Seasonal Prediction of Australian Summer Monsoon Rainfall

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Abstract

Seasonal prediction of Australian summer monsoon rainfall is reviewed. Due to the strong influence of El Niño, rainfall in the pre-monsoon season (late austral spring) is highly predicable using both statistical forecast scheme and dynamical coupled models. Although of far lesser magnitude than rainfall during the monsoon, prediction of pre-monsoon rainfall has great economic values. Even though El Niño persists and typically peaks during austral summer, seasonal rainfall during the monsoon is far less predictable than in the pre-monsoon using either statistical models or dynamical coupled models. We review here the basis for skilful prediction of pre-monsoon rainfall and the lack of skill during the monsoon. We postulate that local air-sea interaction tends to promote predictability in the pre-monsoon and to degrade predictability during the monsoon. Although predictive skill with the dynamical coupled model is hampered by model bias and error, the seasonality of the local air-sea interaction is well depicted in the model, thus suggesting the lower skill during the monsoon is a reflection of intrinsically lower predictability than in the pre-monsoon.

1. Introduction

Seasonal prediction of Australian climate has a long history (e.g., Quayle 1929), in part due to the strong and persistent influence of El Niño/Southern Oscillation (ENSO; e.g., Nicholls and Woodcock 1981). Numerous empirical forecast schemes for seasonal rainfall, which capitalize on the persistence and predictability of ENSO, have been developed (e.g., Nicholls et al. 1982). Some schemes are skilful enough to justify operational usage by the Bureau of Meteorology National Climate Centre (e.g., Drosdowsky and Chambers 2001). Empirical forecast schemes typically have most skill during winter/spring and are least successful during summer, especially in the monsoon region of tropical north Australia. Dynamical coupled model forecasts of seasonal monsoon rainfall, as will be shown below, also exhibit better skill in the pre-monsoon season than during the heart of the monsoon. We review here the basis for skilful prediction of pre-monsoon rainfall, whether by statistical models or by dynamical models, and postulate that skilful prediction of rainfall during the monsoon is limited by local air-sea interaction.

2. Monsoon-ENSO Relationship

Seasonal prediction of Australian rainfall predominantly stems from the strong influence that El Niño/Southern Oscillation exerts on Australian climate (e.g., McBride and Nicholls 1983). The impact of ENSO is demonstrated by composite rainfall anomalies for 12 large El Niño events (Fig. 1). Eastern and northern Australia tend to experience drought during El Niño (and pluvial during La Nina) during winter and spring (Fig. 1a). The reduction across the north-eastern tropical portion of the continent is thought to stem from the direct impact of the Southern Oscillation: the eastward shift of the Walker circulation during El Niño results in anomalous subsidence and enhanced surface pressure across tropical north-eastern Australia as anticipated by the tropically-trapped response to positive anomalous sea surface temperatures (SST) in the central-eastern equatorial Pacific (e.g., Gill 1980). The reduction in rainfall across the southern portions of the continent, extending from Western Australia in the west to Victoria in the east, is thought to stem from the Rossby wave teleconnection to higher latitude, excited by the reduced rainfall in Indonesian region associated with the eastward shift of the Walker circulation (e.g., Karoly 1989). This wave train results in an equivalent barotropic ridge across the southern portions of the continent, thereby deflecting poleward the rain-bearing extratopcial weather systems. The reduced rainfall during El Niño in the Indonesian region, which drives this teleconnection, is partly driven by the enhanced SST in the central Pacific but also by the co-varying cold SST anomalies in the Indonesian region that typically accompany El Niño during austral winter-spring (e.g., Hendon 2003).

Although El Niño tends to peak in austral summer, the impact of El Niño on Australian rainfall (Fig. 1b), especially in the monsoonal region in the north, weakens dramatically from spring into summer (e.g., Nicholls et al. 1982, McBride and Nicholls 1983). This seasonal variation of the relationship with ENSO is quantified by the correlation of observed Australian monsoon region rainfall (rainfall averaged over Australian land points north of 25°S, hereafter AMR) with the Nino34 SST index (Fig. 2a). The negative correlation between rainfall and Nino34 drops from over -0.5 in spring (September-November) to about -0.3 in summer (December-February). Nicholls et al. (1982) further show that onset of the wet season in northern Australia (onset being defined as the date of achieving an accumulation of a certain fraction of the total wet-season rainfall) is strongly correlated with the state of El Niño, but that total rainfall during the monsoon is not. That is, rainfall leading up to the onset of the summer monsoon is more related to ENSO than is the rainfall that occurs after monsoon onset.

Insight into the lack of relationship between AMR and ENSO during the monsoon is gained by examining the seasonal relationship of AMR with SST. During the pre-monsoon (Fig. 3a) the pattern of SST correlation associated with AMR is indicative of La Niña (or El Niño): enhanced (decreased) AMR is associated with strong negative (positive) correlation in the eastern equatorial Pacific and strong positive (negative) correlation in the seas surrounding the north and east of Australia. However, these correlations weaken dramatically in summer (Fig. 3b), and the local positive correlation to the north of Australia even changes sign. That is, in the pre-monsoon AMR is associated with locally warm SST to the north of Australia but during the monsoon AMR has little or even negative relationship with local SST. This change in sign of the correlation of AMR with local SST is summarized in Fig. 2b. During the pre-monsoon AMR and local SST are positively correlated at ~0.6 but this drops to ~-0.1 during the monsoon. This change in correlation between AMR and local SST is also reflected in a change in the relationship between local SST and El Niño: local SST is negatively correlated with El Niño in the pre-monsoon but uncorrelated over even positively correlated with El Niño post monsoon onset (e.g., Hendon 2003).

Seasonally varying air-sea interaction to the north of Australia has been posited to explain the dramatic drop in correlation between AMR and local and remote SST in going from the pre-monsoon into the monsoon season (e.g., Nicholls 1981; Hendon 2003; Wu and Kirtman 2007). The strong positive correlation of AMR with local SST in the pre-monsoon season occurs before the summer monsoon circulation is established (i.e., when northern Australia is still in a trade wind regime). During the winter (JJA) and spring (SON), the Australian monsoon region experiences trade easterlies. Anomalous easterlies (for instance, as driven remotely by El Niño in the Pacific) at this time of year, then would act to increase the total windspeed (easterly anomaly acting on an easterly basic state) thereby producing surface cooling through increase latent and sensible heat flux. Thus, a positive feedback is produced with negative local SST anomalies acting to raise surface pressure and producing stronger easterly anomalies. This positive feedback between easterly winds and negative SST anomalies overcomes the damping of the cold SST anomalies by the enhanced shortwave radiation anomalies associated with decreased cloudiness (e.g. Hendon 2003). Little role for oceanic heat transports for SST variations is indicated in this region of Indonesian seas, although a positive Bjerknes feedback between easterly winds and cold SST along the Java-Sumatra coast could also contribute to a positive feedback between rainfall and SST in the pre-monsoon.

Once the Australian summer monsoon onsets and the mean winds to the north of Australia become westerly (e.g, Troup 1961), anomalous easterlies (for instance as driven by El Niño), will now acting on a westerly basic state and will thus decrease the total windspeed, thereby acting to warm the ocean surface. The positive feedback along the Java-Sumatra coast will also disappear as the seasonal thermocline deepens. Hence, easterly anomalies during the summer monsoon will produce a negative air-sea feedback. Together with the damping effect of the shortwave anomalies (i.e. increased shortwave due to decreased cloudiness when the SST is cold), a cold SST anomaly established in the pre-monsoon will tend to be rapidly damped post-monsoon onset. The positive feedback during the pre-monsoon and negative feedback during monsoon is offered as an explanation for the strong correlation between El Niño and the onset date of the monsoon (and El Niño and pre-monsoon rainfall) and for a weakening of the negative correlation between El Niño and northern Australia rainfall once the monsoon onsets. It also accounts for the change in sign of the SST anomaly to the north of Australia during El Niño from negative in pre-monsoon to weakly positive post onset (e.g., Hendon 2003).

This seasonally varying relationship of local SST and rainfall, which we postulate stems from seasonally varying air-sea interaction, is demonstrated by the point-by-point correlation of observed SST and observed rainfall (Fig. 4 top panels; see also Wu and Kirtman 2007). In the pre-monsoon season (SON), rainfall and SST are strongly positively correlated in the seas surrounding Australia. This strong correlation disappears and even becomes negative in summer. Note that the strong positive correlation in the eastern and central Pacific, associated primarily with rainfall forced by El Niño-related SST variations, is independent of season.

3. Seasonal Prediction of Wet Season Onset

The strong correlation of pre-monsoon Australian rainfall with ENSO can be exploited to make prediction of the Australian wet season onset. Wet season onset, defined by some practically important fractional accumulation of total monsoon rainfall, typically occurs well in advance of the dramatic reversal of tropospheric circulation that accompanies monsoon onset (e.g., Troup 1961). Nicholls et al. (1982) demonstrated that onset of the wet season at Darwin, based on an accumulation of up to 30% of the total monsoon season rainfall, could be predicted months in advance based on the current state of ENSO (i.e. using Darwin surface pressure). Lo et al. (2007) built on this idea and devised a scheme to predict onset of wet season throughout northern Australia. They defined onset as the date of an accumulation of 50 mm rainfall after 1 September, which is a useful accumulation for the cattle industry in northern Australia (McCown 1981). Wet season onset is around mid-to-late October in the far north and east of the continent and around late November to early December in the central and west regions (Fig. 5a). The standard deviation of this onset date is around 20 days. Lo et al. (2007) used the SOI from the preceding winter (June-August) to forecast the probability that the date of onset will be earlier or later than the mean date. Their scheme was based on logistic regression with 1-degree gridded rainfall. At times of strong anomalies in the winter SOI, their forecasts are reliably emphatic. Their scheme produces skilful forecasts of wet season onset date across the majority of northern Australia, especially in the Top End, Cape York, and central Queensland (Fig. 5b).

4. Dynamical Coupled Model Forecasts

Coupled climate models are now routinely used to make seasonal climate predictions (e.g., Wang et al. 2007). Here we focus on forecast skill in the Australian monsoon using the Bureau of Meteorology coupled model forecast system, POAMA (Predictive Ocean Atmosphere Model for Australia; Alves et al. 2003). POAMA is representative of the state of the art of dynamical coupled model forecast systems, but it does exhibit mean state bias and other errors that limits the utility of its predictions (e.g., Zhao and Hendon 2009). Multimodel ensembling can overcome many of the errors and biases of a single model (e.g., Wang et al 2007), so the results presented here based on a single model should be viewed as conservative estimates of what actually can be currently achieved.

POAMA is based on an atmospheric GCM with modest resolution (T47L17) coupled to a version of GFDL MOM2 ocean model (2° zonal by ½ ° latitude resolution in low latitudes). Forecasts are initialized with observed ocean and atmosphere initial conditions. Here we discuss forecast skill based on the ensemble mean of retrospective 9 month forecasts for the period 1980-2006. The ensemble mean was formed from ten forecasts that were initialized on the first of each month. Mean-state bias is removed by forming anomalies relative to the forecast model climatology, which is a function of forecast lead time. POAMA can skilfully predict El Niño 2-3 seasons in advance (i.e., anomaly correlation of Nino34 SST index remains above 0.6 to beyond 9 month lead time; Alves et al. 2003; Zhao and Hendon 2009). Mean state drift, especially related to the over-development of the equatorial Pacific cold tongue, does limit utility of these El Niño forecasts because although the mean state drift can be removed, the atmospheric teleconnection of ENSO degrades with increasing forecast lead time as the ENSO mode spuriously shifts westward. The forecast model also underestimates the mean land based monsoonal rainfall (Fig. 6b), although the seasonality is well depicted. On the other hand, the intensity of the monsoonal circulation, as depicted by the seasonal development of the monsoonal westerlies to the north of Australia (e.g., Troup 1961), is well simulated (Fig. 6a), which presumably reflects a good depiction of the seasonal evolution of convection across the broader maritime continent region. The bias in averaged-Australian rainfall stems primarily from a too-rapid decline of rainfall into central portions of the continent. This sort of bias is also detectable in the monsoons over South America and Africa. The impact of this mean-state rainfall bias on forecast skill is unknown (recall that the mean bias is removed but the effects of the bias on the variability is not). A critical area for model improvement is the representation of land-based rainfall.

Forecast skill for monsoon region rainfall is displayed in Fig. 7 for 1, 3 and 5 month lead time for the pre-monsoon (SON) and monsoon (DJF) seasons. Clearly, POAMA has no skill during the monsoon, while pre-monsoon rainfall is skilfully predicted at short lead times (1 and 3 month). The skill in the pre-monsoon stems from POAMA's ability to predict ENSO and to then simulate ENSO's teleconnection to Australian rainfall (Fig. 2a). Interestingly, POAMA overestimates the impact of ENSO on Australian rainfall during the monsoon especially at longer lead time (i.e., POAMA simulates a strong negative correlation of monsoon rainfall with Nino34 when the observed relationship should be weak; Fig. 2a). This behavior is also evident in other models (Wang et al. 2007), suggesting that some key processes (including internal variability) are missing in current forecast models. It could also reflects the westward bias of the ENSO mode in the Pacific at longer lead time, thereby resulting in a stronger impact than observed (e.g., Zhao and Hendon 2009). On the other hand, POAMA does simulate the strong seasonality of the relationship of local SST and rainfall in the monsoon region (i.e., strong positive correlation in the pre-monsoon that then weakens or changes sign during the monsoon; Figs. 2b and 4). Hence, it would appear that the seasonality of the critical air-sea interaction in the region to the north of Australia is captured in the forecasts, which suggests that future improvement of model bias may alleviate the erroneously strong ENSO teleconnection during the monsoon.

5. Conclusions

Seasonal mean Australian monsoon rainfall is not predictable with either a state of the art dynamical coupled model forecast system or with empirical schemes based on the state of ENSO (and other tropical SST anomalies). Pre-monsoon rainfall is predictable and predictions of the pre-monsoon (including onset of the wet-season) are of practical use. Seasonally varying air-sea interaction acts to promote local SST anomalies to the north of

Australia in the pre-monsoon that compliment remote forcing of rainfall by ENSO, thus adding to the predictability of rainfall stemming from predictability of ENSO. During the monsoon, local air-sea interaction acts to suppress local SST anomalies, thereby detracting from the predictability stemming from remote forcing of ENSO. There would appear to be some prospect for improved dynamical model prediction during the monsoon by reduction of mean-model bias and a better representation of land-based rainfall. However, the nature of air-sea feedbacks during the monsoon suggests an upper limit of predictability that is much reduced compared to that during the pre-monsoon.

6. References

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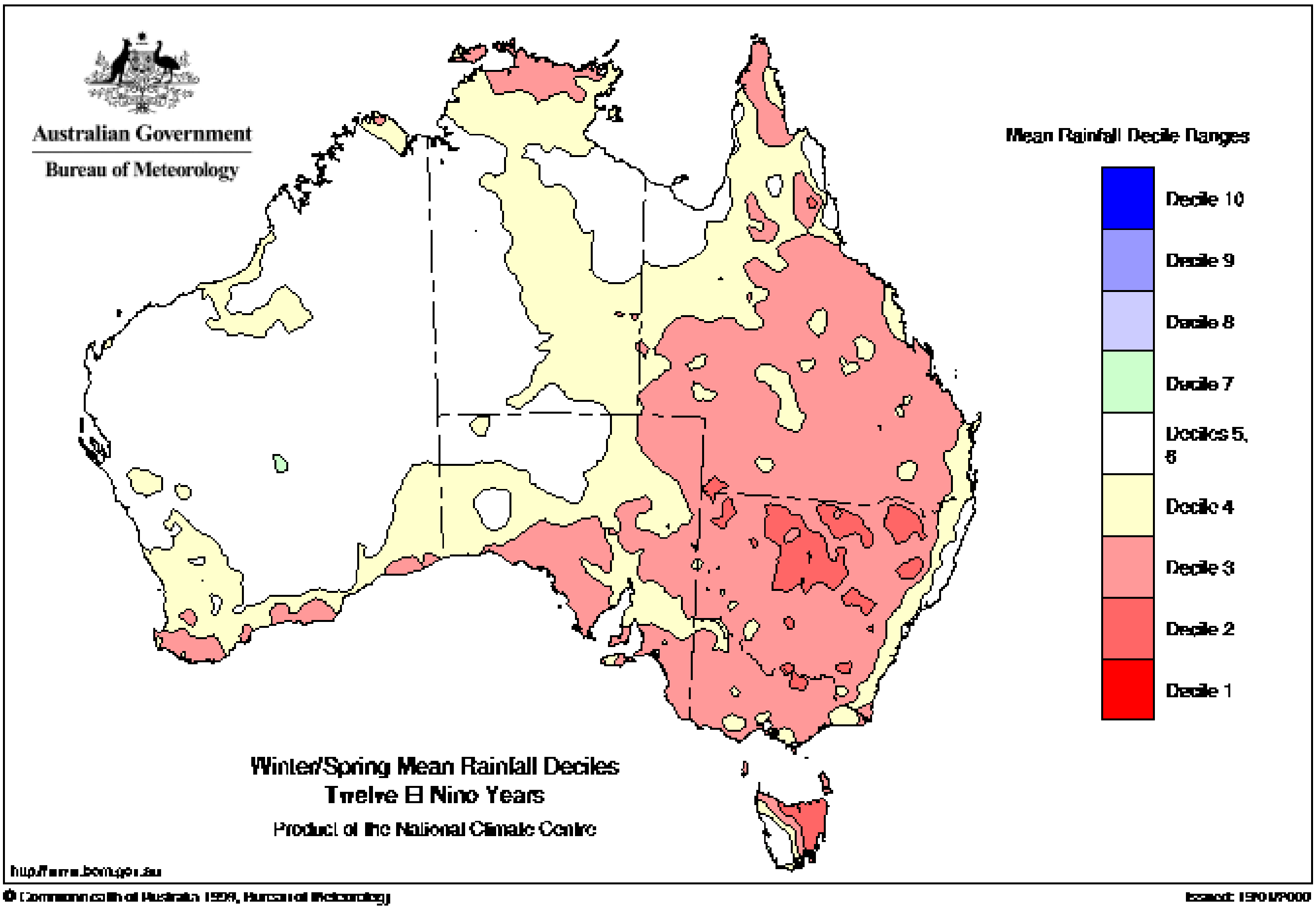
Fig. 1: Composite rainfall deciles for 12 moderate-strong El Niño events (1905, 1914, 1940, 1941, 1946, 1965, 1972, 1977, 1982, 1991, 1994 and 1997). Top: Austral winter-spring (June-November); Bottom: Austral summer, (December-February). Analyses supplied by National Climate Centre, Australia.



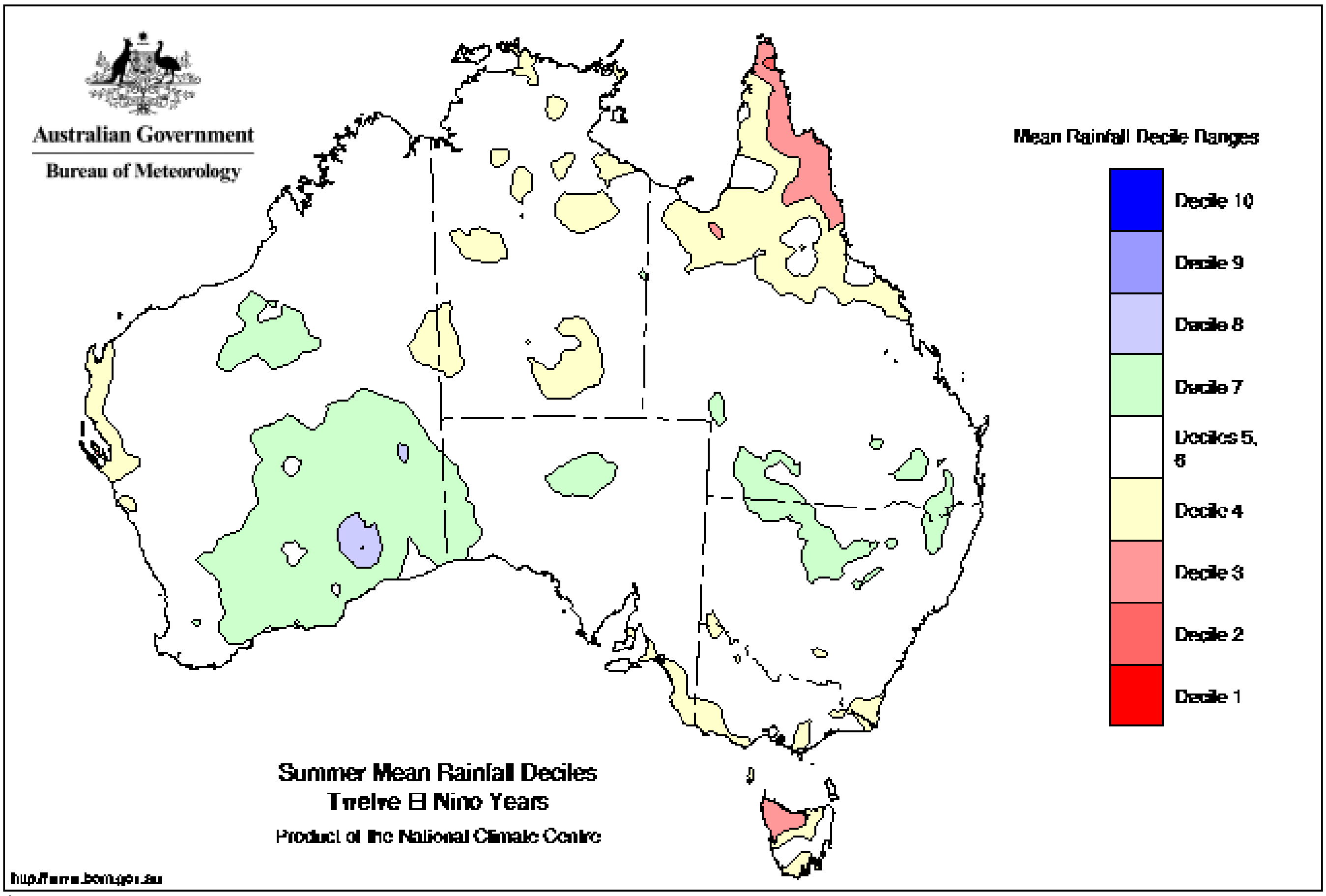


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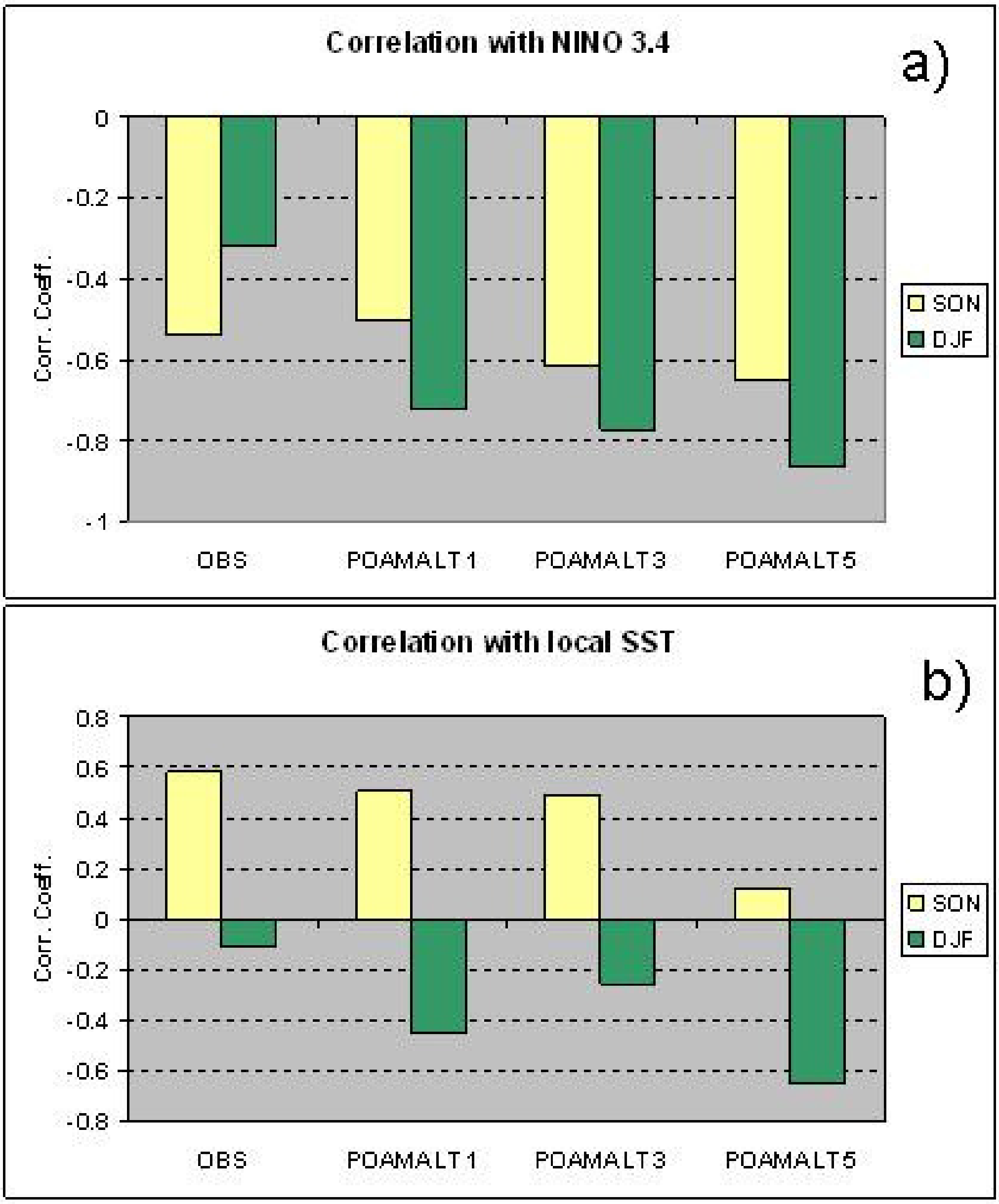
Fig. 2: Correlation of Australian rainfall (north of 25S) with (a) Nino34 SST index and (b) local SST to north of Australia (10S-Eq, 110E-140E) for DJF (monsoon season) and SON (pre-monsoon season). Observed relationships are on left. Predictions are at 1, 3, and 5 month lead time.



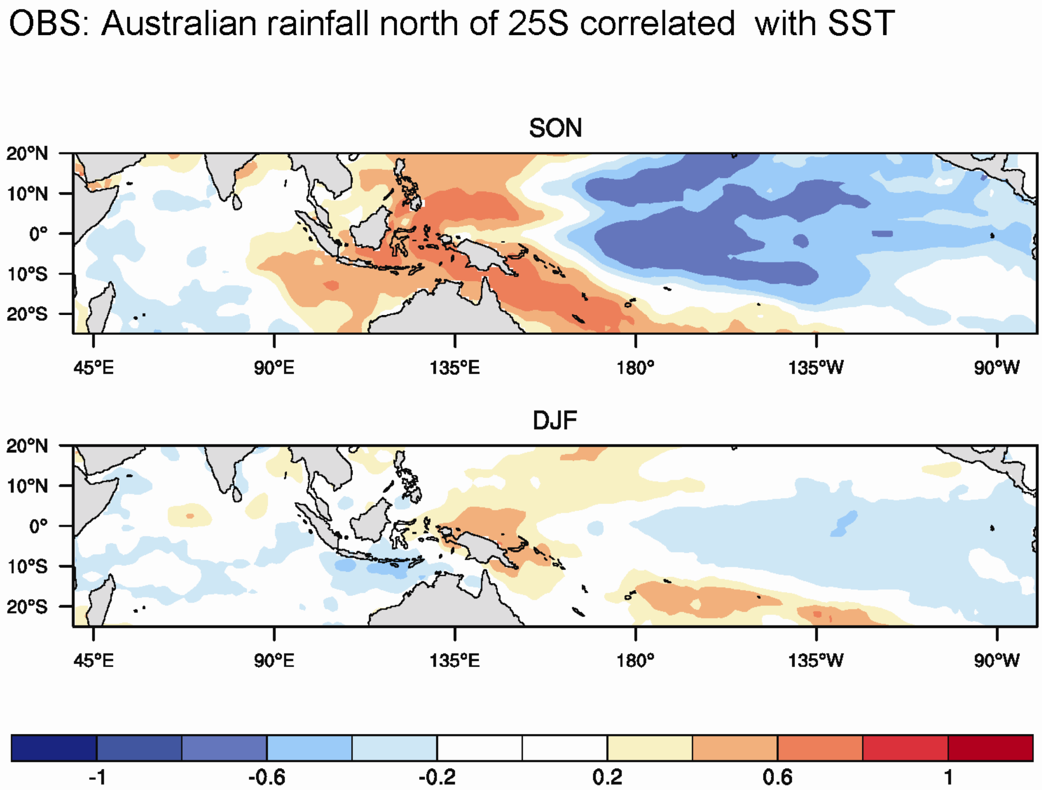


Fig. 3: Correlation of time series of observed north Australian rainfall (land points north of 25S) with observed SST (HadISST) for (a) SON, and (b) DJF for period 1980-2006..

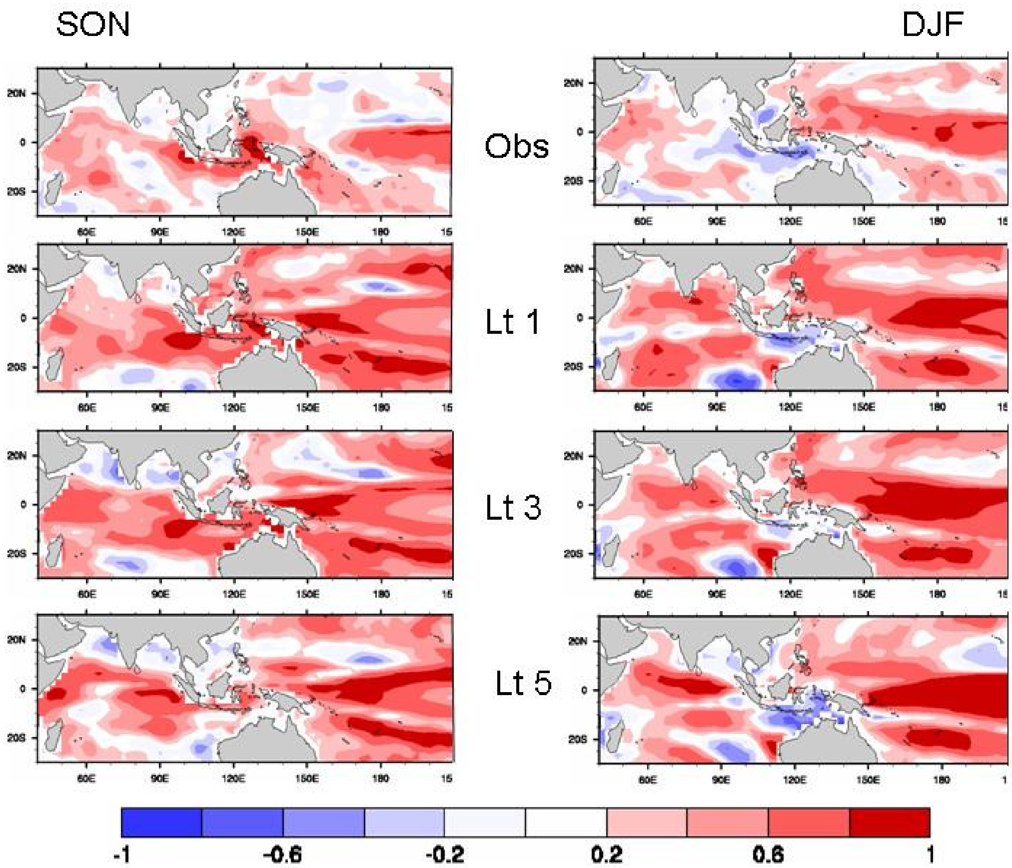


Fig. 4: Point-by-point correlation of seasonal mean rainfall with SST 1980-2006. Observations are at top. Lower panels based on POAMA forecasts. SON season is left panels; DJF season is right panels.

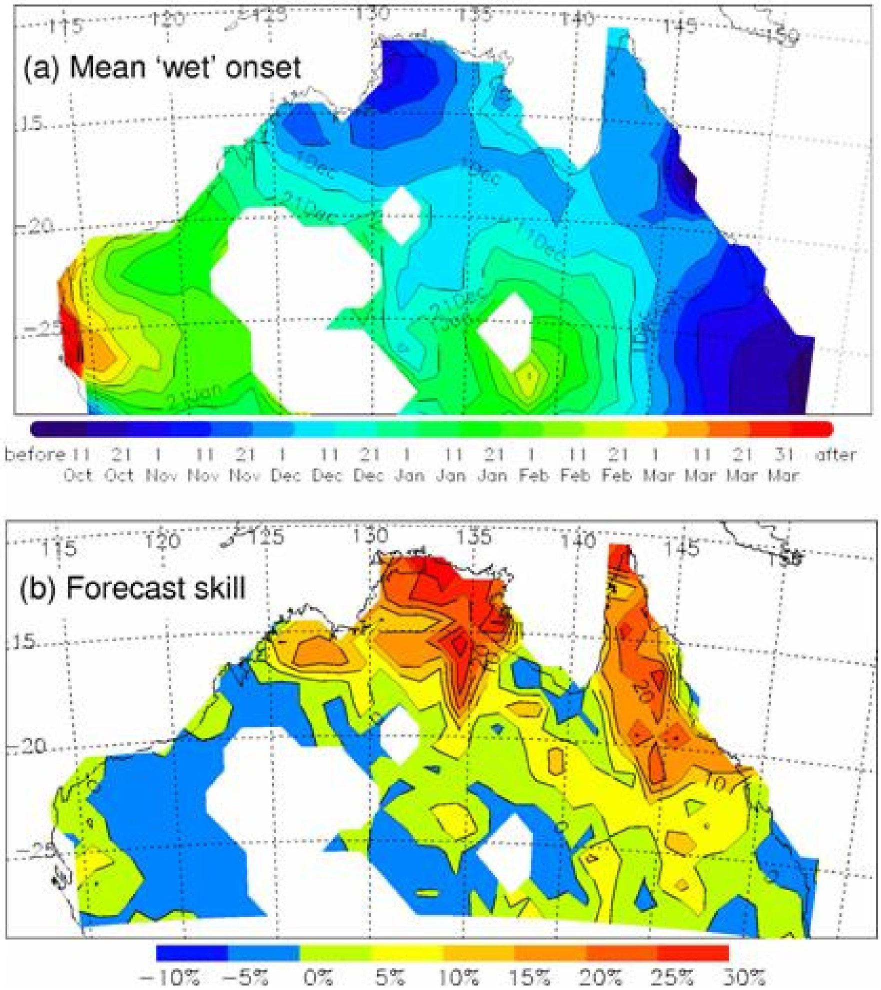


Fig. 5. (a) Mean wet-season onset date for the period 1948/49-2004/05. Wet season onset is defined by date of accumulation of 50 mm rainfall from 1st September. (b) Brier skill score of cross-validated forecasts of wet season onset date, expressed as a percentage improvement over a reference climatological forecast strategy. Forecasts of probability of a later/earlier than normal onset are made using July-August SOI as the predictor (adapted from Lo et al. 2007).

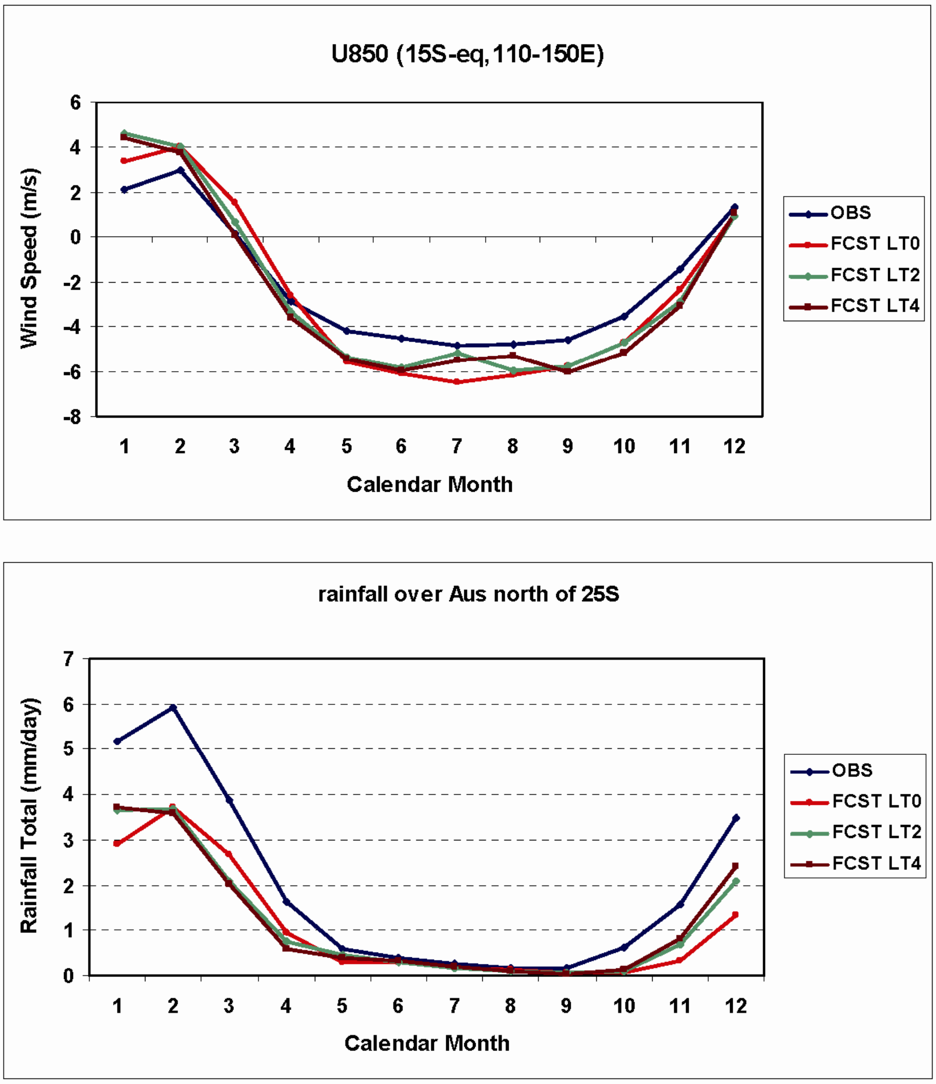


Fig. 6: Observed and predicted seasonal cycles of a) zonal wind 850 hPa (15ºS-Eq, 110-150ºE) and mean rainfall for Australian land points north of 25ºS. Predictions are at lead times 0, 2, and 4 months.

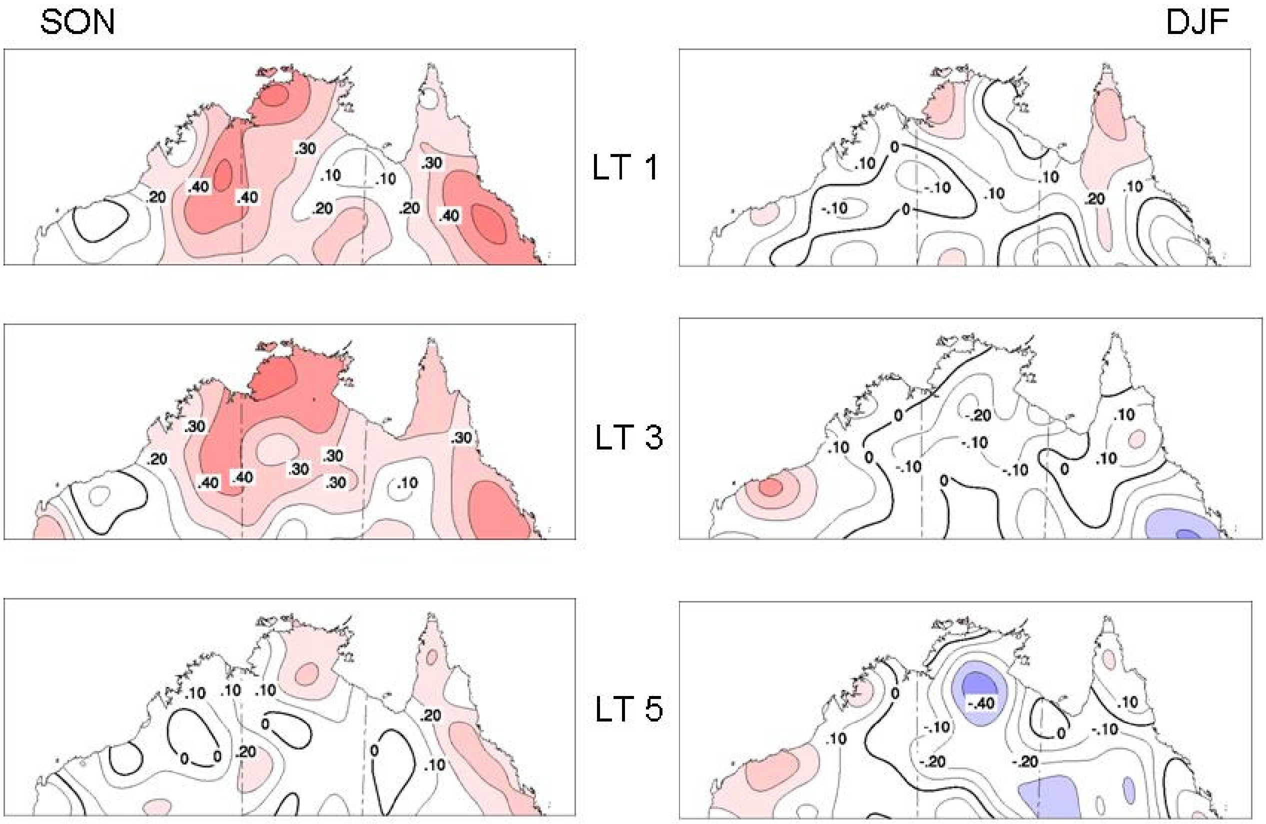


Fig. 7: Anomaly correlation of predicted seasonal rainfall for SON (left) and DJF (right) at lead times (top) 1, (middle) 3, and (bottom) 5 months. Contour interval is 0.1 with values greater 0.2 shaded.