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Dynamics and predictability of the El Niño-Southern Oscillation: An Australian perspective on progress and challenges

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Capsule summary (30 words max.): Many scientific challenges remain that need to be addressed in order to manage risk of future ENSO impacts in countries like Australia that are strongly affected by ENSO event diversity.

Abstract:

El Niño and La Niña, the warm and cold phases of the El Niño Southern Oscillation (ENSO), cause significant year-to-year disruptions in global climate including in the atmosphere, oceans and cryosphere. Australia is one of the countries where its climate, including droughts and flooding rains, is highly sensitive to the temporal and spatial variations of ENSO. The dramatic impacts of ENSO on the environment, society, health, and economies worldwide make the application of reliable ENSO predictions a powerful way to manage risks and resources. An improved understanding of ENSO dynamics in a changing climate has the potential to lead to more accurate and reliable ENSO predictions by facilitating improved forecast systems. This motivated an Australian national workshop on ENSO dynamics and prediction that was held in Sydney, Australia, in November 2017. This workshop followed the aftermath of the 2015/16 extreme El Niño which exhibited different characteristics to previous extreme El Niños and whose early evolution since 2014 was challenging to predict. This essay summarizes the collective workshop perspective on recent progress and challenges in understanding ENSO dynamics and predictability, and improving forecast systems. While this essay discusses key issues from an Australian perspective, many of the same issues are important for other ENSO-affected countries, and for the international ENSO research community.

1. Motivation

1.1. The Australian context

ENSO has long been recognized to strongly influence global and regional climate. Australian climate is particularly impacted by ENSO (e.g., McBride and Nicholls 1983; Ropelewski and Halpert 1987; Power et al. 1998). The associated changes in circulation, rainfall and temperatures are strong enough to impact its terrestrial and marine ecosystems (e.g. Nicholls 1985, 1991; Norman and Nicholls 1991; Holbrook et al. 2009). Although the impact can vary markedly from decade to decade (Power et al. 1999), bushfires, heatwaves and droughts generally tend to be more severe during El Niño years (e.g., Williams and Karoly 1999; Loughran et al. 2016), while the frequency of tropical cyclones across the north and flooding throughout much of the east tend to be enhanced during La Niña (e.g., Nicholls 1979; Werner and Holbrook 2011; Power and Callaghan 2016). To provide timely information on the likelihood of upcoming disruption of climate, ENSO outlooks have been issued routinely by the Australian Bureau of Meteorology since 2000.

The complex dynamics of ENSO manifest in diverse spatial and temporal evolution across events that lead to differing regional impacts (e.g., Power et al.1999; Ashok et al. 2007; Wang and Hendon 2007; Capotondi et al. 2015a). For instance, in Australia, the magnitude of an El Niño event alone does not provide clear guidance on its impacts (Power et al. 2006; Wang and Hendon 2007; Chung and Power 2017). For example, the impact of the 1997/98 extreme El Niño was limited to the south-eastern region and Tasmania, but much more severe and widespread drought occurred during the moderate 2002/03 El Niño (Wang and Hendon 2007; Taschetto and England 2009; Lim and Hendon 2015), leading to a massive 25% drop in agricultural output (Lu and Hedley 2004).

The 2002/03 event was not only notably weaker in intensity than the 1997/98 extreme event, but also exhibited a characteristically different pattern of sea surface temperature (SST) anomalies. The 1997/98 El Niño had SST anomalies (~+3°C) that peaked toward South America while those during 2002/03 event peaked in the central Pacific (~+1°C). The contrast in spatial patterns fits the notion of two archetype structures of ENSO: "Eastern Pacific" (EP) and "Central Pacific" (CP) events (e.g., Ashok et al. 2007; Kao and Yu 2009) following an earlier assessment of ENSO SST patterns by Trenberth and Stepaniak (2001). This is illustrated in Fig. 1 which also shows that an event may not necessarily fall into either category – a pattern that is a mix of EP and CP types is possible as part of the ENSO continuum arising from non-linear dynamics, stochasticity, and remote forcing, which can also give rise to temporal evolution diversity (e.g., Takahashi et al. 2011; Dommenget et al. 2013; Lee et al. 2014; Takahashi and Dewitte 2016). This intrinsic ENSO complexity was recently summarized by Timmermann et al. (2018). As such, a clear classification of certain ENSO events into EP and CP can be difficult and be sensitive to the choice of index (e.g., Capotondi et al. 2015a).

The typical surface temperature and rainfall anomaly patterns associated with EP and CP ENSO are different over Australia, as well as other regions across the globe (Fig. 2). Specifically, CP events tend to be associated with larger and more widespread rainfall and temperature changes in Australia than EP events – analogous to the difference in impacts between the 2002/03 and 1997/98 events, even though EP El Niños tend to be stronger than CP events (e.g., Capotondi et al. 2015a; Fig. 1). Investigating the cause for the differing impact between EP and CP events is still an open area of research, but based on investigating the difference between 2002/03 and 1997/98 events, the contrast may be due to the forcing center of CP events that is closer to Australia (Wang and Hendon 2007; Lim and Hendon 2015). This could also illustrate the more general result, that impacts in Australia are more tightly linked to the magnitude of La Niña than they are to the magnitude of El Niño (Power et al. 2006), as stronger La Niña events tend to be of a CP type (Fig. 1). As such, predicting the spatial structure of ENSO events is important for impact preparedness over regions like Australia (Hendon et al. 2009). Apart from classification of individual events, other factors such as event precursors, local processes (e.g., antecedent soil moisture, anomalies in regional seas), random disturbances, as well as other modes of climate variability, also matter in determining impacts.

The Australian continent extends from the tropics to the mid-latitudes, and is surrounded by warm tropical Indo-Pacific oceans to the north and the Southern Ocean to the south. Thus, it is not only affected by direct tropical impacts of ENSO via the Southern Oscillation but also by extratropical teleconnections due to ENSO-induced changes in tropical convection. Furthermore, Australian climate is affected by a rich interplay between ENSO and other climatic events such as the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM) (e.g. Hendon et al. 2007; Meyers et al. 2007; Risbey et al. 2009; Cai et al. 2011; Taschetto et al. 2011; Pui et al. 2012; Lim and Hendon 2015). Ocean surface temperature variations surrounding northern Australia, which tend to covary with ENSO also exert strong influence on Australian climate (e.g., Drosdowsky and Chambers 2001; Hendon et al. 2012; Ummenhofer et al. 2015) and may even affect development of ENSO itself (Nicholls 1984).

This complexity of impacts and interactions combined with the uniqueness of every ENSO event poses grand challenges for predicting Australian climate. For example, unlike the extreme 1997/98 event, the extreme 1982/83 El Niño, which is also classified as an EP event, had a particularly strong impact on Australia, likely due to relatively strong cold sea surface anomaly to the north-northeast of Australia (van Rensch et al. 2015). Severe drought gripped the eastern half of the country, marked by the historically catastrophic ‘Ash Wednesday’ bushfires in the southeast (Voice and Gauntlett 1984). For these reasons, and given Australia's susceptibility to future climate change, ENSO is at the forefront of climate research in Australia.

1.2. Unexpected turns of events

Following the extreme El Niño events in 1982/83 and 1997/98, the most recent major El Niño event occurred in 2015/16 (Blunden and Arndt 2016; Xue and Kumar 2017; L'Heureux et al. 2017). This first extreme El Niño of the 21st Century (Santoso et al. 2017) followed a "false alarm" in 2014. In 2014, the equatorial Pacific warm water volume (WWV) increased rapidly during the austral autumn following a strong westerly wind burst (WWB) event, reaching a level not seen since 1997 (McPhaden 2015). Increased WWV and increased activity of WWBs are typical precursors for an El Niño (see Table 1 for WWV and WWB definitions). However, the much anticipated big El Niño did not emerge at the end of 2014 (Hannam 2014), but it did instead in 2015.

The "roller-coaster" evolution of the 2014-2016 events and their prediction are illustrated in Figure 3, using the *ENSO Outlook* indicator from the Australian Bureau of Meteorology. The Bureau raised its *ENSO Outlook* to "watch" in February and March 2014, and subsequently elevated to "alert" in April-July, indicating the increasing possibility of an El Niño (of any magnitude) later in the year. This coincided with a spike in WWV that often precedes El Niño events, in line with the ENSO recharge oscillator theory (Jin 1997). However, the outlook status was downgraded back to "watch" in August-October, and then elevated again to "alert" in November-January. This outlook variation appears to be in line with WWV decline since the previous April before a slight increase again around July. A strong El Niño never materialized, which was later shown to be due to a combination of impeding factors, such as muted WWB activity (Menkes et al. 2014) and an occurrence of intense easterly wind burst (Hu and Fedorov 2016), as well as a mean-state associated with the negative phase of the Interdecadal Pacific Oscillation (IPO) that is less favourable for Bjerknes feedbacks at the root of El Niño growth (Wang and Hendon 2017) and an anomalously warm Indian Ocean surface (Dong and McPhaden 2018) – both factors are associated with stronger Pacific Walker Circulation. The tropical Pacific was nonetheless left anomalously warm, but fell short to being considered an El Niño condition (e.g., Santoso et al. 2017).

In early 2015 clear signs of an emerging El Niño were detected, and the outlook status was raised to "event" in May 2015 (Watkins 2015). A strong El Niño developed in the latter half of 2015. The tropical Pacific then cooled, with a borderline La Niña developing in austral summer of 2016-17 declared by some agencies (but not the Bureau) followed by the Bureau's official declaration of a weak La Niña in December 2017.

Amidst the widespread speculation in early 2014 of a strong El Niño that year, the Bureau's coupled model, POAMA (Predictive Ocean Atmosphere Model for Australia), predicted only a weak event when initialized in austral autumn 2014 (Wang and Hendon 2017; see their Fig. 3a). In contrast, other models surveyed by the Bureau predicted a strong El Niño for 2014 (http://www.bom.gov.au/climate/ahead/archive/models/201405-ms.shtml). On the other hand, while issuing a stronger forecast for El Niño in 2015 than in 2014, POAMA initially underestimated the strength of the 2015/16 El Niño (Fig. 3b of Wang and Hendon 2017; the observed Niño3 falls outside the forecast 5-95% uncertainty range), and was weaker than the other surveyed models, until POAMA was initialized with late austral winter conditions (see the Bureau's 2015 archive; e.g., http://www.bom.gov.au/climate/ahead/archive/models/201508-ms.shtml). This is not surprising though as predicting the magnitude of ENSO is challenging, more so than predicting the phase, especially early in the year when signal-to-noise ratio is low.

The challenge in anticipating and predicting the evolution and magnitude of the 2014-2016 chain of events, led to much retrospection about the state of our understanding of ENSO dynamics beyond the classical recharge-discharge oscillator theory, as well as the current state of the art climate models used to make predictions.

At an international ENSO workshop held in Sydney in 2015, key aspects of ENSO extremes and the associated open questions were discussed (Santoso et al. 2015). However, at that meeting, our knowledge of extreme El Niño was largely based on the 1982/83 and 1997/98 events – the only two extreme El Niño events in the modern instrumental record that showed distinct characteristics from other ENSO events. These characteristics include: (i) intense WWB activity in the western/central Pacific during event onset and development phases; (ii) a dramatic eastward and equatorward shift of atmospheric convection as El Niño emerges and matures, thereby inducing unusually high rainfall in the climatologically dry and cold eastern equatorial Pacific; and (iii) prominent eastward propagation of anomalous SSTs along the equatorial Pacific Ocean over event onset to decay phase[1]. However, the latter two properties, which had previously been thought to typify an extreme El Niño, were less apparent during the 2015/16 El Niño (Santoso et al. 2017). In particular, while the 2015/16 El Niño did produce heavy rainfall over the eastern equatorial Pacific with December-February average rainfall in the Niño3 region (5°S-5°N, 150°W-90°W) close to 5 mm day^{-1}, a threshold used by Cai et al. (2014) to define an extreme El Niño, it exhibited record breaking rainfall over the Central Pacific, in stark contrast to the relatively weak El Niño-related rainfall in 1982/83 and 1997/98 events (Santoso et al. 2017).

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[1] The propagation signature is diagnosed as the time-longitude slope of maximum equatorial SST anomaly (5°N-5°S average) over 160°E – 80°W from May of the El Niño development year to the following May when the event subsides, following Santoso et al. (2013).

The peculiarity of the 2015/16 event, the volatile 2014-2015 ENSO outlook (Fig. 3) and the complex ENSO behaviour and its impacts over Australia (section 1.1), motivated a second workshop on ENSO dynamics and prediction which was held in Sydney, Australia in November 2017 and involved 25 Australian ENSO researchers (www.climatescience.org.au/content/1182-enso-dynamics-workshop). Here we present the outcomes of this workshop, outlining recent research progress, knowledge gaps, impediments and recommendations to further advance ENSO research and prediction systems and service. These issues are discussed within each of five themes outlined in section 2, based largely on the studies presented by the workshop participants as referenced therein. A summary is provided in section 3 along with closing remarks on infrastructures and synergy behind ENSO research in Australia. Definitions of some terminologies discussed in the paper are provided in Table 1.

2. Discussions

2.1. Insights from the 2015/16 El Niño

The emergence of the strong 2015/16 El Niño showed that an extreme El Niño does not necessarily exhibit SST anomalies peaking toward the far eastern Pacific as in the 1982/83 and 1997/98 events, which have until recently been used as a benchmark for defining an extreme El Niño (see Santoso et al. 2017 for a review). The global climate context for the 2015/16 El Niño was different from that for the1982/83 and 1997/98 events (see also Newman et al. 2018). For instance, there was a much more significant and persistent signature of extra-tropical influence in the 2015/16 El Niño, with warm SST anomalies extending from the north-eastern Pacific to the Central Pacific associated with the North

Pacific Meridional Mode, than in the 1982/83 and 1997/98 events (Santoso et al. 2017; Paek et al. 2017).

Unlike the previous two extremes, the large amplitude of the 2015/16 El Niño was built upon an already abnormally warm tropical Pacific from 2014, rather than relying solely on a vigorous Bjerknes feedback (Abellán et al. 2017). The weak 2014/15 El Niño-like condition prevented a large discharge of warm water out of the equatorial Pacific (Levine and McPhaden 2016) that would normally occur following a strong El Niño. This allowed anomalous equatorial warming to persist into 2015, priming the ocean for the subsequent El Niño. The suite of processes leading up to the 2015/16 El Niño, along with a build-up of ocean heat content in the off-equatorial Western Pacific over the previous decade, may have triggered a shift in the phase of the IPO, from negative before to positive after 2014 (Meehl et al. 2016). This can be invoked to partially explain the difference in amplitude between the 2014/15 and 2015/16 events (Wang and Hendon 2017), as a mean state associated with a positive IPO is more conducive to the Bjerknes positive feedbacks for El Niño development in the eastern Pacific (e.g., Zhao et al. 2016) – although the IPO itself is, in turn, partially a long-term imprint of ENSO variability (Power and Colman 2006; Newman et al. 2016). The subsequent decay of the 2015/16 event was also different from the 1982/83 and 1997/98 events in that it had persistent warm SST anomalies near the dateline, which lingered right through the austral fall of 2016 and significantly delayed the Bjerknes feedback required for the development of a following La Niña (Lim and Hendon 2017).

The distinctive characteristics of the 2015/16 extreme El Niño demonstrate that our observational record is still too short to fully sample the diversity of ENSO characteristics. Furthermore, there are uncertainties in observed SST data prior to the satellite era especially before the 1950s when observations were sparse and ship recording practices were not homogeneous (e.g., Ishii et al. 2005). This is particularly the case for meteorological variables over the ocean, meaning that comparisons to past events using a single index based on SST, and other variables for that matter, may not be accurate in terms of relative strength or variability. These issues mean that multiple observational products and indices beyond the commonly used ENSO metrics in operational forecast (e.g., Niño3.4, WWV, WWB, Southern Oscillation Index) are required to capture the diversity of ENSO extremes. Refinement of existing indices is also needed to better describe ENSO event diversity (e.g., Sullivan et al. 2016). In addition, the background climate upon which ENSO evolves is changing due to greenhouse warming and internal multi-decadal variability. To detect these long-term changes and the impact on ENSO characteristics, continuous high-quality observations are critical and so are reliable paleo-reconstructions for resolving characteristics of past ENSO events.

2.2. ENSO predictability

According to conventional ENSO theory (e.g., Jin 1997), WWV is a key precursor and hence predictor for ENSO. Consequently, WWV or the associated subsurface information is utilized in initializing forecast models to help alleviate the drop in ENSO prediction skill in austral autumn – widely known as the "(boreal) spring predictability barrier" (Webster and Yang 1992). However, anomalous WWV, while necessary, is not the only requirement for development of ENSO events, as demonstrated by the 2014 case. El Niño is typically triggered by a series of WWBs in the western/central Pacific (Vecchi and Harrison 2000). On the other hand, a negative WWV anomaly during austral autumn appears to be a better predictor for strong La Niña events than any other type of ENSO event (Santoso et al. 2017).

A better understanding of the relationship between WWV, WWB, and ENSO is important in ENSO prediction.

On this front, Neske and McGregor (2018) showed that WWBs themselves can create a significant WWV response that can be decomposed into two components: the "adjusted response" (which relies on slow ocean dynamics associated with Rossby wave reflection as depicted by the recharge oscillator theory) and the "instantaneous response" (which represents surface Ekman transport in response to WWB). The adjusted response is identified as the source of predictability and it has weakened since the start of the 21st Century – the reason for this decline remains unclear but may be associated with a shift in the background climate toward the cold phase of the IPO (Zhao et al. 2016) through modulation of governing ENSO processes (e.g., WWBs, WWV, etc.). The instantaneous response, which has increased in prominence in recent decades, emphasizes that ENSO is event-like rather than cyclical. This research highlights that the balance of the two components can vary on decadal time scales, giving rise to decadal modulation of ENSO predictability.

ENSO predictability does not lie solely within the tropical Pacific. Climate variability in other oceanic basins also plays a role. Remote climate anomalies induce atmospheric changes that are transmitted into the tropical Pacific through atmospheric planetary waves or changes in the Walker Circulation, thereby affecting ENSO evolution. This remote influence is highlighted by two recent studies that investigated the predictability of recent La Niña events. Using two coupled models, Luo et al. (2017) showed that the Indian and Atlantic Ocean warming contributed to the two-year lead predictability of the 2010-2012 series of La Niña events. The multi-year surface warming in these oceans enhanced the Trade Winds over the central-western Pacific that tend to favour La Niña development. The role of the Indian Ocean was emphasized by Lim and Hendon (2017) who showed that the appearance of La

Niña in 2016, although weak, was promoted by earlier than normal development of a record strong negative IOD, which tends to enhance convection over the Indo-Pacific warm pool thereby strengthening the Pacific Trade Winds. They showed that using realistic ocean conditions in the Indian Ocean in late April 2016 was sufficient to produce the strong negative IOD during austral winter and spring and was necessary for delivering an improved La Niña forecast.

2.3. Response to greenhouse forcing

While the Pacific Ocean is projected to warm in the future, and that the anthropogenic warming is already evident in the western part of the basin (Wang et al. 2016), there is still uncertainty around whether ENSO events (typically measured through equatorial Pacific SST anomalies) will change in terms of their spatial patterns, amplitude, and frequency. Climate models produce contrasting projections due to different relative importance of ENSO feedback processes, different patterns of changes in the mean climate, as well as different depictions of decadal variability (e.g., Collins et al. 2010; DiNezio et al. 2012; Kim et al. 2014a; Chen et al. 2017). The power spectra of ENSO SST variability also exhibit large discrepancies across models and paleo reconstructions (Hope et al. 2017). However, there is a better inter-model consensus on a general increase in ENSO-driven tropical rainfall in the equatorial central and eastern Pacific in response to global warming, reflecting the consensus for more mean warming in the eastern equatorial Pacific (Power et al. 2013; Chung et al. 2014).

According to CMIP5 scenario simulations, the projected weakening of the Walker Circulation in the 21st century (e.g., Vecchi et al. 2006; Kociuba and Power 2014) with faster warming in the eastern equatorial Pacific than in the surrounding oceans is expected to shift atmospheric convection into this usually cold and dry region, resulting in more occurrences of heavy precipitation that characterize an extreme El Niño (Cai et al. 2014). The projection does not arise from the climatological increase in mean rainfall and is robust when using atmospheric vertical velocity (Cai et al. 2017). The associated weakening of the climatological equatorial ocean currents is expected to promote eastward propagating SST anomalies – a characteristic of the 1982/83 and 1997/98 extreme El Niño events (Santoso et al. 2013). On the other hand, increased occurrences of extreme La Niña events characterized by anomalous surface cooling in Central Pacific could also arise due to faster warming of the Maritime Continent and eastern Pacific than the Central Pacific (Cai et al. 2015b). The warming background climate can enhance ENSO teleconnection and thus its impact, even if the SST anomalies themselves do not intensify (Cai et al. 2015a; Power et al. 2018). Even if global warming is kept below 1.5°C or 2°C, the risk associated with increased extreme El Niño frequency and ENSO-related major rainfall disruptions is likely to persist or even increase (Wang et al. 2017; Power et al. 2017a). In fact, global warming might have already made ENSO events more disruptive (Power et al. 2017a), enhancing ENSO-driven variability in many regions around the world (Bonfils et al. 2015; Power et al. 2018).

These projections may be sensitive to model deficiencies in simulating ENSO. As shown by Vijayeta and Dommenget (2017) using the recharge oscillator framework, models tend to underestimate ENSO feedback processes. Realistic simulation of ENSO behavior may stem from error-compensation rather than from correct simulation of the governing feedback processes. Confidence in projections is also reduced by the inability of climate models to capture decadal 'La Niña-like' trends as strong as those observed in the Pacific in recent decades (e.g., Kociuba and Power 2014; England et al. 2014), and a tendency to overestimate Pacific warming over the past 50 years (Power et al. 2017b). Possible reasons include model underestimation of internal variability (Kociuba and Power 2014; Power et al. 2017b), biases in the upper ocean thermal stratification (Kohyama et al. 2017), as well as biases in the inter-basin warming contrast across the three oceans and in the SST-cloud forcing feedback (Luo et al. 2018). To reduce uncertainty in ENSO future projections, it is clear that much work needs to be done to improve climate models.

2.4. ENSO modelling

Poor simulation of ENSO is often linked to the persistent 'cold-tongue' bias in which the cold upwelled water in the eastern equatorial Pacific extends too far west toward the Maritime Continent (Fig. 4a). A "double Intertropical Convergence Zone (ITCZ)" is also associated with this cold tongue bias. These biases can affect ENSO simulation through misrepresentation of air-sea feedbacks (Kim et al. 2014b; Wengel et al. 2018). Graham et al. (2017) showed that the cold tongue bias leads to a propensity for occurrences of spatially double-peaked ENSO SST anomalies (peaking concurrently in both the eastern and central Pacific), which are not apparent in historical observations.

Another important ENSO feature is its synchronisation to the annual cycle, with peak SST anomalies typically occurring during austral summer. However, many models still do not represent this accurately (Fig. 4b). Worse, in some models (such as those highlighted in Fig. 4b) the seasonality is completely reversed (Taschetto et al. 2014). A suite of important processes shapes ENSO seasonality and the incorrect seasonality indicates that the underlying ENSO dynamics (e.g., SST-cloud and thermocline feedbacks) in the models are unlikely to be correct (Rashid and Hirst 2016). This, together with the bias in anomaly patterns, has ramifications for determining ENSO teleconnections and predicting ENSO impacts on rainfall, for instance.

How these unrealistic ENSO features affect future projections needs to be carefully considered and investigated through detailed analysis of the underlying coupled feedbacks (e.g., Guilyardi et al. 2016; Capotondi et al. 2015b), which are also dependent upon the mean state. As an example, Rashid et al. (2016) found that the strengths of the zonal wind stress forcing and wind-convection coupling simulated by the CMIP5 models largely determine whether the ENSO amplitude will increase or decrease under global warming in those models. Importantly, improvement of the model's mean state is critical. For instance, by taking into account the effect of ocean currents on the momentum transfer to the atmosphere (Pacanowski 1987), Luo et al. (2005) found a notable reduction in the cold tongue bias in their climate model.

The equatorial Pacific cold tongue is also affected by small-scale oceanic processes such as tropical instability waves (TIWs). TIWs are not well resolved by current state-of-the-art climate models which are still run at relatively coarse ocean resolution. TIWs heat the Pacific cold tongue at a rate comparable to atmospheric heating (up to 1°C/month; e.g., Menkes et al. 2006) and can potentially be an important nonlinear negative feedback on ENSO (An and Jin 2004). Research into TIWs influence on ENSO is still limited. Holmes et al. (2018) address how TIWs modify the response of the Central and Eastern Pacific to WWBs, providing a first estimate of TIWs contribution to ENSO irregularity, with implications for ENSO prediction (also see Ham and Kang 2011).

In addition, the Pacific cold tongue is a region of strong atmospheric heat uptake, and vigorous turbulent mixing that transports this heat into the ocean interior. Recent research by Holmes et al. (in preparation) has highlighted the global significance of air-sea fluxes and turbulent mixing in this region for modulating ocean heat uptake. However, the parameterization of this vertical mixing in climate models remains a difficult task, and improvements are required in order to reduce model biases (e.g., Sasaki et al. 2013; Zhu and Zhang 2018).

2.5. Low frequency variability

ENSO properties vary on decadal and longer time scales (e.g., Holbrook et al. 2014; Wittenberg 2015; Power and Smith 2007) through changes in air-sea feedbacks linked to noise, chaotic dynamics, and slow variations in the mean state (e.g., Wittenberg 2009; Newman et al. 2011; Wittenberg et al. 2014; Zhao et al. 2016). While the mean-state variations are thought to be in part a rectified effect of changes in ENSO (e.g., Power and Colman 2006; Ogata et al. 2013), they also affect the interactions between ENSO and other modes of variability such as the SAM (e.g. Lim et al. 2016), as well as their eventual impact, such as on atmospheric cyclones and anticyclones. It is therefore crucial to understand the processes governing mean-state changes and their impact on ENSO.

The impact of mean-state change was highlighted by the 1970s climate shift that saw the Pacific climate system transition into a positive IPO that lasted until the late 1990s. Since then, the issue has been reignited by the recent short-lived slowdown in global surface warming that coincided with a negative IPO phase (approx. 1999-2012). In contrast to the preceding positive IPO, this negative IPO period was marked by a lack of strong El Niño, more frequent Central Pacific El Niños, more prominent La Niñas (e.g., see Fig. 3 of Santoso et al. 2017), and reduced seasonal predictability (Zhao et al. 2016). This change in ENSO characteristics and predictability was attributed by Zhao et al. (2016) to reduction in the strength of the Bjerknes feedback in the central and eastern Pacific as a result of the IPO-related colder surface temperatures and enhanced mean Walker Circulation.

The IPO can be partially explained as the accumulated response to interdecadal variability in ENSO activity (Power et al. 2006; Newman et al. 2016). However, other factors may be involved, and the extent to which the IPO influences ENSO activity requires further study. More research is needed into the processes governing decadal variability, including those during the slowdown period as well as periods of more rapid warming. For instance, the cause for the unprecedented strength of the Pacific Trade Winds during the global warming hiatus period (England et al. 2014) needs to be better understood, including the roles of interbasin warming contrast, radiative forcing, and ENSO rectification onto the mean-state. Modelling studies have shown that these factors can influence the strength of Pacific climate change (e.g., Luo et al. 2018; Kohyama et al. 2017).

Recent studies indicate that warming trends in other ocean basins could be the cause for the record strong Pacific trade winds during 1999-2012. In particular, the role of the Atlantic warming trend appears to be important (e.g., McGregor et al. 2014; Luo et al. 2017). Models tend to underestimate the recent Pacific wind acceleration and to have strong climatological biases in the Atlantic Ocean. Indeed, there is an inter-model relationship between these two aspects (Kajtar et al. 2017; McGregor et al. 2018), highlighting the need to account for other basins in studying Pacific decadal variability.

In addition, using an eddy-permitting ocean model, Maher et al. (2017) showed that the recent Pacific Trade Wind acceleration can explain heat content trends in the Pacific Ocean, and in the Indian Ocean via the Indonesian Throughflow. They also showed that these heat content anomalies do not entirely dissipate with the abatement of the Pacific winds, leaving residual heat in the ocean. The impact of low-frequency subduction of heat on ENSO processes, particularly over decadal timescales, warrants further investigation.

3. Summary and closing remarks

The following key issues were raised during the workshop:

- **Characteristics of ENSO extremes:** The 2015/16 El Niño demonstrated potential diversity in extreme El Niño events than previously realized. It highlights the need for a better understanding of the causes and predictability of extreme ENSO events, supported by high-quality observational data and metrics toward better monitoring, predicting, and analyzing future events.
- **ENSO predictability:** There is scope to improve our understanding of ENSO development and ENSO representation in climate models, toward better operational predictive capability. Other than WWV and WWBs, climate variability and trends outside the tropical Pacific are also important factors. Decadal variability and long-term changes of these factors have important implications for the decadal predictability of ENSO.
- **Response to greenhouse forcing:** There is an indication that extreme ENSO events may become more frequent in a warmer future, and the present global warming may already be great enough to exacerbate the ENSO-induced rainfall disruption in the Pacific. Given existing model biases, there is a need to continually revise these assessments with improved models (e.g., CMIP6).
- **Model bias:** Current state-of-the-art climate models still have problems simulating the detailed nuances of ENSO and its seasonality, and these problems may be linked to the persistent cold tongue bias and its broader effects (e.g., double ITCZ bias) as well as biases in other basins that can impact ENSO through atmospheric and oceanic teleconnections.

- **Synoptic-scale oceanic processes:** Tropical instability waves, which are not well resolved in climate models, are an under-represented source of ocean mixing. Our understanding of ENSO irregularity would benefit from quantifying the relative effects of ocean noise and atmospheric stochasticity.
- **Mechanisms for decadal variability and trends:** Further research is needed to clarify the manner in which the IPO and other aspects of decadal variability interact with ENSO, and the extent to which the IPO is attributed to red noise associated with ENSO and other factors including external forcing and the role of remote oceanic basins.

The key elements of our discussions are summarized in Figure 5 which highlights areas of challenges and the ramifications associated with understanding ENSO dynamics and predictability. While ENSO predictability and the regional impacts can vary across events and decades (e.g., Power et al. 1999; Barnston et al. 2012; Karamperidou et al. 2014; Zhao et al. 2016) and ENSO predictability limit is not yet known (e.g., Newman and Sardeshmukh 2017), improved understanding of the interaction of these processes and their depiction in climate models could ultimately improve seasonal forecasts, decadal predictions, and future projections of ENSO. This should also lead to more accurate identification of ENSO impacts, with longer lead times and potential benefits to improved climate risk management. These are especially important for Australia given the pronounced and complex ENSO impacts on its regional climate (section 1), but this should also be applicable to all other ENSO-affected countries. The way forward is to sustain and expand ENSO research through further advances in modelling, observations, theoretical frameworks, forecasts, analysis techniques, and development of new metrics/indices, coordinated across a collaborative international research environment.

Such endeavors have been ongoing in Australia and nurtured by various government initiatives, organizations, universities, and industries. Research collaboration and student training across institutions are fostered through, for example, the currently active National Environmental Science Program (www.environment.gov.au/science/nesp), and the Australian Research Council (ARC) Centre of Excellence for Climate Extremes (https://climateextremes.org.au), both of which integrate various ENSO related topics within their overarching research programs. The ARC Centre has extended the collaborative network to include several international institutions. ENSO is a core research element in the recently established Centre for Southern Hemisphere Oceans Research (CSHOR; https://cshor.csiro.au), which is a partnership between the CSIRO and Qingdao National Laboratory for Marine Science and Technology (QNLM), with UNSW and University of Tasmania as partners.

Australia has the National Computational Infrastructure (NCI) that provides high-performance computing and data intensive services to researchers, supporting model development such as Australia's national climate model, the Australian Community Climate and Earth System Simulator (ACCESS) that contributes to CMIP and IPCC. The development of ACCESS has involved close international partnerships, particularly with the UK Met Office (UKMO) and the US Geophysical Fluid Dynamics Laboratory (GFDL).

The seasonal forecast system that is used to produce ENSO outlook continues to advance at the Bureau, with POAMA to be replaced in 2018 by the seasonal forecast version of ACCESS (ACCESS-S) which is of a higher resolution and better than POAMA in distinguishing between EP and CP El Niño events, particularly at increasing lead times (Hudson et al. 2017).   Development and improvement of the Bureau's coupled model predictions systems rely heavily on the partnership with the UKMO, but have also been and continue to be strongly supported by various agricultural research and development corporations with matching funding from the Australian Government through the Managing Climate Variability Program (http://managingclimate.gov.au). Some of the key focus of the Bureau's research directions toward improved seasonal predictions include tackling key model biases that are affecting the simulation and prediction of ENSO diversity, improving data assimilation techniques for more accurate forecast model initialization, extending ENSO prediction lead times, and exploring the potential for multi-year prediction of ENSO.

Observing the tropical Pacific for ENSO, of which the TAO/TRITON mooring arrays (www.pmel.noaa.gov/gtmba) have been instrumental, is an integral part of international effort in ocean observations under the auspices of Global Ocean Observing System (GOOS). While not a contributor to TAO/TRITON, Australia is a major contributor to GOOS through deployment of Argo floats operated by the Integrated Marine Observing System (IMOS; imos.org.au). The global array of Argo profiling floats provides real-time data of temperature, salinity, and currents up to 2000-m depth over the global oceans including the tropical Pacific. The Bureau relies on Argo subsurface temperature and salinity data for initializing their seasonal prediction models.

Australian ENSO researchers have also actively participated in international initiatives and organizations, such as the World Climate Research Program, TPOS 2020, IPCC, among many others, that in turn foster and enrich ENSO research activities. The future success of ENSO research and prediction in Australia will certainly benefit from sustained cross-institutional synergies in a conducive environment of the multi-national network.

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Table 1. Definitions of terms discussed in this article.

Terminology	**Definition**
Bjerknes feedback[a]	Positive air-sea coupled feedback along the equator in which a positive SST anomaly during an El Niño growth phase induces westerly wind anomalies that deepen the thermocline thereby reinforcing the positive SST anomaly, and the cycle continues taking El Niño to its peak. The converse occurs during a La Niña.
Interdecadal Pacific Oscillation (IPO)[b]	Ocean-atmosphere variability in the Pacific Ocean operating on 10-30 year time scales with a near-global pattern resembling that of El Niño and La Niña during its positive/warm and negative/cold phases, respectively. The IPO could be a long-term integration of various processes including interannual and decadal components of ENSO variability, stochastic air-sea fluxes, as well as other sources of low-frequency variability.
Indian Ocean Dipole (IOD)[c]	Year-to-year climate variability in the Indian Ocean that peaks in austral spring with its positive phase exhibiting a pool of anomalously cold sea surface off Java-Sumatra, and anomalously warm sea surface off Africa. Such pattern is associated with weaker Walker Circulation over the Indian Ocean, and often coincides, but not always, with a developing El Niño. The converse occurs during the negative phase and La Niña.
Southern Annular Mode (SAM)[d]	Vacillations in atmospheric pressure over extratropical Southern Hemisphere to Antarctica associated with stronger westerly wind at high latitudes and weaker westerlies at mid latitudes during its positive phase, and conversely during the negative phase.

Walker Circulation[a]	Large-scale zonal atmospheric circulation in the tropical Pacific marked by easterly winds blowing from the colder eastern Pacific toward the Western Pacific warm pool where warm air rises and moves eastward as it loses moisture before eventually descending in the eastern Pacific. The Walker Circulation weakens during an El Niño and strengthens during a La Niña, and the *Southern Oscillation* refers to the associated vacillation of atmospheric pressure in the tropical western and eastern Pacific.
Warm water volume (WWV)[e]	Volume of water above 20°C isotherm across the equatorial Pacific (5°S-5°N, 120°E-80°W) as a proxy of upper equatorial Pacific Ocean heat content. Anomalously high WWV around austral autumn is a necessary condition for an El Niño at the end of the year. The opposite is true for La Niña.
Westerly wind burst (WWB)[f]	Sustained west-to-east winds over the western and central equatorial Pacific, typically exceeding a certain threshold (e.g., 2 m s^{-1}) and lasting more than a few days.

[a] Bjerknes (1969)

[b] Power et al. (1999), Newman et al. (2016), Henley et al. (2016)

[c] Saji et al. (1999)

[d] Thompson and Wallace (2000)

[e] Meinen and McPhaden (2000)

[f] Vecchi and Harrison (2000), Puy et al. (2016)

Figure captions

Figure 1. ENSO diversity over 1980-2017. (a) Eastern Pacific (EP) ENSO index (EPI) versus Central Pacific (CP) index (CPI) averaged over December-February (DJF) when ENSO events typically peak, where circle size corresponds to ENSO amplitude and the color indicates the type (EP, CP, EP/CP). (b)-(e) Composite of DJF SST anomalies for each type of ENSO events. (f) SST anomaly over the equatorial Pacific (averaged over 5°S-5°N) marked by different colors that signify event types in (a). The EPI and CPI are based on those of Sullivan et al. (2016), defined as Niño3 – 0.5*Niño4 and Niño4 – 0.5*Niño3, respectively (where the Niño indices are first normalized). Niño3 and Niño4 indices are SST anomalies averaged over (5°S–5°N,150°W–90°W) and (5°S–5°N, 160°E–150°W), respectively. An arbitrary threshold (Thr) can be applied to the indices to classify each year into EP, CP, or a mix (EP/CP). In this case, 0.7 of the index standard deviation (sdev.) is used (dotted lines), with the 1982/83 and 1997/98 extreme El Niño being classified as EP events (dark red) in which EPI > EP Thr and CPI < CP Thr. In this way, the 2015/16 and 1991/92 El Niños can be classified as both EP and CP (red), and the events in yellow are CP El Niños (CPI > CP Thr, EPI < EP Thr). The same applies for La Niñas but using negative thresholds. Note how the event classification can change with subtle shift in the thresholds. The size of the circles corresponds to the magnitude of the Niño3.4 anomaly: large circles for |Niño3.4| > 1.8 sdev; medium circles for 1 sdev < |Niño3.4| < 1.8 sdev; small circles for 0.5 sdev < |Niño3.4| < 1 sdev. Gray circles are considered as neutral years (|Niño3.4| < 0.5 sdev). The NOAA Extended Reconstructed SST version 5 (ERSSTv5; Huang et al. 2017) is used in this analysis with linear trends removed.

Figure 2. Surface air temperature (SAT) and rainfall anomaly patterns associated with (a) Eastern Pacific and (b) Central Pacific ENSO shown as the regression of SAT (color shading)

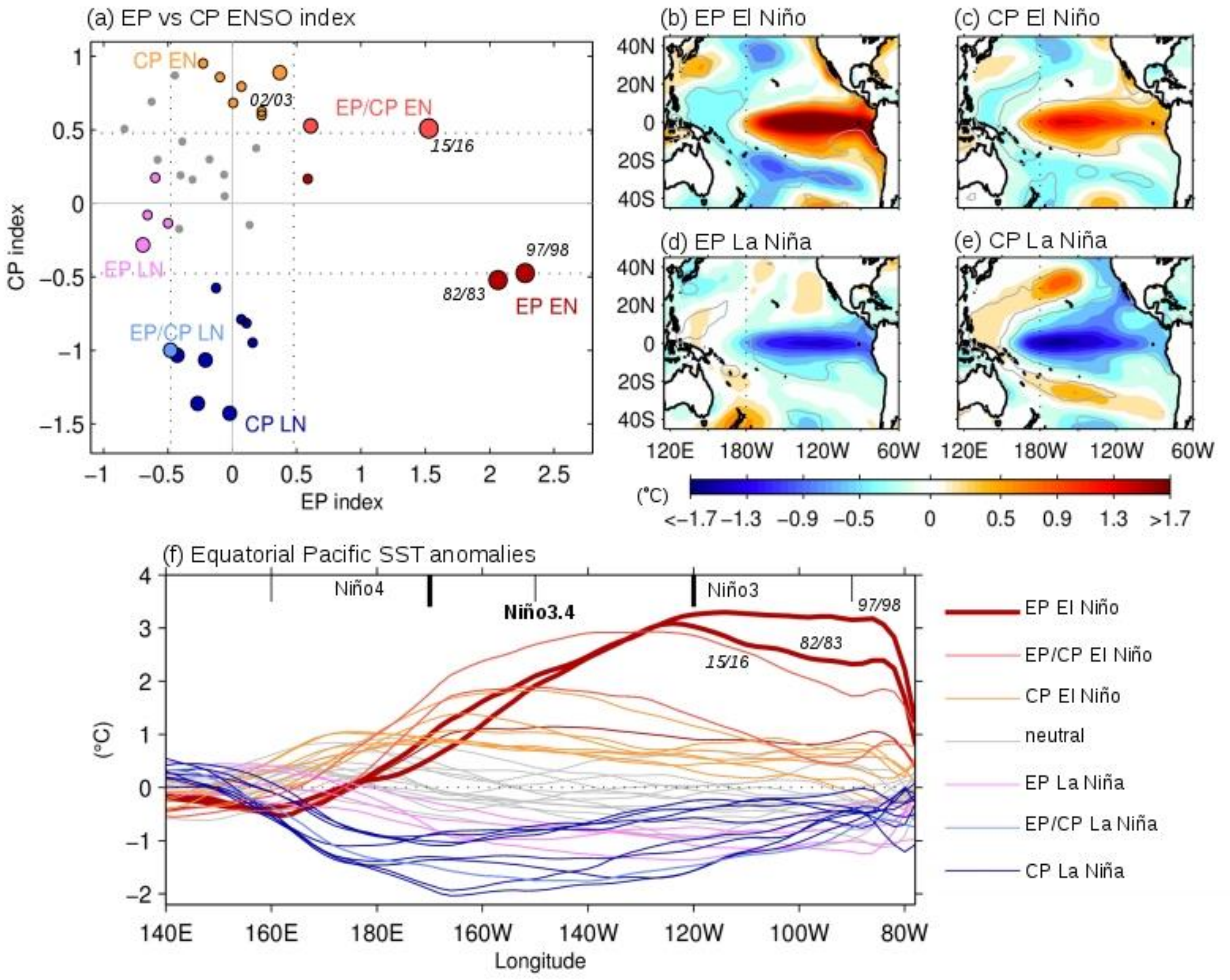
and rainfall anomalies (contours) against the EP and CP ENSO indices of Sullivan et al. (2016) defined in Fig. 1. Units are in °C and mm day^{-1} per standard deviation. The analysis uses monthly data of NCEP/NCAR Reanalysis (Kalnay et al. 1996) for SAT, CPC Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997), and NOAA Extended Reconstructed SST version 5 (ERSSTv5; Huang et al. 2017) to calculate the ENSO indices from 1980 to 2016, with monthly climatology and long-term trends removed. Stippling indicates rainfall regression coefficients that are statistically significant above the 95% level.

Figure 3. ENSO Outlook of the Australian Bureau of Meteorology along with the anomaly of temperature averaged over the top 300 m in the equatorial Pacific Ocean as a proxy of warm water volume (WWV; black) and the Niño3.4 index (green) from January 2013 to February 2018. The outlook is produced based on a survey of Bureau's own coupled seasonal forecast model and seven others from leading international climate agencies (generally WMO Global Producing Centers of Long Range Forecasts). The explanation for the outlook can be found in www.bom.gov.au/climate/enso/outlook/#tabs=ENSO-Outlook-history. The WWV data can be accessed from www.pmel.noaa.gov/tao/wwv/data/. The Niño3.4 index is an average of sea surface temperature (SST) over (5°S–5°N, 170°W–120°W) calculated based on NOAA ERSST version 5 (ERSSTv5) dataset (www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.v5.html).

Figure 4. Climate model bias in sea surface temperature and ENSO seasonality as part of the many challenges facing ENSO research. (a) Difference in SST between multi-model ensemble mean and observed (ERSSTv5) exhibiting the classical 'cold-tongue' bias (color shading). The climatological observed and multi-model mean SSTs are shown in black and

red contours, respectively. Twenty CMIP5 models are utilized, with stippling indicating 18 or more models exhibiting the same sign in the bias. (b) Standard deviation of the Niño3.4 index in the CMIP5 models with annual mean of the standard deviation removed. Observed and multi-model mean seasonal climatologies are shown in thick black and red dashed lines, respectively, both indicate a peak of ENSO variability around austral summer and lowest variability in austral autumn. The most biased models in terms of the annual cycle are highlighted in thick colored lines.

Figure 5. Factors affecting ENSO and the societal implications. ENSO characteristics are influenced by many factors including coupled feedback processes, atmospheric and oceanic noise, and climate forcing from other oceanic basins, as well as the basic mean state which evolves on long time scales. All of these components interact with one another and are influenced by external forcing (e.g., greenhouse gasses, aerosols, solar variability), which in turn influences the predictability and impacts of ENSO.



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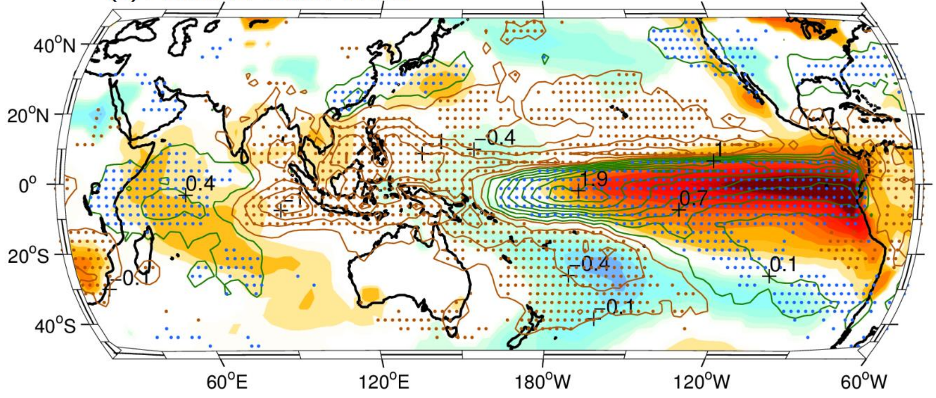
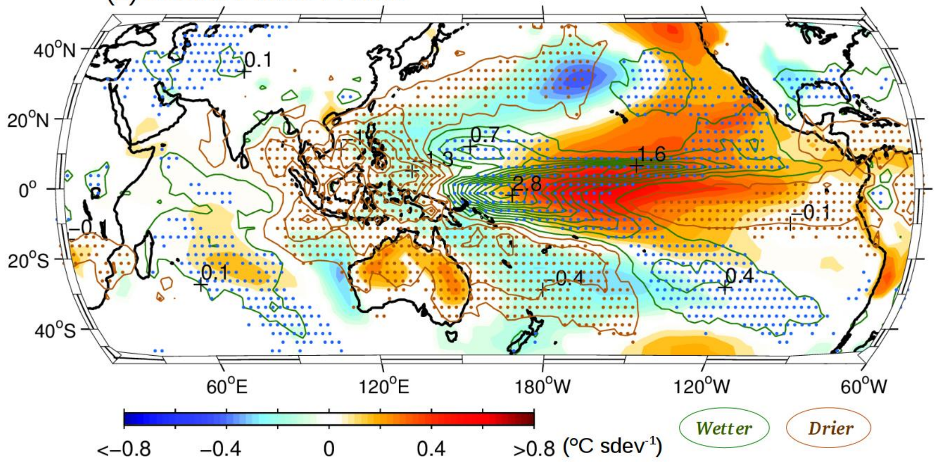
(a) Eastern Pacific El Niño



(b) Central Pacific El Niño



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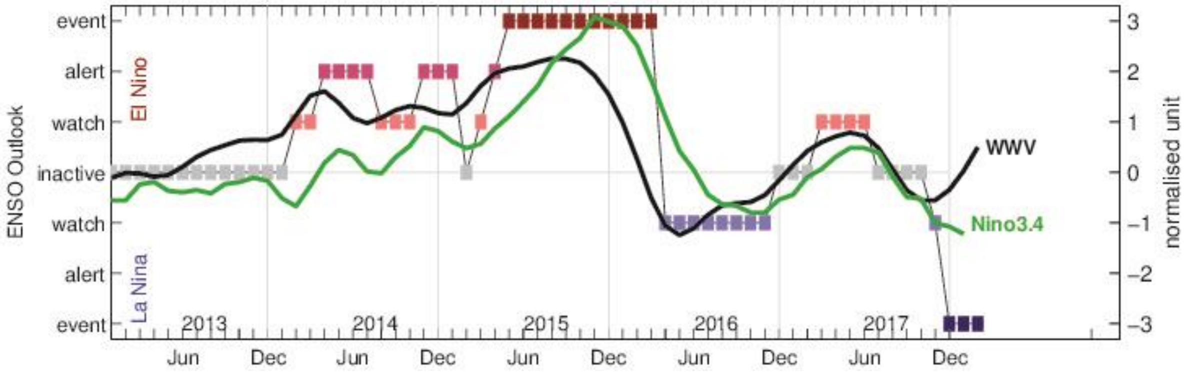

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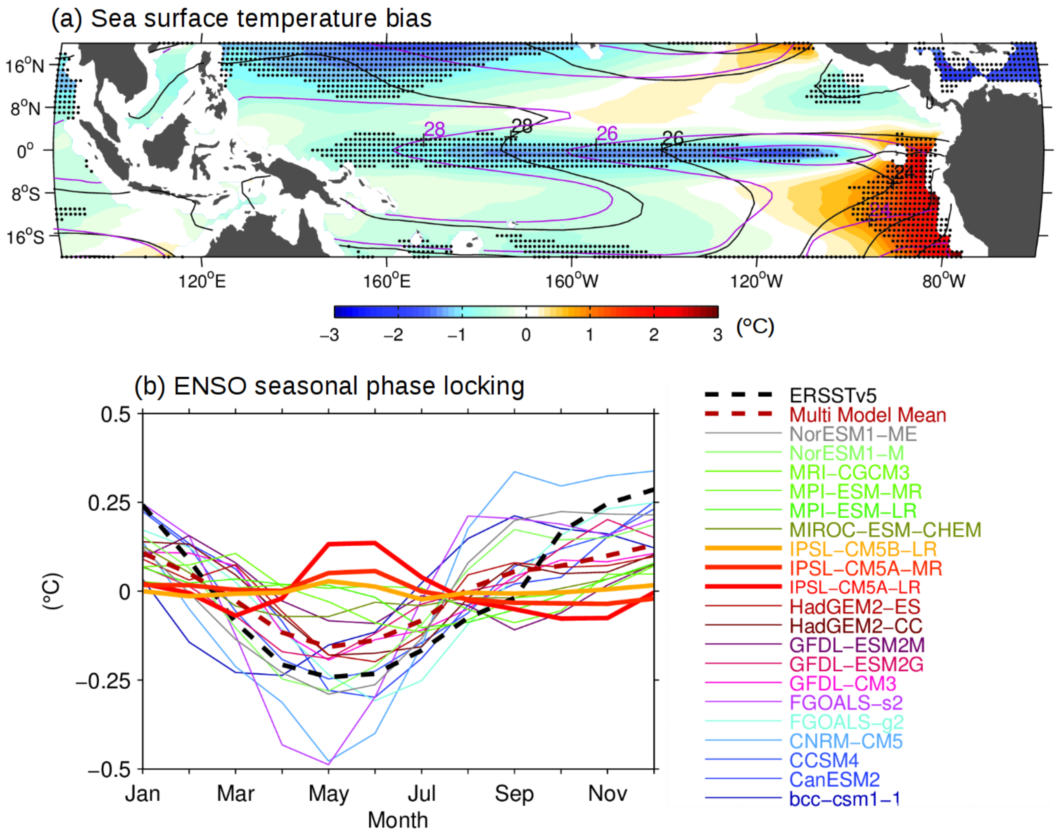

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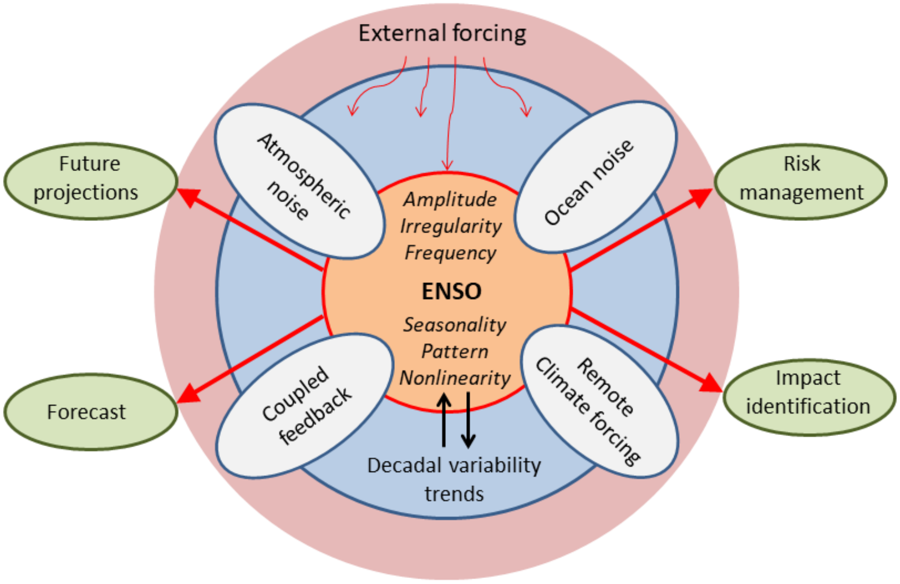

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