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Prospects for predicting two flavors of El Niño

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[1] Global climatic impacts of El Niño are sensitive to details of the surface warming of the equatorial Pacific Ocean, which vary between each El Niño event. The ability to predict the differences in pattern of anomalous ocean temperatures is explored for two prominent types of El Niño, traditional cold tongue events that have maximum surface warming in the eastern Pacific, and warm pool events that have maximum warming in the central Pacific. We assess seasonal predictions of the two types of El Niño using the Australian Bureau of Meteorology coupled ocean-atmosphere seasonal forecast model. Prediction of the major differences in pattern of anomalous ocean surface temperature between the two types of El Niño is limited to less than 1 season lead time, which is much shorter than for prediction of the occurrence of El Niño but which does have important practical application for prediction of regional climate. Improved understanding of the mechanisms of warm pool events and reduction of systematic model biases of the mean state and the coupled modes of variability in the Pacific warm pool/cold tongue should lead to improved skill for predicting regional climate variability associated with El Niño. **Citation:** Hendon, H. H., E. Lim, G. Wang, O. Alves, and D. Hudson (2009), Prospects for predicting two flavors of El Niño, *Geophys. Res. Lett.*, *36*, L19713, doi:10.1029/2009GL040100.

1. Introduction

[2] El Niño events have been traditionally defined using indices of sea surface temperature (SST) that capture the broad scale warming of the equatorial eastern Pacific, such as the Niño3 Index (the SST anomaly averaged 5°N-5°S, 90°W-150°W [e.g., *Trenberth*, 1997]). Assessed using such indices, El Niño can be predicted 2–3 seasons in advance using dynamical and statistical models [e.g., *Latif et al.*, 1998]. However, simply diagnosing and predicting El Niño based on a broad scale index like Niño3 may provide little insight into resulting climatic impacts around the globe: El Niño events have different flavors or different patterns of anomalous warming of the equatorial Pacific [e.g., *Trenberth and Stepaniak*, 2001] for which many of the global climate anomalies associated with El Niño are sensitive. For instance, sensitivity to the flavor of El Niño has been shown for rainfall and surface temperature in Asia and North America [e.g., *Larkin and Harrison* 2005; *Ashok et al.*, 2007; *Weng et al.*, 2007], the Indian monsoon [*Kumar et al.*, 2006], Australian rainfall [*Wang and Hendon*, 2007; *Lim et al.*, 2009], and even Atlantic hurricanes [*Kim et al.*, 2009]. Although skilful prediction of El Niño, based on broad scale measures of equatorial Pacific warming, has been established, it is an outstanding question whether the different flavors or vintages of El Niño and, ultimately, their associated global climate impacts are predictable. We address this question by first reviewing the premise that there are two main sorts of El Niño events (those that have peak warming in the eastern Pacific and those that have warming more concentrated in the central Pacific) and then assess their predictability using the POAMA coupled seasonal forecast model that is run at the Australian Bureau of Meteorology.

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2. Two Types of El Niño

[3] Much of the inter-El Niño variation of SST that is relevant for resulting global climate variations is related to the relative warming of the central Pacific compared to that in the eastern Pacific [*Larkin and Harrison*, 2005; *Kumar et al.*, 2006; *Ashok et al.*, 2007; *Wang and Hendon*, 2007; *Weng et al.*, 2007; *Kim et al.*, 2009; *Lim et al.*, 2009]. Following *Kug et al.* [2009], El Niño events with the strongest SST anomaly in the eastern Pacific are referred to as cold tongue events and their mechanism and basis for predictability (i.e., the delayed oscillator or recharge/discharge paradigm) are well understood [e.g., *Neelin et al.*, 1998]. The Niño3 index, which is strongly correlated with the leading mode of tropical Pacific SST variability, is useful for characterizing the cold tongue events [e.g., *Ashok et al.*, 2007; *Kug et al.*, 2009]. El Niño events that have maximum SST anomaly concentrated in the central Pacific are referred to equivalently as date line [*Larkin and Harrison*, 2005], Modoki or "pseudo" [*Ashok et al.*, 2007], central Pacific [*Kao and Yu*, 2009], and warm pool [*Kug et al.*, 2009] El Niño events. Although development of SST anomalies in the central Pacific has been interpreted to be part of the evolution of El Niño [e.g., *Trenberth and Stepaniak*, 2001], warm pool events do develop without evolving into or from cold tongue El Niños [*Ashok et al.*, 2007]. The mechanism of warm pool events is fundamentally different from the delayed oscillator/recharge-discharge paradigm [*Kao and Yu*, 2009; *Kug et al.*, 2009]. SST variations in the cold tongue are mainly governed by vertical displacements of the thermocline in response to westerly stress anomalies but surface temperature variations in the warm pool are governed by zonal advection and surface heat flux variations [e.g., *Wang and McPhaden*, 2000; *Kug et al.*, 2009]. However, the coupled dynamics that act to confine warm pool events to the central Pacific are not fully understood.

[4] Alternative indices have been proposed to monitor the warm pool events [e.g., *Trenberth and Stepaniak*, 2001; *Ashok et al.*, 2007; *Kug et al.*, 2009]. Here we primarily use the El Niño Modoki Index (EMI), which is equivalent to the principal component of the second leading mode of tropical

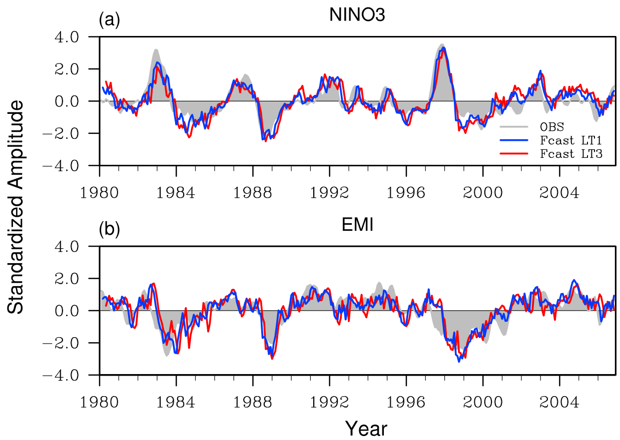

Figure 1. Time series of three-month mean anomalies of (a) Niño3 and (b) EMI indices from observations (shaded grey) and ensemble-mean predictions at 1 (blue) and 3 (red) month lead time. Anomalies are normalized by the standard deviation of the observed indices. The three month predictions for lead time 1 (3) months are from initial conditions, for instance, on 1 August (1 June) for the following SON season.

Pacific SST variability [*Ashok et al.*, 2007]. The EMI is defined as the SST anomaly for [165°E-140°W, 10°S-10°N]-1/2 [110°W-70°W, 15°S-5°N] -1/2[125°E-145°E, 10°S-20°N], where [] indicates the spatial average over the specified domain. Some of the important intra-El Niño variability of SST in the central Pacific is captured by other El Niño indices that are focused in the central Pacific such as the Niño4 index (defined as the SST anomaly averaged in the domain 5°N-5°S, 160°E-150°W [e.g., *Kug et al.*, 2009; *Kim et al.*, 2009]), but the EMI is tuned to capture variability that is independent of the Niño3 index [*Ashok et al.*, 2007]. For instance, during austral spring (September–November) the correlation of the EMI with the Niño3 index for the period 1980–2006 is only 0.20, whereas the correlation of the Niño4 index with the Niño3 index is 0.77.

[5] Time series of the 3-month running mean EMI and the Niño3 indices are shown in Figure 1 for the period 1980–2006. Observed behavior is diagnosed using the HadISST data [*Rayner et al.*, 2003]. The strong 1982, 1987 and 1997 El Niño events are characterized by strong loading on the Niño3 index and weak to negative loading on the EMI. These El Niño events have maximum SST anomaly in the eastern Pacific and are considered to be cold tongue events. In contrast, some El Niño events in the early 1990s and early 2000s were characterized by weak to moderate loading on the Niño3 index but positive loading on the EMI, indicative of a positive SST anomaly more focused toward the central Pacific that characterizes warm pool events. While the focus here is on El Niño, the EMI also captures some of the asymmetry between El Niño and La Niña events: negative loading on the EMI during La Niña events (e.g., 1988, 1999, Figure 1) reflects that the cold anomalies during La Niña tend to be shifted further west in the Pacific than are the warm anomalies during El Niño [*Hoerling et al.*, 1997].

[6] The different patterns of SST anomalies for the two types of events is diagnosed by compositing together anomalies from similar years for cold tongue events when Niño3 >1.0 standardized units and for warm pool events when EMI > 0.7 standardized units. We focus on the SST anomalies during austral spring (September–November; SON), when, for instance, Australia experiences significant impacts from both types of El Niños [*Wang and Hendon*, 2007; *Lim et al.*, 2009]. These composite are representative of the El Niño-related anomalies from about July through to about February in the following year, after which the cold tongue events typically begin to decay while the warm pool events tend to be more persistent [e.g., *Kug et al.*, 2009]. The cold tongue events (1982, 1987, and 1997) are characterized by maximum SST anomaly in the eastern Pacific (Figure 2a), a strong Niño3 index and a weak EMI (Table 1). In contrast, the warm pool events (1986, 1990, 1991, 1993, 1994, 2002, and 2004) are characterized by maximum SST anomaly in the central Pacific with weak SST anomaly in the eastern Pacific (Figure 2b), a strong EMI and a modest Niño3 index (Table 1). Similar composites of SST anomalies for cold tongue and warm pool events, using different seasons and definitions of events, have been calculated by *Ashok et al.* [2007] and *Kim et al.* [2009].

3. Dynamical Seasonal Prediction

[7] The skill of predicting cold tongue and warm pool El Niños, focusing specifically on the ability to predict the differences in their pattern of SST, is explored with the Australian Bureau of Meteorology seasonal forecast model POAMA (Predictive Ocean Atmosphere Model for Australia) [*Alves et al.*, 2003]. For this study we use a 10-member ensemble of nine-month hindcasts for January 1980 through December 2006 using version POAMA1.5b [e.g., *Zhao and Hendon*, 2009]. Hindcasts were generated from observed ocean and atmosphere initial conditions beginning on the 1st of each month. We adopt the terminology that a lead time of 0 month means, for instance, a seasonal forecast initialized on 1 January that is valid for the months of January–March. Forecasts of 3-month mean SST and rainfall

Table 1. Anomalies of the Niño3 Index, EMI, and Australian-Mean Rainfall Composited for Cold Tongue and Warm Pool El Niño Events During Austral Spring From Observations and Predictions at Lead Time 1 and 3 Months[a]

	Nino3			EMI			Australian Rain		
	Observed	LT 1	LT 3	Observed	LT 1	LT 3	Observed	LT 1	LT 3
Cold tongue El Niño	2.2	1.7	1.4	−0.4	0.6	0.9	−0.5	−0.2	−0.1
Warm pool El Niño	0.3	0.3	0.4	1.0	0.8	0.8	−0.7	−0.4	−0.4

[a]Anomalies expressed in units of standard deviations. Observed (predicted) anomalies have been standardized by the respective observed (predicted) standard deviations in 1980–2006.

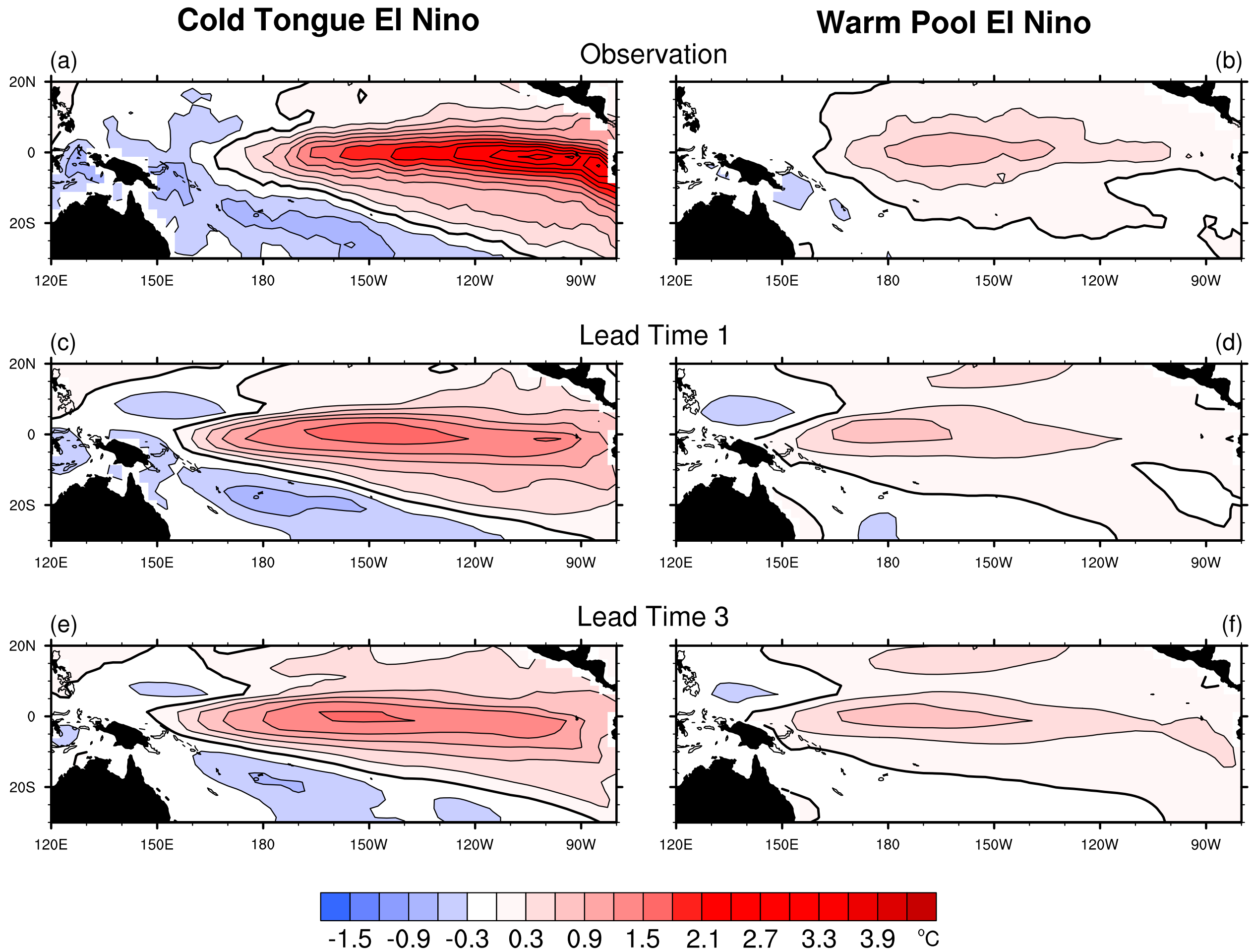

Figure 2. Composited SST anomaly for (left) 3 cold tongue El Niño events and (right) 7 warm pool El Niño events during September–November. (a and b) Observations and ensemble-mean forecasts (c and d) at 1 month lead and (e and f) at 3 month lead. Contour interval is 0.3°C (blue shading negative and red shading positive anomalies).

are verified against HadISST and gridded observed Australian rainfall [*Jones and Weymouth*, 1997], respectively. Forecast anomalies are formed relative to the forecast model climatology, which is a function of start month and lead time. In this fashion, the mean bias from the forecasts is removed.

[8] Forecasts from the POAMA1.5b system are first assessed for the ability to predict the EMI and Niño3 indices. The ensemble mean forecasts of the three-month mean EMI and Niño3 indices are shown in Figure 1 for lead times of 1 and 3 months. Predictive skill for the two indices appears to be similar. Importantly, most of the large excursions for both indices are well forecast out to at least 3 month lead time, although there are some notable exceptions (e.g., erroneous predictions of positive EMI prior to the peak of El Niño in 1982 and 1997).

[9] A quantitative analysis of forecast skill is provided in Figure 3. Using 3-month mean data for all start months, the Niño3 index is predictable at least 6 months in advance, as indicated by the standardized rms error remaining below 1.0 (Figure 3b) and the correlation remaining above 0.6 (Figure 3a). The model forecasts are always better than persistence (not shown), which historically has been a difficult benchmark to beat due to the long timescale of El Niño behavior. Furthermore, the normalized standard deviation of the predicted Niño3 index remains near 1 (Figure 3c), which indicates that the Niño3 index is predicted with realistic amplitude. The correlation for predictions of the EMI also remains above 0.6 and the normalized rms error remains below 1 to lead time 6 months. However, the predicted EMI has 20% larger amplitude than observed for the first 2 months and thereafter looses amplitude, thus indicating that model drift is acting to limit the ability to predict the difference between cold tongue and warm pool El Niños.

[10] The impact of model drift is further demonstrated by considering forecast skill of the Nino4 SST index. Correlation skill for Niño4 is comparable to Niño3 at short lead time, but better than Niño3 at lead times beyond 3 months (Figure 3a). However, the normalized rms error is worse at all lead times, although still less than one (Figure 3b). This greater rms error for Niño4 reflects the 20–40% greater-than-observed amplitude of predicted Niño4 (Figure 3c). This bias in Nino4 amplitude is attributed to the cold tongue El Niño mode in POAMA shifting westward compared to observed, which we relate to mean state bias in the cold tongue that develops early in the forecast.

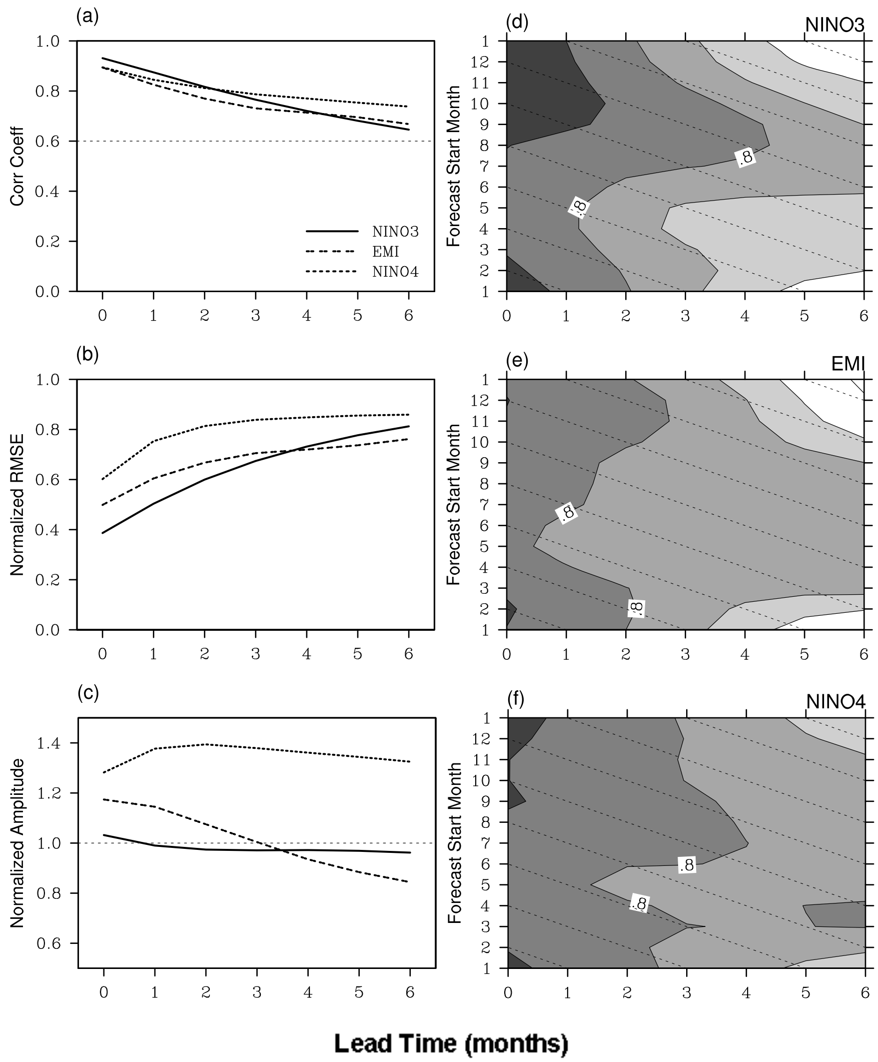

Figure 3. (a) Correlation, (b) normalized root mean square error, and (c) normalized amplitude for forecasts of the 3-month mean Niño3, EMI and Nino4 SST indices using predictions from all start months 1980–2006. The rms error and amplitude in Figures 3b and 3c are normalized by the standard deviation of the observed indices. Correlation as a function of start month and lead time for 3-month mean predictions of (d) Niño3, (e) EMI, and (f) Niño4 (contour interval 0.1, shading for r > 0.6). Sloping dotted lines signify constant verification time.

[11] Seasonality of the predictive skill of the SST indices is assessed by computing the correlation as a function of start month and lead time (Figures 3d–3f). Predictive skill for the Niño3 index exhibits a well known "spring predictability barrier", whereby skill for Niño3 increases for forecast initialized after the northern spring season. Interestingly, predictive skill of the EMI and Niño4 indices exhibits much less of a "spring barrier". It is tempting; therefore, to infer that warm pool events may be predictable earlier in the year than cold tongue events [e.g., *Kim et al.*, 2009]. However, prediction of a warm pool event requires a prediction of strong EMI (and Niño4) but simultaneous with an accurate prediction of a weak Niño3, so ultimately prediction of the warm pool events would appear to be limited by the ability to predict the broad scale warming in the eastern Pacific as monitored by the Niño3 index.

[12] Although we have demonstrated predictive skill for some important indices of El Niño, faithful prediction of the distinction between patterns of anomalous SST is ultimately required in order to make predictions of the regional climate variability during El Niño. The ability to differentiate the pattern of SST anomaly for warm pool and cold tongue events is demonstrated in Figures 2c–2f. Larger amplitude of the SST anomaly in the eastern Pacific for the cold tongue events and smaller amplitude in the eastern Pacific for the warm pool events are seen to be maintained in the forecasts out to a lead time of 3 month, but the patterns increasingly become indistinguishable at longer lead time. Pattern correlation (over the tropical Pacific) quantifies the distinction. For the observed behavior, the pattern correlation between the anomalies for the cold tongue and warm pool events that are shown in Figures 2a and 2b is modest (r=0.52), reflecting that the patterns of SST for the two types of El Niño events are indeed more dissimilar than similar (i.e., the explained variance of one field by the other is $r^2 \sim 25\%$). The patterns are less distinguishable from each

other in the forecasts at lead time 1 month (r=0.70) than are the observed patterns, but the forecasts of each pattern are still well correlated with reality (r∼0.82–0.88). However, by lead time 3 months the ability to distinctly predict the two patterns is diminished, with the predicted patterns now appearing more like each other (r=0.85) than either is correlated with reality (r=0.84 and 0.79 for the warm pool and cold tongue events, respectively). This is also confirmed by comparison of the composited predictions of the two indices at lead time 3 months (Table 1). This lack of distinction at longer lead time is postulated to stem primarily from the spurious westward displacement of the maximum SST anomaly in cold tongue events, which we attribute to drift of the model's cold tongue El Niño mode. Distinguishing the actual patterns of predicted SST for the two types of El Niño events appears to be currently possible with POAMA only for 0–2 month lead time.

[13] This ability to predict the different patterns of SST during El Niño events, although limited to a lead time of less than one season, does provide practical benefit for prediction of Australian rainfall (for more details of the regional variation of rainfall skill for warm pool and cold tongue events see *Lim et al.* [2009]). Widespread reduction of rainfall across Australia during warm pool events, despite the occurrence of a relatively weak El Niño as indicated by the Niño3 index, is predicted out to lead time 3 months (Table 1), which reflects the similar but slightly stronger negative correlation of Australian-mean rainfall with the EMI (−0.55) than with the Niño3 index (−0.42) based on observations for the period 1980–2006. The ability to predict the pattern of SST anomaly during El Niño and the associated remote response in rainfall can help anticipate and understand, for instance, wide-spread Australian drought in the face of an apparently weak El Niño event as measured by the Niño3 index, for instance as occurred in 2002 [*Power et al.*, 2006; *Wang and Hendon* 2007; *Lim et al.*, 2009]. Because operational seasonal forecasts are routinely issued for the upcoming season with a ∼1 month lead time, skilful prediction of the distinction between cold tongue and warm pool El Niño events would appear to have immediate practical value.

4. Conclusions

[14] The ability to predict regional climate anomalies stemming from El Niño requires not only a prediction of its occurrence but also of its type. We have demonstrated skill using the POAMA model for predicting two main types of El Niño (cold tongue and warm pool), including some of the regional climate impacts, but useful skill in predicting their distinction is currently limited to a lead time of less than one season. The forecast model used here suffers from a common systematic bias whereby the SST anomaly associated with the cold tongue El Niño shifts westward with increasing lead time [*Zhao and Hendon*, 2009], thereby interfering with and weakening the warm pool El Niños. Ongoing model improvements that are aimed at improving the representation of the mean state and coupled variability of the Pacific warm pool/cold tongue should result in better depiction and prediction of coupled behavior in the central and western Pacific.

[15] The expected upper limit of predictability of the warm pool El Niños is unknown but the current skill for predicting the EMI (and Niño4), which does not exhibit as much of a "spring barrier" as does Niño3, suggests it might be greater than for cold tongue El Niños. However, prediction of a warm pool event requires skill in simultaneously predicting a large EMI (and Niño4) and a weak Niño3. Thus, the Niño3 "spring predictability barrier" would appear to ultimately limit prediction of warm pool events, which contrasts with the conclusion reached by *Kim et al.* [2009]. Nonetheless, with improved understanding of the mechanisms of the warm pool El Niño events and with improved forecast models that have reduced drift in both the mean state and in the modes of coupled variability, prospects appear to be good for improved prediction of regional climate resulting from different flavors of El Niño.

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