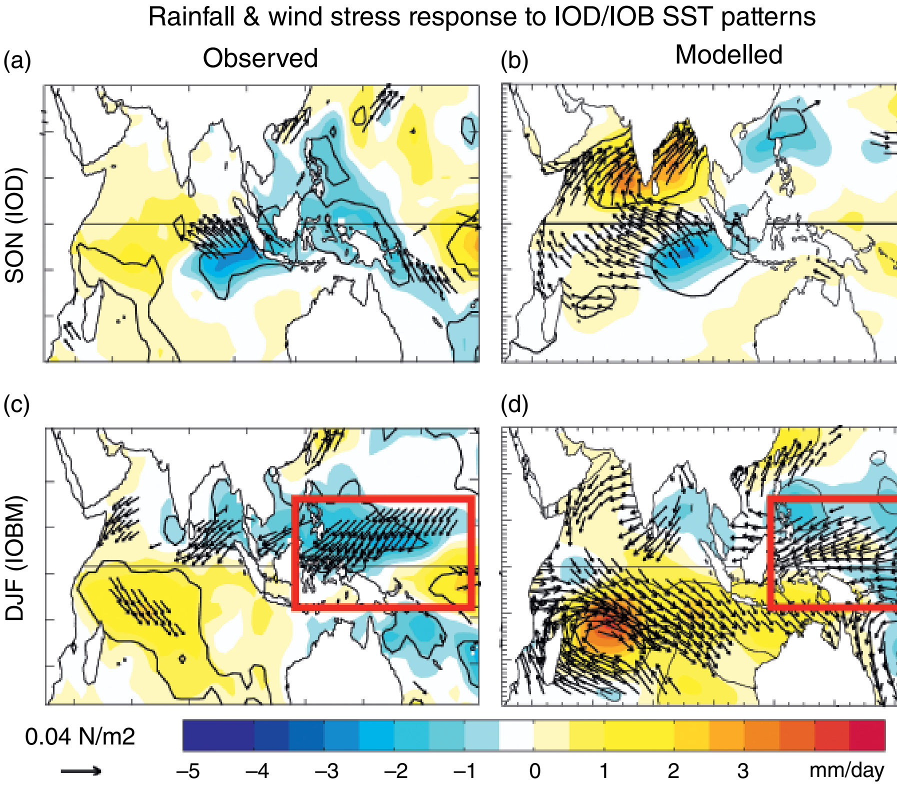


Figure 11.2 Adapted from Dayan et al. (2015). Rainfall (colors) and wind stress (vectors) anomalies driven by the anomalous (a, b) SON IOD and (c, d) DJF IOBM SST anomaly patterns deduced from observations (as a regression to the IOD/IOBM indices after having linearly removed the ENSO signal) and ECHAM-5 simulations forced by the IOD/IOBM patterns.

et al., 2017), while others interpret this as an IOD influence on the *following year's* ENSO (e.g. Clarke & van Gorder, 2003; Izumo et al., 2010; Izumo et al., 2014; Jourdain et al., 2016). The effect of the IOD on *following year's* ENSO also relies on the Indian Ocean–induced western Pacific wind variability. Those studies hypothesize that the western Pacific westerly anomalies induced by a cold pole of the positive IOD in the eastern Indian Ocean suddenly disappear in boreal winter in relation with the fast IOD decay at that season. This sudden release of the wind forces upwelling Kelvin waves (Izumo et al., 2016), which lead to central and eastern Pacific cooling and transition to La Niña through the Bjerknes feedback (Izumo et al., 2010). Jourdain et al. (2016) suggest that the tendency of positive IOD events to lead La Niña events by ~14 months tends to be more robust than the opposite relation in observations and CMIP models.

The studies discussed above suggest that both IOBM and IOD could play a role in leading rapid phase transition of ENSO. Basically, both phenomena affect ENSO by modulating western Pacific wind variability. Annamalai et al. (2005), Ohba and Ueda (2007), and Dayan et al. (2015) argued that the wind anomalies over the western Pacific remotely induced by the positive and negative poles of the IOD tend to cancel each other (Figure 11.2a, b), so that the IOBM is more efficient at inducing anomalies over the western Pacific (Figure 11.2c, d). To the contrary, other studies argue that higher ambient SST in the eastern Indian Ocean favors a larger convective response to the IOD eastern pole, which dominates the wind response in the western Pacific (e.g. Izumo et al., 2010; Saji et al., 2018). Irrespective of which study is correct, the sudden demise of the IOD eastern pole in boreal winter will induce a fast wind change over the Pacific that is more efficient to force an oceanic response and trigger an ENSO (Izumo et al., 2015). This is corroborated by Ha et al. (2017), who also showed that co-occurring IOBM and IOD leads to a more efficient ENSO phase transition in CMIP5 simulation.

Independently or together, the IOD and IOBM thus favor ENSO phase transitions, hence strengthening ENSO's biennial tendency, i.e. shortening its period (Kug & Kang, 2006; Izumo et al., 2010, 2014). Modeling studies that artificially constrain the Indian Ocean to a climatological state support a strong influence of Indian Ocean variability on ENSO (Yu et al., 2002; Wu & Kirtman 2004; Behera et al., 2006; Dommenget et al., 2006; Obha & Watanabe 2012; Frauen & Dommenget 2012; Santoso et al., 2012; Terray et al., 2015; Dommenget & Yu, 2017; Kajtar et al., 2017). These model studies indicate that an interactive Indian Ocean consistently shortens ENSO's dominant period. However, results are more scattered for ENSO amplitude, with studies suggesting that Indian Ocean variability either increases (Yu et al., 2002; Wu & Kirtman, 2004) or decreases (Dommenget et al., 2006; Frauen & Dommenget, 2012; Santoso et al., 2012; Terray et al., 2015; Dommenget & Yu 2017; Kajtar et al., 2017) ENSO variance. One can, however, note that the most recent studies, which establish their results on longer simulations, mostly suggest that Indian Ocean variability decreases ENSO variance, implying a damping influence on ENSO.

The IOBM and IOD influences on ENSO phase transition respectively have important consequences for ENSO modeling and predictability. The IOBM co-occurs almost systematically with ENSO (r ~ 0.8), so that it can be viewed as an integral part of the ENSO cycle, favoring its turnabout, and hence necessary to be well represented in models in order to capture the ENSO phase transitions. In contrast, some IOD events occur independently from ENSO (r ~ 0.6), and hence yield independent information that provides a potential additional source of predictability. Clarke and Van Gorder (2003) for instance demonstrated that including Indian Ocean information considerably improved ENSO forecasts at 10–15 month lead times. More specifically, using the IOD index as a precursor yields a large improvement of ENSO peak intensity hindcasts at 14 months' lead time in observations and CMIP5 models (Izumo et al., 2010; Dayan et al., 2014; Jourdain et al., 2016). Izumo et al. (2014) further found that this improvement is superior than that obtained using an IOBM index.

While most studies have so far focused on the potential influence of the tropical Indian Ocean on ENSO, some studies also suggested that SST anomalies in the subtropical Indian Ocean can also act as an ENSO precursor (e.g. Terray, 2011; Boschat et al., 2013). Other studies have emphasized the Indonesian throughflow oceanic channel rather than the atmospheric bridge for the Indian Ocean influence on the Pacific (Wajsowicz & Schneider, 2001; Yuan et al., 2011). There is a strong volume, heat, and freshwater transport from the Pacific to the Indian Ocean through the throughflow (e.g. Gordon et al., 2010). Coupled climate model experiments blocking the throughflow hence produce a Pacific mean state change that in turns generally reduces ENSO variance and shifts its centers of action eastward (Wajsowicz & Schneider, 2001; Santoso et al., 2011; Kajtar et al., 2015). Some studies argued that the IOD could also contribute to ENSO onset through coastal Kelvin waves propagating through the Indonesian seas and into the Pacific as equatorial Kelvin waves (Yuan et al., 2011), but this pathway seems much less efficient than that associated with the atmospheric bridge (Izumo et al., 2016).

11.3. ATLANTIC OCEAN

The Atlantic Ocean hosts three main regions with prominent interannual SST variations: the North Tropical Atlantic (NTA), the equatorial Atlantic, and the southern subtropical Atlantic. The NTA warming/cooling is maximum during boreal spring and is caused either by ENSO teleconnections (Chiang & Sobel, 2002; Lee et al., 2008) or by the North Atlantic Oscillation with a few months' delay (Czaja et al., 2002). The typical pattern of interannual SSTA over the equatorial Atlantic is often referred to as the Atlantic Niño due to its similarity with the Pacific El Niño. The Atlantic Niño displays positive SSTA in the central and eastern equatorial Atlantic and usually peaks in boreal summer (Keenlyside & Latif, 2007). There is, however, no robust influence of ENSO on the equatorial Atlantic, with only a weak concurrent correlation between ENSO and the equatorial Atlantic SST (Enfield & Mayer, 1997; Keenlyside & Latif, 2007). The last prominent mode of interannual SST variability in the Atlantic is the South Atlantic subtropical dipole mode (Kayano et al., 2013). It is characterized by a northeast–southwest oriented dipole-like pattern of SSTAs peaking in boreal winter. This mode may be influenced by central Pacific (CP) El Niños through the Pacific–South American wave train (Rodrigues et al., 2015). While a number of studies document the ENSO influence on the Atlantic Ocean, with local air-sea coupled processes either maintaining or amplifying those SST anomalies, less attention has been paid to the influence of the Atlantic on ENSO (Melice & Servain, 2003; Latif & Grötzner, 2000; Münnich & Neelin, 2005).

Improved understanding of the dynamical mechanisms, supported by targeted modeling experiments, has recently helped to reach some consensus on the influence of tropical Atlantic SST anomalies on ENSO (Dommenget et al., 2006; Rodríguez-Fonseca et al., 2009; Jansen et al., 2009; Ding et al., 2012; Ham et al., 2013a, 2013b; Polo et al., 2015), challenging the conventional view of the one-way influence of the Pacific on the Atlantic (Latif & Grotzner, 2000; Enfield & Mayer, 1997; Saravanan & Chang 2000; Chiang & Sobel, 2002; Chang et al., 2006).

An NTA cooling has, for instance, been found to lead El Niño (Ham et al., 2013a; L. Wang et al., 2017). The mechanism that may explain this lead-lag relationship is illustrated in Figure 11.3a. An anomalously cold NTA SST during boreal spring suppresses the local convective activity. This gives rise to a low-level anticyclonic flow over the subtropical far-eastern Pacific as the Gill-type response, which induces anomalous southerlies over the subtropical northeastern Pacific (yellow vector in

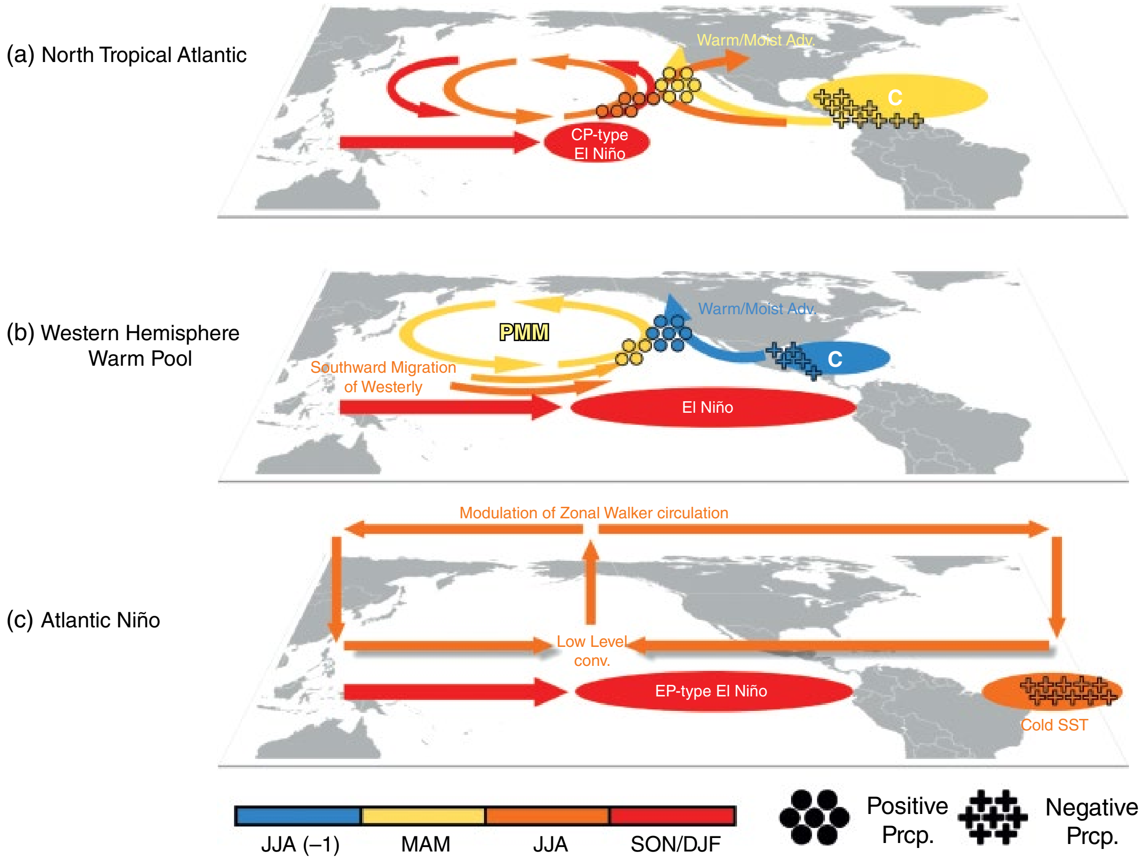


Figure 11.3 Schematic diagram of the influence of the (a) North Tropical Atlantic SST, (b) Western Hemispheric Warm Pool (WHWP), and (c) Atlantic Niño variabilities on the ENSO. The colours denote the season when the signals are robust. The circles and crosses denote the location of positive and negative precipitation anomalies, respectively.

Figure 11.3a). These southerlies lead to a surface warming there through reduced evaporative cooling due to weaker wind speed and warm/wet air advection from further south. This warming in turn induces positive precipitation anomalies under the eastern Pacific ITCZ (orange circle on Figure 11.3a), which plays a critical role in conveying the Atlantic signals to the Pacific due to its strong convective instability and meridional gradient of moist static energy. These precipitation anomalies induce an anomalous low-level cyclonic flow over the subtropical central Pacific, which progressively strengthens and extends to the western Pacific through the wind-evaporation-SST feedback (Xie & Philander, 1994) (red vectors in Figure 11.3a). This results in a westerly wind anomaly over the equatorial western Pacific during boreal summer and fall, favoring an El Niño development. In addition, the NTA could alternatively influence ENSO by inducing a remote westerly anomaly in the equatorial Pacific through atmospheric Kelvin wave response and the Indian Ocean relaying effect (Ham et al., 2013a; Yu et al., 2016).

Recently, Park et al. (2018) further argued that when the sea surface cooling is confined to the Western Hemisphere Warm Pool (WHWP) region, this lead time could be extended up to 17 months. In this framework, SST anomalies over the WHWP in late boreal summer contribute to the emergence of the Pacific meridional mode (PMM) during subsequent boreal spring (yellow in Figure 11.3b), which can further trigger ENSO during the subsequent winter through induced near-equatorial surface wind anomalies (section 11.4). This physical mechanism shares some similarities with that of Ham et al. (2013a), involving initially an atmospheric teleconnection to the subtropical Northern Pacific, and subsequently local air-sea coupling processes that maintain the anomaly and favor its propagation.

Although slightly weaker than that of the NTA, an influence of the equatorial Atlantic on ENSO since the 1970s has been reported. An equatorial Atlantic Niña, characterized by cold conditions in the equatorial Atlantic in boreal summer, tends to be followed by a

Pacific La Niña development two seasons later. While the NTA or WHWP SSTA remotely influence the Pacific through the Pacific ITCZ, the influence of the Atlantic Niño on ENSO is mediated via shifts in the zonal Walker Circulation (Rodríguez-Fonseca et al., 2009; Martin-Rey et al., 2012; Polo et al., 2015). An Atlantic Niña induces anomalous subsidence over the Atlantic and anomalous ascending motion over the central Pacific, which leads to enhanced convection there. This positive convection anomaly results in surface westerly wind anomalies over the equatorial central Pacific (orange vectors in Figure 11.3c), which excite eastward propagating downwelling Kelvin waves (red arrows on Figure 11.3c) and enhance the development of an El Niño event. Atlantic Niño conditions are also statistically linked to the South Atlantic subtropical dipole mode, implying this subtropical mode is a precursor of ENSO with a 1-year lead time (Terray, 2011; Boschat et al., 2013).

Pacemaker climate model experiments, in which observed historical SST is prescribed over the tropical Atlantic, further confirmed the key role played by the tropical Atlantic on ENSO variability. These experiments indicate that the tropical Atlantic contributes to one-fourth of Indo-Pacific SST variance (Rodríguez-Fonseca et al., 2009; Ding et al., 2012; Polo et al., 2015). In addition, decoupling the Atlantic Ocean in coupled models generally strengthens the ocean-atmosphere coupling in the equatorial Pacific and shifts ENSO variations to lower frequencies and stronger ENSO amplitude (e.g. L. Wang et al., 2017; Dommenget et al., 2006, 2017; Frauen & Dommenget, 2012; Kajtar et al., 2017).

The relationship between Atlantic Niño and NTA SST variability is weak, so these modes can be treated as independent precursors of ENSO. In addition, the Atlantic Niño and NTA SSTA preferentially excite distinct ENSO flavors (Ashok et al., 2007; Kug et al., 2009; Kao & Yu, 2009; Yeh et al., 2009). NTA cooling preferentially triggers CP El Niño (Ham et al., 2013b), since the Atlantic-induced anticyclonic flow over the subtropical far-eastern Pacific yields equatorial easterlies, hence suppressing warming in the eastern Pacific. On the other hand, two of the strongest recent El Niño events (i.e. 1982–1983, 1997–1998) were preceded by Atlantic Niña events, suggesting Atlantic Niñas tend to favor eastern Pacific (EP) El Niños (Martin-Rey et al., 2015). This suggests that the NTA and Atlantic Niño variabilities induce different flavors of the El Niño events and hence play rather independent roles (Ham et al., 2013b).

The tropical Atlantic SST variability also appears to have a greater influence on ENSO during recent decades (Cai et al., 2019). The Atlantic Niño in boreal summer is indeed significantly correlated to the following-winter ENSO over 1979–2001, but this relation is much weaker before (Rodríguez-Fonseca et al., 2009). The interdecadal modulation of the Atlantic Niño–ENSO relationship may be partly linked to the phase of the Atlantic Multidecadal Oscillation (AMO) (Martin-Rey et al., 2018). Negative AMO phases are associated with a stronger subtropical high, which leads to stronger easterlies and a shallower thermocline over the equatorial eastern Atlantic. This shoaling enhances the Atlantic Niño variability through a stronger thermocline feedback, and the Atlantic Niño–related SST pattern extended westward (Martin-Rey et al., 2018), which may enhance the Atlantic Niño forcing on ENSO (Losada & Rodríguez-Fonseca, 2016).

Similarly, the negative NTA-ENSO relationship has recently strengthened. L. Wang et al. (2017) showed that the correlation between the boreal spring the NTA SST and following winter Niño-3.4 progressively increases from 1948 to 2016, coincident with AMO phase changes: a positive AMO phase, such as the one observed during 1992–2012, provides a warmer background SST, increasing the local atmospheric response to the NTA SST anomaly and strengthening its impact on ENSO (Ham et al., 2018). Similarly, the influence of the WHWP on ENSO is also stronger after 1985, in relation with a warmer background SST in this region compared to previous decades (Park et al., 2018). However, those decadal variations can be statistical artifacts due to the small number of degrees of freedom. Therefore, how changes in climate background state modulate the influence of the Atlantic on ENSO should be further investigated.

The lagged relationships between the Atlantic SST variations and ENSO indices could potentially increase ENSO prediction skills by using Atlantic precursors. Dayan et al. (2014) argued that using the NTA SST and the index for the Atlantic Niño (i.e. Atl3 index, area-averaged SST over 20–0°W, 3°S–3°N) in addition to the Pacific predictors (i.e. Pacific warm water volume and Niño-3.4 index) significantly increase the Niño-3.4 hindcast skill. The WHWP SST can also significantly increase the statistical ENSO forecast skill up to 17 months' lead (Park et al., 2018). Partially coupled experiments prescribing the observed Atlantic SST indicate an active role of the Atlantic SST not only on ENSO evolution but also on its prediction (Ding et al., 2012). A sensitivity test performed with a dynamical forecast model (Luo et al., 2017) showed that a successful 2-year forecast of the prolonged 2010–2012 La Niña can be performed if warm SSTA in the Atlantic and Indian Ocean are imposed.

However, the dynamical forecast systems using state-of-the-art atmosphere-ocean coupled models do not realistically simulate the Atlantic SST variability (Stockdale et al., 2006; Richter et al., 2014, 2017) or the Atlantic-Pacific connection strength (Ham & Kug, 2015).

Alleviating these biases may improve ENSO forecast by better accounting for Atlantic SST variations. This inability of most current climate models to properly simulate the Atlantic SST variability is attributable to a mean-state warm bias in the eastern equatorial and southeastern tropical Atlantic, a cold bias in the western equatorial and northern tropical Atlantic, and a large error in the equatorial thermocline slope (Richter & Xie, 2008). More work is hence required to improve the representation and prediction of Atlantic climate variability in climate models, its influence on ENSO, and ultimately ENSO prediction skills.

11.4. EXTRATROPICAL PACIFIC

Atmospheric variability outside the tropics has also been suggested to influence ENSO evolution. For instance, the North Pacific Oscillation (NPO; Rogers, 1981; Linkin & Nigam, 2008), the second leading mode of the extratropical atmospheric low-frequency variability over the North Pacific, has been identified as a precursor of ENSO events one year ahead. This lead relation is explained by the seasonal footprinting mechanism (SFM) proposed by Vimont et al. (2001, 2003a, 2003b). In this hypothesis, anomalous winds associated with the southern pole of the NPO induce SSTA in the subtropical North Pacific by altering the heat fluxes, in particular its latent component. The NPO-induced subtropical SSTA signals resemble those of the Pacific Meridional Mode (PMM; Chiang & Vimont, 2004), which has long been recognized as an important player in connecting the extratropical Pacific to ENSO, particularly in triggering ENSO events (e.g. Anderson, 2003; Chiang & Vimont, 2004; Chang et al., 2007; Alexander et al., 2010).

The PMM is characterized by covarying SSTA and surface wind anomalies extending southwestward from near Baja California toward the tropical central Pacific (Figure 11.4). The PMM in boreal spring is tightly related to ENSO in the following winter. Chang et al. (2007) suggested that 70% of the El Niño events between 1958 and 2000 were preceded by SSTA and surface wind anomalies similar to the PMM. For instance, positive SST anomalies are evident off Baja California several months before the onset of the 1986, 1994, 1997, and 2015 El Niño events. These SST anomalies persist and progressively extend southwestward over the following months to reach the western equatorial Pacific (Figure 11.4c), where they can trigger an El Niño event through the Bjerknes feedback (Figure 11.4d).

The PMM itself results from the coupling between the extratropical Pacific Ocean and the overlying atmosphere. An initial warming off Baja California, presumably forced by atmospheric fluctuations via surface heat fluxes, initially enhances convection on the northern edge of the ITCZ. This induces wind anomalies further southwest (Xie & Philander, 1994), where new SSTA can develop, since the wind anomalies are opposed to the climatological northeasterlies and thus reduce the evaporative cooling. This wind-evaporation-SST (WES) feedback (Xie & Philander, 1994) allows SSTA initially induced by the extratropical atmospheric fluctuations to progressively extend southwestward toward the tropical central Pacific and form the spatial pattern associated with the PMM (Figure 11.4). This ocean-atmosphere coupling through the WES feedback also sustains the PMM from boreal winter, when the extratropical atmospheric variability is most active, into the following spring or summer to excite El Niño events.

The SSTA and wind anomalies associated with the PMM resemble the optimal structures of ENSO development identified by linear inverse models (Penland & Sardeshmukh, 1995; Xue et al., 1997). Larson and Kirtman (2014) also reported some skill using the PMM to forecast ENSO events in North American Multi-Model Ensemble (NMME) experiments. Different mechanisms through which the PMM anomalies could trigger ENSO events have been proposed. First, the PMM-related surface wind anomalies can excite downwelling Kelvin waves in response to the equatorial westerlies and to the reflection of off-equatorial Rossby waves, that propagate eastward to trigger El Niño events (e.g. Alexander et al., 2010). Alternatively, wind anomalies during the PMM positive phase may also directly recharge the ocean heat content in the equatorial Pacific via a modulation of the trade winds intensity, favoring an El Niño onset (Anderson, 2004; Anderson & Maloney, 2006; Anderson et al., 2013).

The PMM has been further recognized in recent years as a major contributor to ENSO diversity (e.g. Yu et al., 2010, 2017; Capotondi et al., 2015; Yang et al., 2018; Yu & Fang, 2018). The PMM could contribute to at least two aspects of ENSO diversity: its spatial pattern (or flavor) and its evolution. The SFM mechanism is arguably more efficient at exciting CP rather EP El Niño events (Yu & Kao, 2007; Kao & Yu, 2009). This argument is supported by the similarity between CP El Niños and PMM spatial patterns, with SSTA confined to the central Pacific and extending into the northeastern Pacific (Kao & Yu, 2009). In addition, as compared to EP El Niños, CP El Niños are not accompanied by significant subsurface ocean heat content variations across the Pacific basin (Kao & Yu, 2009), suggesting that CP El Niños' underlying dynamics is less dependent on the equatorial Pacific thermocline variations and more related to external forcings. Consistent with this argument, Kim et al. (2012) showed that the performance of NCEP's Climate Forecast System model in simulating CP El Niños was related to its ability to simulate the PMM. These studies point towards a close relationship between extratropical Pacific processes and

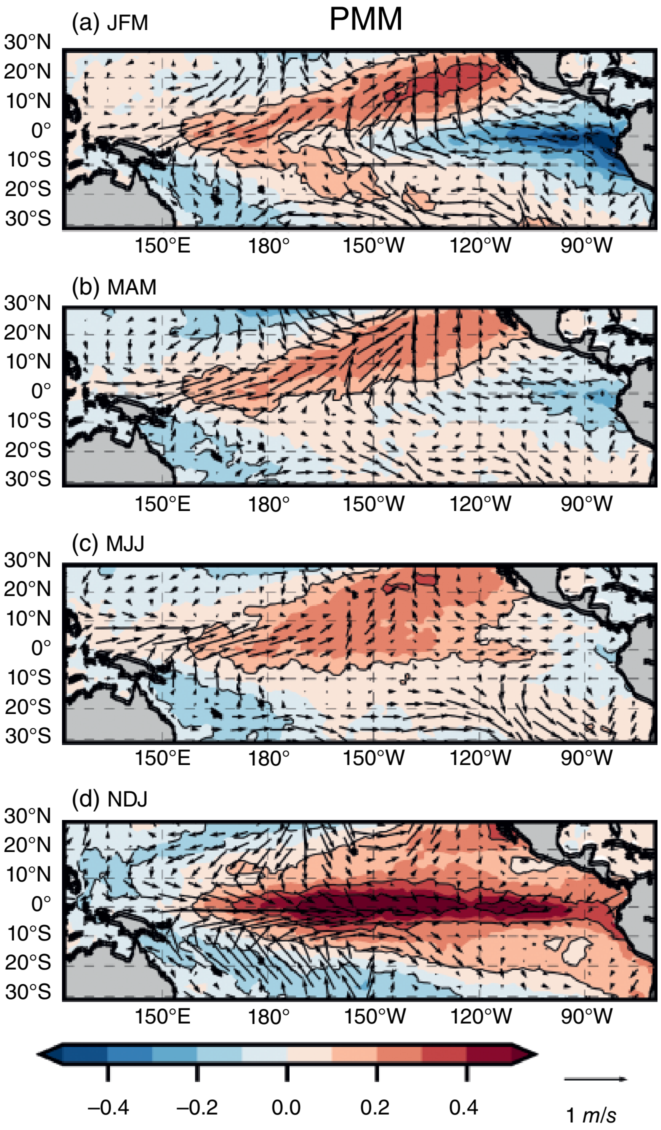


Figure 11.4 SST (contours) and surface wind (vectors) anomalies regressed onto the MAM PMM index at various leads and lags (in months) using NCEP-NCAR reanalysis data during the period 1958–2014. The PMM index is from http://www.aos.wisc.edu/~dvimont/MModes/Home.html

CP El Niños. However, some CP events, such as in 2004–2005 and 2009–2010, were not preceded by a PMM precursor, indicating that other physical processes can also yield CP events.

The PMM and SFM also contribute to diversity in ENSO evolution. Yu and Fang (2018) suggested that the SFM is a key source of complexity in ENSO transitions: while the recharge oscillator mechanism mostly produces a cyclic pattern of transition (i.e., El Niño to La Niña or La Niña to El Niño), the SFM mechanism produces three types of ENSO transition patterns: a cyclic pattern, an episodic pattern (i.e., El Niño or La Niña preceded by a ENSO-neutral state), and a multiyear ENSO pattern. They also indicated that the SFM can favor multiyear La Niña events but not El Niño events, though other studies suggest strong discharge during strong El Niño and Indian Ocean SSTA can be also responsible for the multiyear La Niña (Luo et al., 2017). Their study suggests that forcing from extratropical Pacific may be one of the reasons why multiyear La Niña events occur more often than multiyear El Niño events (Ohba & Ueda, 2009; Hu et al., 2014).

In addition to the PMM in the extratropical Northeastern Pacific, other regions of the extratropical Pacific have also been suggested to influence ENSO, including the southeastern Pacific (Zhang et al., 2014) and the northwestern Pacific (S.-Y. Wang et al., 2012). Zhang et al. (2014) identified a Southern-Hemispheric analogue to the SFM in the southeastern Pacific, which they termed the southern PMM. The southern PMM is also characterized by covarying SSTA and trade wind anomalies, which extend from the Peruvian coast toward the equatorial central Pacific. The southern PMM is capable of influencing the deep tropics through its connection with cold tongue ocean dynamics (e.g. mean advection) and impacting the development of the EP El Niños (Zhang et al., 2014; You & Furtado, 2017). The northwestern Pacific also hosts covarying SST and wind patterns similar to the PMM, which may induce oceanic Kelvin wave activity in the western tropical Pacific and later lead to ENSO events (S.-Y. Wang et al., 2012). This mode was suggested to be also related to NPO.

11.5. DISCUSSION

In this chapter, we reviewed possible remote influences of SST anomalies in various regions outside the tropical Pacific on ENSO evolution. Various climate modes in the Indian Ocean (IOD, IOBM), the Atlantic (NTA, Atlantic Niño, WHWP) or the extratropical Pacific (NPO, PMM) can trigger or alter ENSO events, generally by altering the western Pacific wind variability (e.g. Kug et al., 2005). Every ENSO event is, however, not preceded by those precursors, as an ENSO event can occur spontaneously through coupled dynamics internal to the tropical Pacific. On the other hand, some ENSO events are preceded (and potentially influenced) by a combination of these precursors. Tables 11.1 and 11.2 summarize which precursors preceded each ENSO event over the 1980–2017 period. Based on a 0.5 standard deviation criterion, each of these precursors preceded 4 to 7 El Niño events out of 12, and 4 to 7 La Niña events out of 12. Interestingly, stronger ENSO events tend to be preceded by more active precursors, the very strong 1997–1998 El Niño being preceded by 6 precursors out of 7 and the weak 2004–2005 El Niño event being preceded by none. Although the historical dataset is really too short to conclude, it is conceivable that the combination of several remote forcings can enhance the ENSO amplitude.

The lagged correlations between Niño-3.4 SST and precursor indices, introduced in this chapter, are significant as shown in Table 11.3. However, these correlations may be partly the result of ENSO influencing many regions and having a biennial tendency (Jourdain et al., 2016; Stuecker et al., 2017). To exclude this possibility, we recomputed these correlations after linearly removing the simultaneous Niño-3.4 SST. This generally increases the correlations for most indices, suggesting that these precursors independently influence the Pacific and are not solely a result of ENSO teleconnections. That is, the internal variabilities over the Indian, Atlantic, and extratropical oceans, might be more important for affecting ENSO characteristics than the ENSO-induced variability over each basin.

Among 24 El Niño and La Niña events, the PMM frequently co-occurred with ENSO events (13 events), and the partial correlation is high (Table 11.3), suggesting that the PMM index is an important precursor of ENSO as discussed in section 11.4. On the other hand, four positive NPO events preceded El Niño events, consistent with the SFM argument, but three negative NPO events

Table 11.1 Niño-3.4 index and various precursor indices for individual El Niño events. Shading indicates the case that the index is greater (or less) than 0.5 std, 1 std, and 1.5 std (−0.5 std, −1 std, and −1.5 std) and the sign is consistent with the relation on ENSO discussed in the text. Each index is averaged value from two SST datasets of ERSST and HADISST.

Year	Niño-3.4 ND(0)J(1)	IODSON(-1)	IOBMD(-1) JF(0)	NTAMAM(0)	ANiñoJJA(0)	WHWPJAS(-1)	NPOD(-1) JF(0)	PMMFMAM(0)
82/83	2.18	−0.76	−0.52	−0.20	−1.87	1.45	−0.53	0.69
86/87	1.04	0.33	−0.81	−1.33	−0.15	−0.50	1.09	1.37
87/88	0.95	0.79	0.24	0.87	1.57	−0.75	−0.25	−0.57
91/92	1.48	−0.79	0.76	−0.93	0.74	0.10	−1.05	0.57
94/95	1.11	−0.19	−0.86	−1.07	−1.17	−0.60	−0.01	1.02
97/98	2.36	−1.79	−1.10	−0.33	−1.33	−1.70	1.94	0.67
02/03	1.19	−0.74	0.57	−0.37	0.24	−0.25	−0.44	−0.21
04/05	0.64	−0.24	0.24	0.30	−0.48	−0.30	0.39	0.33
06/07	0.91	−1.17	−1.14	0.23	0.20	1.40	−1.11	−0.34
09/10	1.57	0.07	−0.33	−1.50	−0.67	−0.95	0.09	−0.72
14/15	0.71	−0.33	−0.33	−1.30	−0.52	−1.10	0.54	0.93
15/16	2.62	−0.17	−0.10	−0.83	−0.78	−0.40	1.34	1.85

Table 11.2 Niño-3.4 index and various precursor indices for individual La Niña events. Shading indicates the case that the index is greater (or less) than 0.5 std, 1 std, and 1.5 std (–0.5 std, –1 std, and –1.5 std) and the sign is consistent with the relation on ENSO discussed in the text. Each index is averaged value from two SST datasets of ERSST and HADISST.

YEAR	Niño-3.4 ND(0)J(1)	IODSON(-1)	IOBWD(-1) JF(0)	NTAMAM(0)	ANiñoJJA(0)	WHWPJAS(-1)	NPOD(-1) JF(0)	PMMFMAM(0)
83/84	−1.03	1.60	1.52	1.23	−1.30	0.25	1.09	−1.75
84/85	−1.26	0.33	−0.86	−0.13	1.07	1.10	0.74	−0.43
88/89	−2.06	0.88	2.00	1.13	1.96	2.10	−0.89	0.44
95/96	−0.87	1.98	−0.38	0.30	1.15	−1.30	0.61	0.97
98/99	−1.54	2.74	2.57	1.80	1.13	0.30	−1.04	−2.10
99/00	−1.66	−1.36	−1.00	−0.57	1.46	1.65	−1.66	−2.00
00/01	−0.85	−0.12	−0.62	0.00	−0.83	0.00	−0.67	−1.56
05/06	−0.78	0.10	0.14	1.77	−1.57	−0.25	0.48	0.52
07/08	−1.64	1.74	0.43	0.27	0.52	0.05	−0.18	−0.40
08/09	−0.75	0.33	−1.10	0.07	1.24	−0.25	−1.20	−1.80
10/11	−1.62	−0.19	1.43	2.77	0.96	0.00	0.93	−0.28
11/12	−1.03	−1.67	−1.38	0.10	−0.72	0.95	−0.58	−1.01

Table 11.3 Correlation and partial correlation with Niño-3.4 SST at ND(0)J(1). The partial correlation is calculated after removing the effect of the simultaneous Niño-3.4 SST.

	IOD SON(-1)	IOBW D(-1)JF(0)	NTA MAM(0)	Anino JJA(0)	WHWP JAS(-1)	NPO D(-1)JF(0)	NPMM FMAM(0)
Correlation	−0.40**	−0.27**	−0.48**	−0.45**	−0.33**	−0.21*	−0.50**
Partial correlation	−0.44**	−0.32**	−0.62**	−0.09	−0.32**	−0.25**	−0.50**

[*] 90% significant
[**] 95% significant

also preceded El Niño events, indicating a false alarm. Likewise, six negative NPO events are related to La Niña events, but still four positive NPO events are found for La Niña cases. This suggests that ENSO response to the NPO-related forcing are not as systematic as for the PMM forcing. Interestingly, the PMM index is significantly correlated to NPO index (cor = 0.45), but most NPO false alarm events did not co-occur with coincident PMM events, except for the 2008–2009 La Niña event. The partial correlation with Niño-3.4 SSTA is highest for the NTA index, suggesting that it is a good indicator for ENSO development. The Atlantic Niño events frequently co-occurred with ENSO events (13 events), but the partial correlation is quite weak (–0.09). This weak relationship suggests that Atlantic Niño hardly affects ENSO phase but may possibly modulate ENSO magnitude.

Cai et al. (2019) showed that using Indian and Atlantic ocean precursors improves ENSO prediction skill and the skill improvement is particularly more distinctive in the recent decades. However, Tables 11.1 and 11.2 show that the Indian Ocean precursors are closely related to ENSO events during 1980–1999, but this relationship weakened recently to some extent. This contradictory result might be related to the decadal changes in ENSO stability. In the past decades (1980–1999), ENSO amplitude is strong and the phase transition is clear so that internal Pacific precursors such as heat content can be a dominant factor in driving ENSO evolution, and the external remote forcings mostly play a role in enhancing ENSO variability. In recent decades (2000–2018), however, ENSO stability is weak so that external factors are more prominent in generating ENSO events. It might be also linked to why El Niño diversity is evident in recent decades. This speculation deserves further investigation.

Our understanding of ENSO's remote forcings is still in its infancy, with large uncertainty largely related to the short observational record. In particular, the observed relationship between ENSO and remote precursors has changed on the interdecadal timescales (Melice & Servain, 2003; Münnich & Neelin, 2005; Park et al., 2018; Cai et al., 2019). Therefore, it is difficult to quantitatively measure how much each precursor contributes to the evolution of ENSO events. Current ENSO predictive skill is limited particularly for a long lead time, possibly due to our immature understanding of relative contributions of ENSO's remote forcings to ENSO development.

To overcome these observational issues, many studies have used climate models to support the observational arguments and quantitatively estimate the relative contributions to ENSO evolution. Current climate models simulate to some extent the effects of the remote forcings on ENSO from the Indian Ocean (Kug et al., 2012; Jourdain et al., 2016; Ha et al., 2017), the Atlantic Ocean (Keenlyside et al., 2013; Ham & Kug, 2015; Park et al., 2018), and the extratropics (Vimont et al., 2003b). Various decoupled experiments, by switching off the feedbacks from the Indian or the Atlantic Oceans, confirmed that interbasin interactions play a significant role in ENSO variability (Yu et al., 2002; Wu & Kirtman, 2004; Obha & Watanabe 2012; Terray et al., 2015; Dommenget & Yu, 2017; Kajtar et al., 2017). The most recent studies examining the role of each remote region within the same modeling framework further indicate that interactions with the Indian and Atlantic Oceans provide a delayed negative feedback to ENSO but also increase ENSO frequency (Terray et al., 2015; Kajtar et al., 2017; Dommenget & Yu, 2017).

However, current climate models tend to underestimate the effect of remote forcing on ENSO compared to the observational estimates, with a weaker impact of the NTA (Ham & Kug, 2015), the Atlantic Niño (Kucharski et al., 2015), and the Indian Ocean basin (Kug et al., 2012) on the Pacific basin. The underestimation and misrepresentation of remote impacts on ENSO in current climate models are related to model's systematic biases (Richter et al., 2014; McGregor et al., 2018; Luo et al., 2018; Kajtar et al., 2018). For example, the underestimation of the NTA SST effect is possibly related to the dry bias over the Atlantic warm pool area (Ham & Kug, 2015). The weaker equatorial Atlantic SST gradient may also lead to a weak convective response to Atlantic SSTA and a weaker shift of the Walker Circulation, resulting in an unrealistic impact of Atlantic SSTA on the Pacific wind variability. Biases in the distribution of climatological precipitation over the Indo-Pacific warm pool region may be an important factor in the underestimated strength of the Indian Ocean feedback (Kug & Ham, 2012). All these studies suggest that a realistic representation of the model mean state can substantially improve the model's ability to simulate the influence of remote regions on ENSO evolution, which will eventually lead to improved ENSO predictive skill in dynamical forecast models.

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