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Seasonal Climate Prediction in the Pacific using the POAMA coupled model forecast system

CAWCR Technical Report No. 048

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Enquiries should be addressed to:

Andy Cottrill
Centre for Australian Weather and Climate Research:
A partnership between the Bureau of Meteorology and CSIRO
GPO Box 1289, Melbourne
Victoria 3001, Australia

A.Cottrill@bom.gov.au

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Contents

List of Figures

List of Tables

1. ABSTRACT

The tropical Pacific Ocean basin is home to over 20 Pacific Island nations, many of which are sensitive to climate extremes from the El Niño-Southern Oscillation (ENSO) and rainfall variability associated the Inter-Tropical Convergence Zone and the South Pacific Convergence Zone. These Pacific Island countries are highly dependent on agriculture, fishing and tourism as a major source of food production and income, which can vary greatly depending on the weather and climate experienced from year to year. Hence, the provision of skilful seasonal forecasts is important to allow these countries to prepare for changes in rainfall and impending droughts associated with the changes in ENSO.

The Australian Bureau of Meteorology has developed a dynamical seasonal forecast system POAMA (Predictive Ocean-Atmosphere Model for Australia), which is a state of the art seasonal to inter-annual forecast system based on a coupled model of the ocean and atmosphere. The model has good skill at predicting El Niño and La Niña up to 9 months in advance and it is capable of simulating the spatial and temporal variability of tropical rainfall associated with ENSO. Consequently, the variability of rainfall patterns across the Pacific region is skilfully predicted by POAMA at short lead times. The availability of seasonal forecasts from dynamical models will aid Pacific Island countries to improve economic returns in agriculture and other industries and reduce impacts from storms, floods and droughts associated with the extremes of El Niño and La Niña.

2. INTRODUCTION

As part of the Australian Government AusAID International Climate Change Adaptation Initiative, the Pacific Adaptation Strategy Assistance Program (PASAP) is providing assistance to 14 Pacific Island nations and Timor-Leste to assess key climate vulnerabilities and risks, formulate adaptation strategies and plans, and integrate adaptation into decision making especially focusing on climate vulnerable sectors including water resources, food security, and coastal zone management. PASAP is supporting the Australian Bureau of Meteorology (BoM) to develop improved seasonal climate prediction services for the 15 countries (Kuleshov et al. 2012), with the region shown in Fig. 1. Although the main motivation for the PASAP program is to assist Pacific Island nations to adapt to a changing climate, improving the quality and uptake of seasonal climate predictions is viewed as a no-regrets means of improving resilience and management practices of climate sensitive enterprises even in the absence of climate change.

Since 2004, the BoM has had a partnership with Pacific Island nations to provide seasonal climate outlooks through the Pacific Island Climate Prediction Project (http://www.bom.gov.au/climate/pi-cpp/index.shtml). These outlooks are based on statistical relationships between sea surface temperature (SST) variations, primarily those associated with El Niño/La Niña, and local climate in the Pacific. He and Barnston (1996) have previously reported on similar statistically-based seasonal forecast for the Pacific region. Although these statistical forecasts have merit, especially in the Pacific region where El Niño/La Niña impacts are strong, the PASAP seasonal prediction project recognizes the strong potential benefit of dynamical coupled model forecasts over statistically based forecasts due to the capability to handle non-stationary climate, to better predict extremes, and to forecast all aspects of climate variability rather than just rainfall or temperature.

This paper reports on the effort to produce seasonal climate forecasts for the Pacific Island nations using the BoM coupled model seasonal forecast system POAMA. This paper is organised into the following sections. Section 2 describes the POAMA1.5b forecast system, the seasonal hindcasts for the period 1980–2006 that form the basis for the assessment of forecast skill, and the verification data and methods. The basis for seasonal climate prediction in the Pacific, especially the seasonality of the relationship of local climate to El Niño/La Niña and an assessment of the representation of the El Niño teleconnections in the POAMA1.5b model, is reviewed in Section 3. Analysis of forecast skill for seasonal rainfall and a demonstration of some forecast products are provided in Section 4. The discussion of the results, including the future directions of the PASAP project and the ongoing development of the POAMA forecast system, is provided in Section 5.

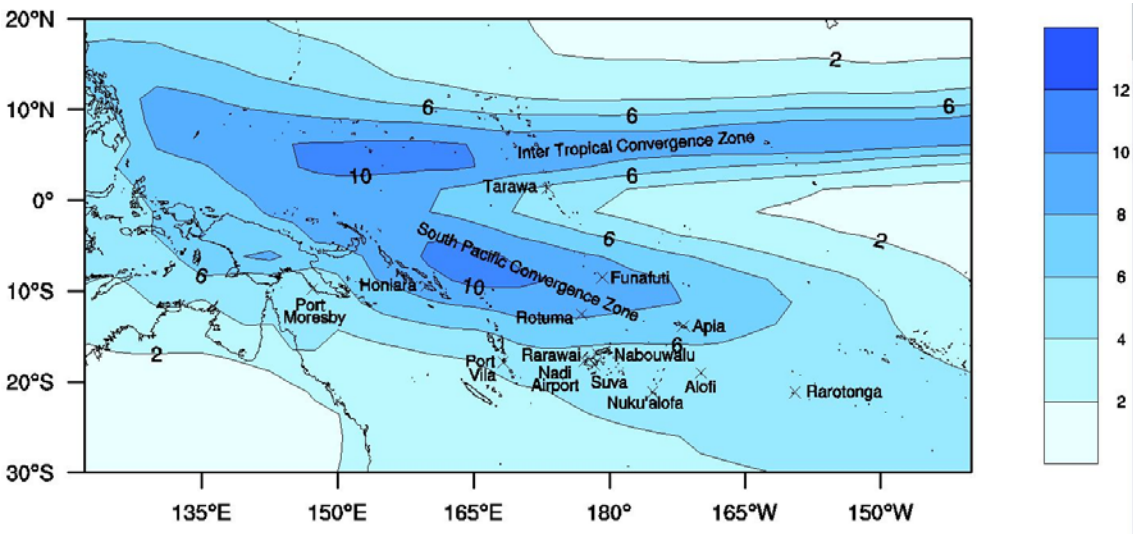

Fig. 1. Location of the 14 Pacific Island stations (indicated by crosses) used in this study overlaid with mean annual rainfall (1980–2006) from CMAP (in mm day^{-1}). Climatological positions of the convergence zones are indicated.

3. POAMA MODEL AND VERIFICATION DATA AND METHODS

3.1 POAMA model

The Predictive Ocean-Atmosphere Model for Australia (POAMA) has been developed at the BoM to provide global seasonal climate forecasts. POAMA is based on a coupled ocean-atmosphere climate model. The operational version of POAMA from 2007–2011 is 1.5b, from which this study is based and from which seasonal outlooks have been developed for the Pacific Islands. The POAMA1.5b system uses the BoM Atmospheric Model BAM3.0 for the atmosphere and the Australian Community Ocean Model (ACOM) version 2 for the ocean (Coleman et al. 2005) which is based on the GFDL MOM2 (Schiller et al. 2002). The nominal grid spacing of the atmospheric model is 2.5° x 2.5°, with 17 vertical levels and for the ocean model is 25 vertical levels, with 2° by 0.5° grid spacing in the tropical ocean. Forecasts are initialised from observed states of the atmosphere/land and ocean. Initial condition uncertainty is accounted for by generating a 10-member ensemble of forecasts from perturbed atmospheric initial conditions (Hudson et al. 2010). A comprehensive set of hindcasts for 9 month duration has been generated from the first of each month for the period 1980–2006 (Hudson et al. 2011; Wang et al. 2008). Based on these hindcasts, forecast skill from POAMA1.5b is good for El Niño conditions in the Pacific (Zhao and Hendon 2009), including the ability to predict some of the key inter-El Niño differences in the pattern of SST anomalies, at least at short lead time (Hendon et al. 2009).

3.2 Verification data

Rainfall forecasts from POAMA are verified against available station records in the Pacific and the gridded monthly analyses from the CPC Merged Analysis for Precipitation (CMAP: Xie and Arkin (1997)). The CMAP rainfall analysis is based on a blend of gauge observations, estimates from various satellites and NCEP-NCAR reanalysis. Monthly rainfall records from 14 stations in ten Pacific Island countries were obtained from the National Climate Centre at the BoM and the Pacific Climate Change Science Programme (PCCSP). The stations were selected based on geographical coverage and availability of complete or nearly complete monthly rainfall records covering the period from 1980–2006. Station locations are identified in Fig. 1.

SST forecasts from POAMA are verified against the analyses from HadISST (Rayner et al. 2003) for 1980 to December 1981 and from Reynolds Ol.v2 (Reynolds et al. 2002) for January 1982 to December 2006. The Niño 3.4 SST index (SST anomaly averaged from 5°N to 5°S and 170°W to 120°W) is used to monitor El Niño conditions in the Pacific. The composite evolution of SST anomaly around each of the rainfall stations during El Niño/La Niña is formed using the average of the analysed SST in the 10 degree latitude by 10 degree longitude boxes around each rainfall station.

3.3 Verification and analysis methods

Forecasts are verified for four standard seasons: austral summer (DJF), autumn (MAM), winter (JJA) and spring (SON). Forecast anomalies from the POAMA model are formed relative to the model's hindcast climatology, which is a function of lead time (LT) and start month for the period 1980–2006. Anomalies of the verification data are formed relative to the climatology for the same 1980–2006 period.

In order to depict typical El Niño and La Niña impacts at the available stations, monthly SST and rainfall data from El Niño and La Niña years were selected from 1980 to 2006 and binned. We include four El Niño years (1982–83, 1986–87, 1987–88 and 1997–98) and four La Niña years (1984–85, 1988–89, 1998–99 and 1999–2000) defined by the Niño 3.4 monthly index being >0.8°C or <-0.8°C respectively. To establish rainfall changes linked with the onset and termination of El Niño and La Niña events, composites run from February of the year in which El Niño (La Niña) generally peaks through to August in the following year. The composites are smoothed using a three month running mean. We make use of the fact that El Niño variations are roughly opposite to La Niña variations and form the El Niño minus La Niña composite. In the composites, we display anomalies of local and Niño 3.4 SST but for rainfall we add the El Niño minus La Niña composite anomaly back into the mean monthly climatological rainfall in order to emphasize the development of the anomaly relative to the seasonal cycle of rainfall.

Along with the standard verification techniques using anomaly correlation and root mean square error based the ensemble mean forecast, probabilistic forecasts are also verified using the hit rate for predicting rainfall in the upper and lower terciles. Probabilistic forecasts are computed using the number of individual ensemble members out of the total ensemble that fall into each category using anomaly data. The tercile thresholds for the forecasts and verification are based on the hindcast and observed climatologies, respectively, and are computed by cross validation, where by the thresholds are calculated by leaving out the target year.

Rainfall forecasts from the POAMA grid are also calibrated to the station data and to the CMAP analyses. The calibration method, described by Johnson and Bowler (2009), optimally adjusts the rainfall variance from the POAMA ensemble to be equal to the observed variance while minimizing the forecast error but retaining the original correlation of the ensemble mean with the observed. This calibration method is sometimes known as the Inflation of Variance (IOV) technique. The calibration is cross validated by the "leave one out" method.

4. BASIS FOR SEASONAL PREDICTION

4.1 El Niño/La Niña rainfall anomalies

The climate over the tropical Pacific Ocean is largely determined by the mean position of the Inter-Tropical Convergence Zone (ITCZ) over northern and central equatorial latitudes and the South Pacific Convergence Zone (SPCZ) over the southwest Pacific Ocean. The mean annual rainfall from CMAP across the tropical Pacific, with the mean location of the ITCZ and the SPCZ are shown in Fig. 1. The ITCZ is formed by converging south-easterly and north-easterly trade winds, resulting in high rainfall. It is generally most active in boreal summer and remains north of the equator east of ~180° all year round (Barry and Chorley 2003; Meehl 1987). The western portion of the ITCZ near Papua New Guinea moves north and south, following the solar forcing maximum and joins the SPCZ, which extends southeast towards Fiji, Tonga and the Cook Islands (Barry and Chorley 2003; Vincent 1994). The SPCZ is characterised by low level convergence between the northeasterly flow west of the south Pacific High and the cooler southeasterly winds from higher latitudes ahead of high-pressure systems moving eastward from the Australia/New Zealand region (Barry and Chorley 2003). The SPCZ is more active in the austral summer (Meehl 1987; Vincent 1994).

Interannually, the locations of the ITCZ and SPCZ vary prominently with the phase of ENSO. In El Niño years, the SPCZ's mean position is further eastwards and more zonally oriented, whereas in La Niña and neutral years, it is located further west towards the Coral Sea region

(Vincent et al. 2011). The location of the SPCZ also affects the location and genesis of tropical cyclones, which occur more frequently in El Niño years east of the dateline and more frequently further west towards the Coral Sea in La Niña years (Chand and Walsh 2009; Kuleshov et al. 2008; Vincent et al. 2011). During El Niño years, the ITCZ is similarly intensified eastward while contracting toward the equator.

The pattern of rainfall anomalies during El Niño/La Niña is displayed in Fig. 2 (a–d), which shows regression of the CMAP rainfall analyses onto the standardised Niño 3.4 SST index. The regressed anomalies are shown for El Niño conditions during the four standard seasons. The primary eastward shift of the SPCZ during El Niño is most prominent in the austral spring and summer and the eastward intensification and equatorward shift of the ITCZ is most prominent in austral autumn and winter. In the SPCZ region in the southwest Pacific, there is very sharp delineation between the positive anomalies to the northeast of the date line and the negative anomalies to the southwest during El Niño. Small east-west shifts of this node in the El Niño rainfall pattern will have profound impacts on the rainfall anomalies at the stations in this region, thus indicating both the challenge and the importance of accurately predicting the east-west and north-south excursions of the SPCZ during El Niño and La Niña years.

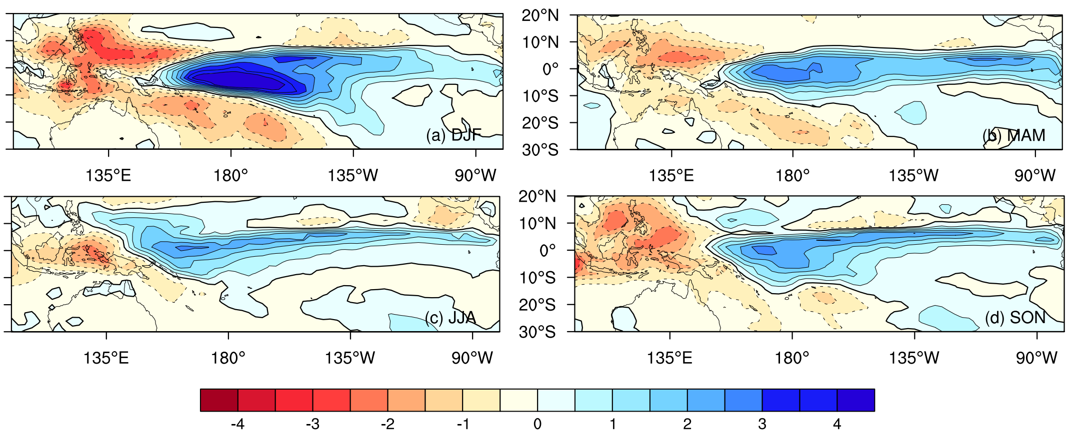

Fig. 2 (a–d). Regression of seasonal mean CMAP rainfall on the standardised Niño 3.4 SST index from Reynolds SST for the period 1982–2006 for DJF (a), MAM (b), JJA (c) and SON (d). Units in mm day^{-1}.

The typical impacts of El Niño and La Niña at the 14 Pacific Island stations are summarized in Table 1, which displays the correlation of the seasonal station rainfall with the Niño 3.4 index. For the stations near the equator and the dateline, (e.g. Tarawa (Betio) and Funafuti), the correlation is strongly positive in all seasons, as anticipated by Figs. 2 (a–d), with a season average correlation of 0.71 at Tarawa. For other stations, the correlations are generally negative in the southwest Pacific and are weakest in the austral winter (JJA). Boldfaced values represent correlation values ($r>=0.4$), which are statistically significant at the 5% level.

Two stations were selected from the 14 stations to represent the different impacts of El Niño and La Niña on rainfall across the Pacific region (Figs. 3a–b). Tarawa is indicative of locations near the equator, where rainfall varies in phase with El Niño. Nadi Airport in the southwest Pacific region is representative of stations that vary out of phase with El Niño. The typical evolution of rainfall and SST during El Niño and La Niña are depicted by forming composites based on the mean of the El Niño and La Niña years described in Section 2. We display anomalies of Niño 3.4 SST and the local SST anomaly around the stations. For rainfall, rather than display the anomalies, we display the total rainfall (the El Niño minus La Niña anomaly is added back into the climatological seasonal cycle) in order to highlight how the El Niño/La Niña variation affects the seasonal cycle of rainfall at each station.

Table 1. Correlation of observed seasonal rainfall and the Niño 3.4 index at 14 Pacific Island stations for 1982–2006. Statistically significant correlation at the 5% level (α=0.025 and r≥0.4 by two-tailed Student-t test with 25 independent samples) is boldfaced.

Station Name and Index	Island Group	DJF	MAM	JJA	SON
Niño 3.4 (1982–2006)					
Equatorial Region					
1. Betio (Tarawa)	Kiribati	**0.57**	**0.62**	**0.88**	**0.76**
2. Funafuti	Tuvalu	**0.51**	0.26	0.31	0.36
SPCZ Region					
3. Nadi Airport	Fiji	**-0.70**	**-0.71**	0.19	**-0.58**
4. Rarawai	Fiji	**-0.73**	**-0.73**	0.14	**-0.58**
5. Nabouwalu	Fiji	**-0.65**	**-0.59**	-0.04	**-0.46**
6. Suva	Fiji	-0.06	**-0.49**	-0.12	-0.19
7. Rotuma	Fiji	-0.37	-0.04	0.06	0.12
8. Nuku'alofa	Tonga	**-0.74**	**-0.45**	0.08	**-0.45**
9. Alofi	Niue	**-0.64**	**-0.50**	0.11	**-0.46**
10. Apia	Samoa	**-0.46**	-0.26	0.18	-0.18
11. Rarotonga	Cook Is	**-0.45**	**-0.58**	-0.31	**-0.49**
12. Honiara	Solomon Is	**-0.51**	**-0.48**	-0.11	-0.31
Southwest Pacific Region					
13 .Port Vila	Vanuatu	**-0.62**	**-0.46**	**-0.60**	**-0.49**
14. Port Moresby	Papua New Guinea	**-0.43**	**-0.54**	0.04	**-0.62**

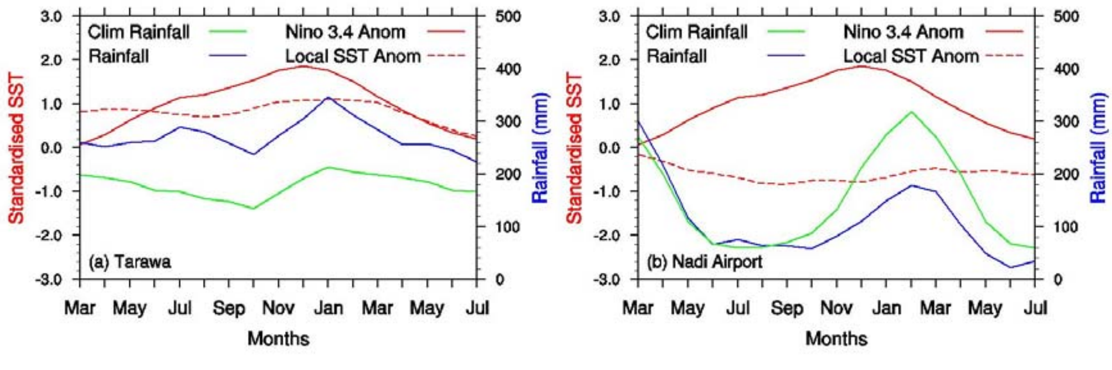

Fig. 3 (a–b). El Niño minus La Niña composite Niño 3.4 SST (solid red curve), rainfall (blue curve) and local SST (dashed red cure) at (a) Tarawa and (b) Nadi Airport. The mean monthly cycle of rainfall for 1980–2008 is shown as the solid green curve and has been added back into the composite rainfall anomalies (blue curve).

Tarawa (Fig. 3a), which lies close to the equator and the international dateline, experiences a relatively weak mean annual cycle of rainfall (averaging 100–200 mm per month), and rainfall is higher during El Niño events and lower during La Niña events. Rainfall anomalies begin to develop early in the El Niño (La Niña) year (March) and last well into the following year (July) when El Niño (La Niña) decays. There is no distinct peak in the anomalies. Local SST is seen to evolve in phase with Niño 3.4 SST, but since the station is located in the western Pacific, the amplitude of the local SST variation is much weaker than that in the Niño 3.4 region further to the east.

Nadi Airport (Fig. 3b) is located on the west side of Viti Levu in Fiji and is representative of many of Pacific Islands in southwest region that exhibits reduced rainfall during El Niño events. In contrast to near-equatorial Tarawa, Nadi Airport's position is at about 18°S and exhibits a pronounced seasonal cycle of rainfall, with a distinct wet season (>200 mm per month) that peaks in February and a dry season (<100 mm per month) centred on July-August (Fig. 3b). Rainfall is distinctly lower (higher) during El Niño (La Niña) events, but in contrast with Tarawa, the anomalies do not develop until later in the El Niño year (September-October), peak sharply in February and decay by about July of the following year. Also in contrast to Tarawa, the local SST anomaly is opposite to the Niño 3.4 anomaly, but again with amplitude is much smaller than for Niño 3.4.

4.2 POAMA prediction of El Niño rainfall patterns

In order to predict rainfall in the Pacific with the POAMA coupled model, not only does El Niño/La Niña need to be well predicted but the regional rainfall anomalies associated with El Niño/La Niña need to be well simulated. Previous studies e.g. (Hendon et al. 2009; Zhao and Hendon 2009) have documented the good forecast skill of POAMA at short lead times (i.e. up to about 3–4 months) for predicting SST anomalies associated with El Niño, including some of its prominent east-west variation in the pattern of the SST anomaly. Here we just summarize those studies by showing the correlation skill for prediction of seasonal mean SST at LT=0 for the four standard seasons (Fig. 4a–d). Skill is assessed using the correlation of anomalies between the ensemble mean forecast and the observations. We focus on forecast skill at LT=0 because this is indicative what can be achieved for real time prediction of seasonal climate. The highest forecast skill is in the equatorial central and eastern Pacific as a result of El Niño behaviour. The correlation skill is highest (>0.8) over the equatorial region in austral spring (SON) and summer (DJF). High skill extends into the northwest and southwest Pacific. This high skill in the southwest Pacific is in the region where SST anomalies tend to be out of phase with those in the central equatorial Pacific during El Niño (e.g. Fig. 3b), and thus bodes well for predicting short term climate for the partner countries in these regions. However, skill in the southwest Pacific is low during austral summer (Fig. 4a), thus suggestion that prediction of regional climate in this region during the peak of the wet season will be challenging.

We now demonstrate POAMA can also simulate the associated rainfall anomalies during El Niño/La Niña. We do this by creating similar regressions as in Figs. 2a–d, but use POAMA's simulated rainfall and standardised Niño 3.4 SST index at LT=0 (Figs. 5a–d). The agreement between simulated (Fig. 5) and observed (Fig. 2) rainfall anomalies during El Niño/La Niña is outstanding, including capturing the seasonality of the rainfall intensity and position, but there are a couple of notable exceptions. The simulated patterns are in general too strong and too zonally elongated and with too strong anomalies of opposite sign at higher latitude. And, the simulated rainfall patterns extend too far west compared to the observed.

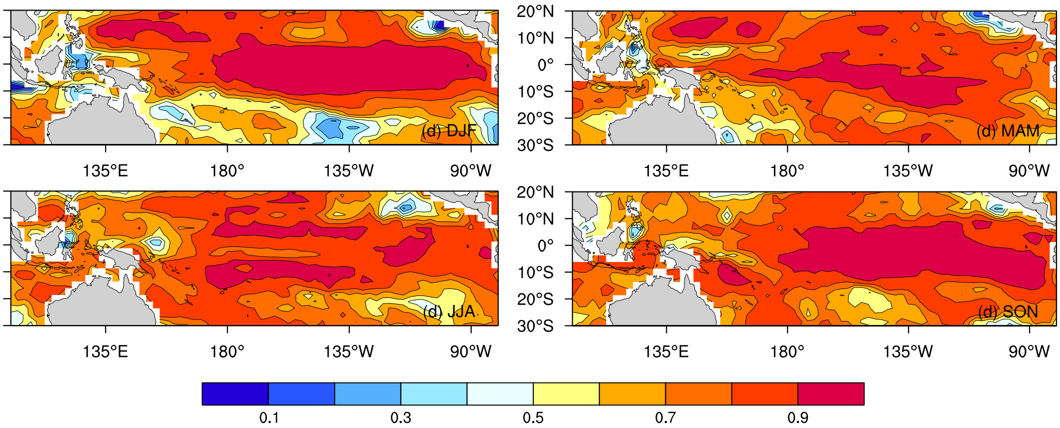

Fig. 4 (a–d). Correlation between Reynolds SST and POAMA1.5b ensemble mean hindcast SST (LT=0) in the period of 1982–2006 for DJF (a), MAM (b), JJA (c) and SON (d).

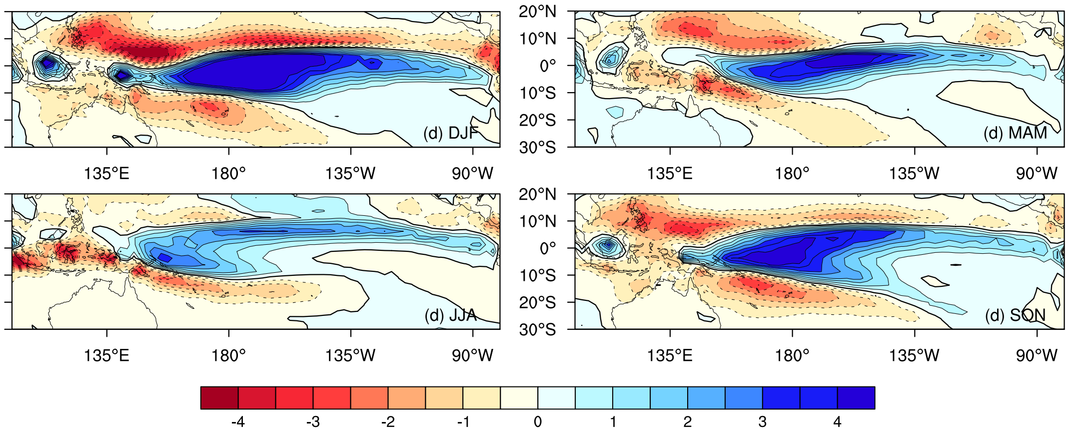

Fig. 5 (a–d). Maps of the regression of predicted ensemble mean rainfall from POAMA1.5b rainfall on the predicted standardised Niño 3.4 index from POAMA1.5b for 1982–2006 for DJF (a), MAM (b), JJA (c) and SON (d). Units in mm day^{-1}.

Nonetheless, we conclude that the combination of good predictions of El Niño (La Niña) related SST variations and good simulation of the El Niño (La Niña) related rainfall anomalies should result in good predictions of rainfall in the Pacific. Although we have discussed mainly the rainfall variations associated with El Niño and La Niña years, POAMA also simulates the mean seasonal rainfall patterns, such as the position of the ITCZ and the SPCZ well (not shown), although the extension of the SPCZ in the Samoan region is a little further south in DJF and MAM than shown by observations from CMAP.

5. RAINFALL FORECAST SKILL

5.1 Correlation of ensemble mean prediction

The ensemble mean prediction of seasonal rainfall anomaly at LT=0 months is verified against CMAP rainfall using correlation (Figs. 6a–d). In all seasons, high forecast skill (r>0.8) is achieved in the equatorial Pacific, where the direct impacts of El Niño dominate. The region of highest skill shifts into the respective summer hemisphere, which is consistent with the latitudinal shift of greatest El Niño impact (e.g. Fig. 2). This region of high skill is wider in the austral summer (DJF) and autumn (MAM) than in austral winter (JJA) and spring (SON). Another region of high skill, although not nearly as high as in the equatorial region, is also evident in the southwest Pacific, which is in the SPCZ region where El Niño rainfall anomalies tend to be of opposite sign to those in the central equatorial Pacific. Interestingly, forecast skill in this SPCZ region is highest in austral summer (DJF), which is the season when, as noted above, forecast skill for local SST is low (Fig. 4a). This suggests that local rainfall in this region is primarily controlled by remote SST. The forecast skill in the SPCZ region is lowest in austral winter (JJA) but recall this is the dry season and so rainfall forecasts in this season are less important.

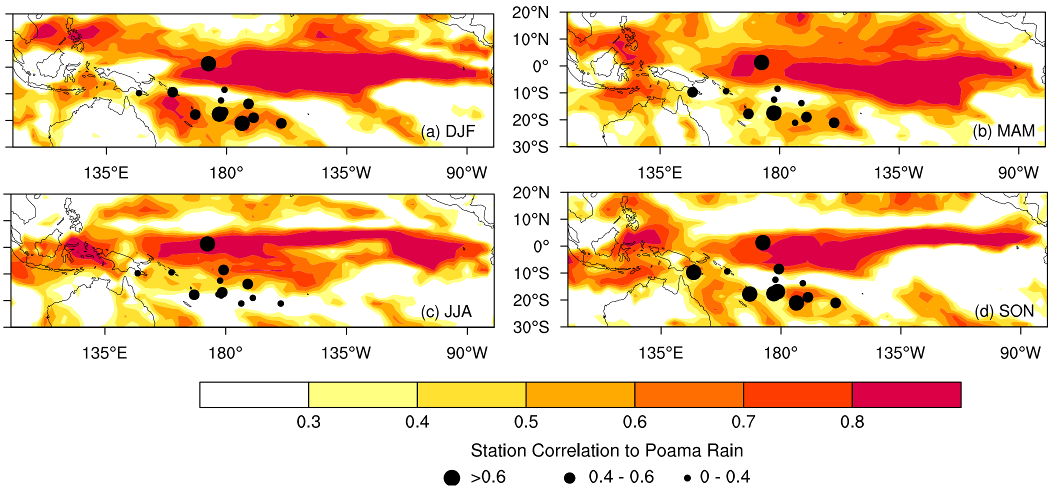

Fig. 6 (a–d). Maps of the correlation of predicted rainfall (ensemble mean) from POAMA1.5b at lead time 0 month verified against CMAP analyse for DJF, MAM, JJA and SON and the period 1980–2006. Black dots show the correlation of predicted rainfall with observed station rainfall using the grid box closest to the station. Small black dots are low skill (<0.4), medium sized dots are moderate skill (0.4 to 0.6) and large dots are high skill (>0.6).

Some indication of the ability of POAMA to predict rainfall at the station level throughout the Pacific Island countries is provided by verifying POAMA against station records. The predicted rainfall at the station location is simply given by a bilinear interpolation of the gridded rainfall prediction from POAMA to the station location. Forecast correlation at each station is indicated by the filled dots in Fig. 6a–d, where the diameter of the circle is proportional to the correlation (see caption). Predictive skill at the station level is qualitatively similar to that at the grid level (using CMAP gridded rainfall), though not surprisingly the correlation skill is slightly lower. Stations with a moderate (>0.4–0.6) or high (>0.6) correlation are generally located in regions with a moderate or high correlation between CMAP and POAMA, such as at Tarawa in all seasons. Stations generally with a low correlation (<0.4) are located in regions with a low correlation between CMAP and POAMA, such as Rotuma and Funafuti in austral summer (DJF). For reference, the correlations between station rainfall and POAMA predictions are tabulated in Table 2. Tarawa, located close to the equator, has the highest correlations, with the highest value in austral winter (JJA), which is interestingly the season with the lowest correlation for all other stations. However, remember Tarawa does not have a dry season like many of the other Pacific Island groups further south. Nabouwalu from Fiji and Port Vila from Vanuatu also have moderate to high correlations in all seasons (>0.4) and are located away from the equator in the southwest Pacific, where rainfall has a strong seasonal cycle and is related to the activity and position of the SPCZ. Rarotonga in the Cook Islands is located in the southeast region of the SPCZ and has correlation values >0.4 in all seasons except austral winter, which is the dry season. In contrast, the correlation values are low (≤0.35) at Rotuma (Fiji), Honiara (Solomon Islands), Funafuti (Tuvalu) and Apia (Samoa) and these stations are located in a narrow zone of low skill along the edge of the SPCZ (Fig. 6). Suva also has low correlation values, especially in austral summer (DJF), and this is most likely due to its location on the southeast side of the island of Viti Levu, where it is exposed to the moist southeasterly trade winds all year round.

Table 2. Correlation of predicted rainfall from POAMA1.5b at LT=0 with observed rainfall at 14 Pacific Island stations for the period 1980–2006. Statistically significant correlation at the 5% level (α=0.025 and r≥0.39 by two-tailed Student-t test with 27 independent samples).

Station Name and Index	Island Group	DJF	MAM	JJA	SON
1980–2006					
Equatorial Region					
1. Betio(Tarawa)	Kiribati	**0.70**	**0.70**	**0.88**	**0.80**
2. Funafuti	Tuvalu	0.32	0.09	**0.51**	**0.40**
SPCZ Region					
3. Nadi Airport	Fiji	**0.61**	**0.59**	0.26	**0.65**
4. Rarawai	Fiji	**0.58**	**0.61**	0.18	**0.49**
5. Nabouwalu	Fiji	**0.53**	**0.43**	**0.52**	**0.72**
6. Suva	Fiji	0.06	0.25	**0.39**	0.36
7. Rotuma	Fiji	0.28	0.35	**0.39**	0.04
8. Nuku'alofa	Tonga	**0.71**	0.30	0.34	**0.60**
9. Alofi	Niue	**0.58**	**0.42**	-0.01	**0.52**
10. Apia	Samoa	**0.46**	0.30	**0.44**	0.19
11. Rarotonga	Cook Is	**0.40**	**0.51**	0.11	**0.44**
12. Honiara	Solomon Is	0.38	0.36	0.31	0.16
Southwest Pacific Region					
13 Port Vila	Vanuatu	**0.57**	**0.51**	**0.49**	**0.60**
14.Port Moresby	Papua New Guinea	0.11	**0.45**	0.24	**0.69**

In summary, based on correlation of the ensemble mean rainfall anomaly, POAMA has good skill for prediction of seasonal mean rainfall at LT=0 in the equatorial region and good skill in the SPCZ during the wet season (DJF) and also austral spring (SON) and autumn (MAM), with lowest skill in austral winter (JJA). This seasonality of skill is seen for both gridded rainfall and at the station level.

5.2 Probabilistic forecast of tercile rainfall and calibration

We also explore forecast skill for probabilistic prediction of tercile rainfall. Tercile thresholds are defined separately for the observed and forecast rainfall, thereby providing a form of calibration for the forecasts. A probability forecast of being in the upper or lower tercile is developed by dividing the number of ensemble members in each of these categories by the total number of members. These probabilistic forecasts are verified forming a 3 category contingency table (Table 3).

Table 3. Contingency table three category (tercile) forecasts. For example, the hit rate (HR) for the lower tercile is calculated using HR = (I/(I+C+F))*100.

Forecast: \ Observed:	Upper	Middle	Lower
Upper	Hits (A)	Misses (D)	Misses (G)
Middle	Misses (B)	Hits (E)	Misses (H)
Lower	Misses (C)	Misses (F)	Hits (I)

Prior to assessing the accuracy of the tercile forecasts, we first assess the reliability, which is the tendency of the forecast tercile probability to occur as often as observed. Fig. 7a shows the attribute diagram of POAMA probabilistic forecasts for combined above upper tercile and below lower tercile rainfall over the tropical western Pacific (10°N–30°S, 135°E–220°E) at LT=0 in the four major seasons. Perfect reliability of forecasts is indicated by the diagonal line. The forecasts falling in the grey areas are considered to be reliable forecasts as they correctly indicate the occurrence/non-occurrence of the event and have smaller magnitudes of error than a climatological forecast. The size of dots indicates forecast frequency in each probability bin (ten bins of equal width of 0.1). The attributes diagram suggests that POAMA can discriminate to the occurrence/non-occurrence of above upper tercile or below lower tercile rainfall events. However, the forecasts are far from being reliable: they tend to be overconfident (e.g., POAMA predicts the occurrence of above tercile rainfall more often than observed).

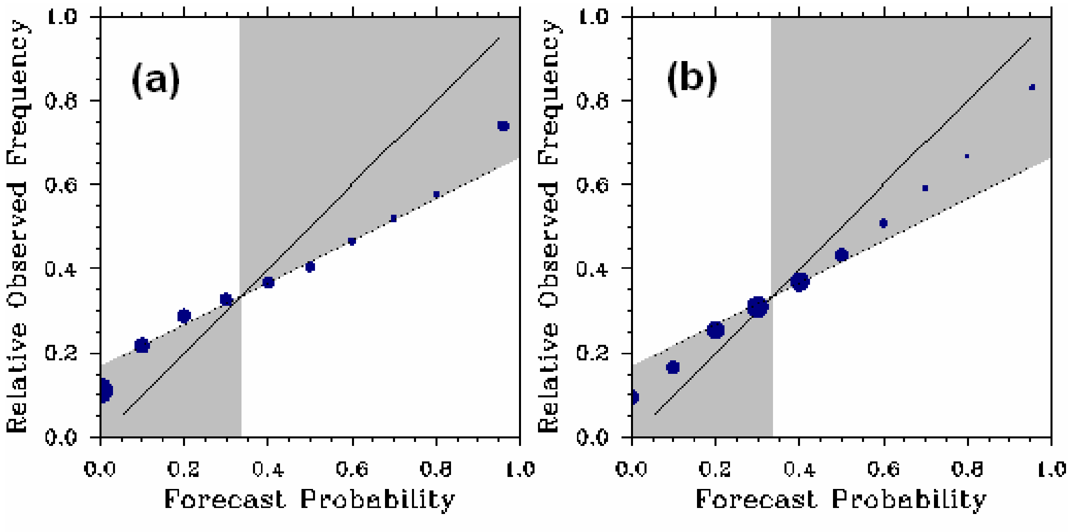

Fig. 7 (a–b). Attribute diagrams of the uncalibrated (a) and calibrated (b) rainfall for the combined upper and lower terciles using all four seasons across the tropical Pacific region using POAMA1.5b hindcast (LT=0) for the period 1980–2006. The grey region indicates forecasts with skill and the solid black line represents perfect reliability. The size of the dot is proportional to the total number of forecasts in each forecast probability bin of fixed width 0.1.

In order to improve the forecast reliability, we calibrated the forecasts using the inflation of variance method (e.g., Johnson and Bowler (2009)). The calibration was cross validated using leave-one-out. The resultant calibrated forecast outcome is plotted in Fig. 7b. Calibration improves the reliability of the forecasts but at the expense of reduced sharpness.

Accuracy of the probabilistic forecasts is assessed using a combined hit rate for the lower and upper tercile for the four standard seasons at the 14 Pacific Island stations (Table 4). Results are shown for uncalibrated and calibrated forecasts. We note that the calibrated rainfall forecasts have slightly lower hit rates than the uncalibrated forecast, which is due to cross-validation procedure when applied to the relatively short record lengths available here. Nonetheless, skilful hit rates exceeding the climatological expected hit rate (33%) is achieved at most stations in most seasons, with the highest hit rates occurring at stations with highest correlation skill (Table 2).

Table 4. Hit rate for forecast of seasonal rainfall being in the upper and lower tercile at 14 Pacific Island stations from POAMA1.5b hindcasts (LT=0) for the period 1980–2006. Columns annotated U and C represent uncalibrated and calibrated forecasts using station data respectively. Statistically significant values with a confidence interval at the 95% level (z=1.96 or 51%) are boldfaced.

Station Name and Index	Island Group	DJF		MAM		JJA		SON	
1980–2006		U	C	U	C	U	C	U	C
Equatorial Region									
1. Betio (Tarawa)	Kiribati	**62**	**58**	**71**	**65**	**85**	**81**	**73**	**66**
2. Funafuti	Tuvalu	37	25	27	7	43	36	36	18
SPCZ Region									
3. Nadi Airport	Fiji	**56**	46	41	37	36	23	**59**	48
4. Rarawai	Fiji	48	43	42	39	34	24	**54**	37
5. Nabouwalu	Fiji	**52**	41	37	27	42	36	**54**	48
6. Suva	Fiji	32	17	39	24	46	28	38	26

7. Rotuma	Fiji	45	20	34	25	47	33	29	9
8. Nuku'alofa	Tonga	**52**	**51**	29	27	35	26	44	42
9. Alofi	Niue	39	35	37	31	30	13	41	36
10. Apia	Samoa	37	30	31	18	45	28	37	18
11. Rarotonga	Cook Is	39	28	37	31	27	17	44	33
12. Honiara	Solomon Is	47	36	31	24	50	31	32	23
Southwest Pacific Region									
13 Port Vila	Vanuatu	47	41	42	41	47	27	47	44
14.Port Moresby	Papua New Guinea	26	19	44	31	37	13	**52**	45

We also assess forecast accuracy using root-mean-square error (RMSE) of the ensemble mean forecasts. We normalised the RMSE (NRMSE) by the observed standard deviation so that NRMSE<1 is indicative of a skilful forecast. Table 5 displays the NRMSE for ensemble forecasts of both uncalibrated and calibrated forecasts. The benefit of calibration is clearly seen in Table 5, where there is a dramatic reduction in NRMSE at all locations due to the calibration (e.g., Johnson and Bowler (2009)). Again, stations with the lowest NRMSE are the stations with highest correlation skill. The results in Table 5 are summarized in Fig. 8a, which is the average NRMSE over all of the 14 stations over all 4 seasons for uncalibrated and calibrated lead time 0 forecasts. Also shown in Fig. 8b is the NRMSE averaged over all grid points in the western Pacific verified against CMAP. In both cases, calibration reduces the NRMSE to less than 1 (i.e. forecasts are skilful compared to climatological forecast).

Table 5. Normalised root mean square error of seasonal mean rainfall forecasts from POAMA1.5b at LT=0 at 14 Pacific Island stations. Columns annotated U and C represent uncalibrated and calibrated forecasts using station data respectively.

Station Name and Index	Island Group	DJF		MAM		JJA		SON	
1980–2006		U	C	U	C	U	C	U	C
Equatorial Region									
1. Betio(Tarawa)	Kiribati	1.05	0.72	0.86	0.72	0.45	0.48	0.58	0.60
2. Funafuti	Tuvalu	1.35	0.95	1.22	1.01	0.90	0.90	1.19	0.94
SPCZ Region									
3. Nadi Airport	Fiji	0.77	0.80	0.78	0.81	1.39	0.98	1.40	0.77
4. Rarawai	Fiji	0.79	0.82	0.76	0.78	1.23	0.99	1.12	0.87
5. Nabouwalu	Fiji	1.04	0.87	0.89	0.92	0.93	0.87	0.71	0.70
6. Suva	Fiji	1.39	1.01	0.98	0.99	0.92	0.92	0.92	0.93
7. Rotuma	Fiji	1.35	0.96	1.01	0.99	0.94	0.95	1.13	1.00
8. Nuku'alofa	Tonga	0.69	0.71	0.96	0.94	1.01	0.95	0.77	0.80
9. Alofi	Niue	0.82	0.84	0.89	0.92	1.26	1.02	0.86	0.88
10. Apia	Samoa	0.91	0.90	1.04	1.00	1.55	0.91	1.08	1.00
11. Rarotonga	Cook Is	1.07	0.94	0.90	0.88	1.27	1.02	0.97	0.93
12. Honiara	Solomon Is	0.94	0.91	1.26	0.94	2.03	0.96	1.56	1.00
Southwest Pacific Region									
13 Port Vila	Vanuatu	0.81	0.83	0.83	0.86	0.85	0.90	0.75	0.81
14.Port Moresby	PapuaNew Guinea	1.65	1.01	1.45	0.95	2.73	0.98	2.07	0.77

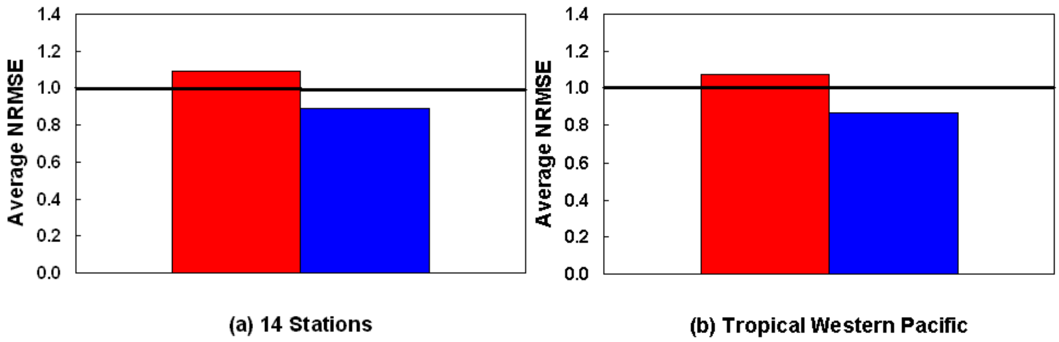

Fig. 8 (a–b). Bar plots of the uncalibrated (red) and calibrated (blue) normalised RMSE for rainfall predictions using ensemble mean at lead time 0 month verified against (a) 14 Pacific Island stations and (b) CMAP (western Pacific domain) for the period 1980–2006. A normalized RMSE<1 is considered skilful.

5.3 Example of forecast products

An expected outcome of this project is the provision of forecast products for the Pacific Island countries. Here we demonstrate two typical forecast products (tercile forecast at a station and calibrated ensemble mean rainfall amount across the western Pacific) that are available in real time. The first example of forecast products is the tercile forecast for DJF 1999 at Tarawa (Fig. 9a) and Nadi Airport (Fig. 9b). The standardised Niño 3.4 SST index was -1.44, indicating that 1999 was a La Niña year. At Tarawa, the probability of uncalibrated rainfall being in the lower tercile was predicted to be 100% whereas calibration reduced this to 80%. The verifying analysis (green bar) was in the lower tercile. Similarly, at Nadi Airport, the probability of being in the upper tercile was 100% for the uncalibrated forecast, while calibration reduced this to 70%. The verifying analysis was in the upper tercile (green bar). These examples of seasonal forecasts during an episode of strong climate forcing (i.e. strong La Niña) show the impact of calibration (less emphatic) and the high skill of the POAMA system.

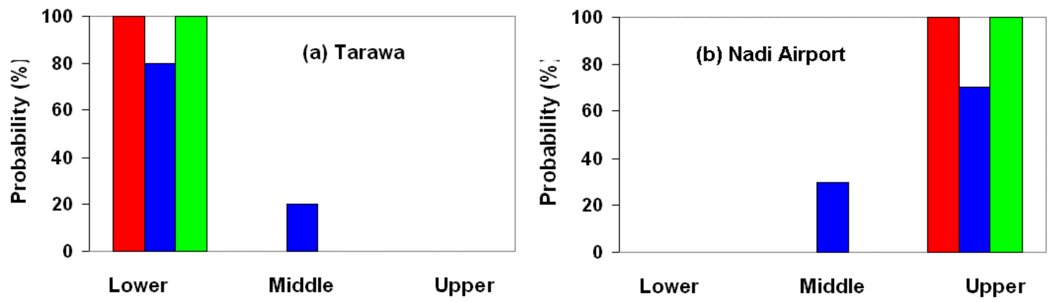

Fig. 9 (a–b). Bar plots of the probabilities of forecast rainfall being in each tercile for DJF 1999 at (a) Tarawa (a) and (b) Nadi Airport. Forecasts are shown for uncalibrated (red) and calibrated (blue) probabilities at (LT=0) for the lower, middle and upper terciles. The verifying rainfall is displayed in green.

The second example is the calibrated ensemble mean rainfall anomaly forecast for DJF 1999 (Fig. 10a). The verifying analysis from CMAP is shown in Fig. 10b. The strong La Niña signal is well represented in the forecast, including the suppressed rainfall in the ITCZ and the westward shift of the SPCZ. These two example forecast products and additional forecast products are made available to the partner countries through a PASAP web page (described below).

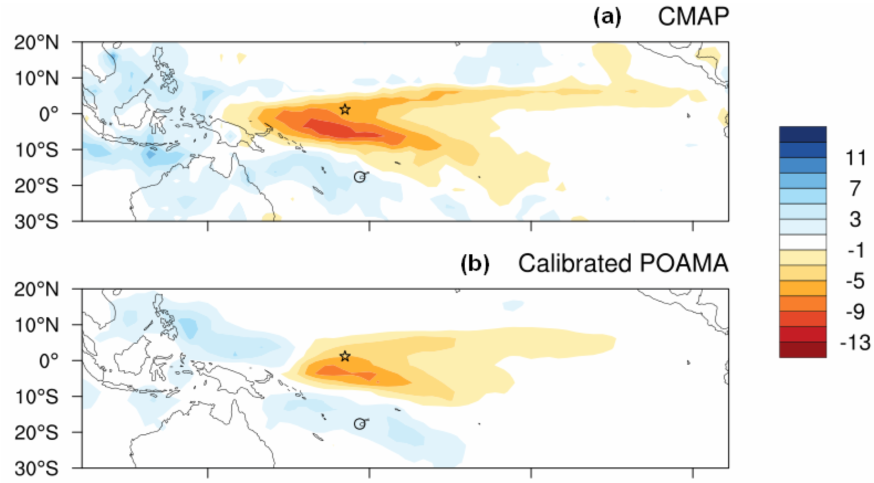

Fig. 10 (a–b). Rainfall anomaly for DJF (1999) from the verifying analysis from CMAP (a) and the calibrated ensemble mean prediction with LT=0 (b). Units are mm d^{-1}.

6. DISCUSSION AND CONCLUSIONS

We have demonstrated the feasibility of making short lead time seasonal climate predictions for the tropical western Pacific using the POAMA coupled model forecast system. Because of the strong impacts of El Niño and La Niña in the region and the good ability to predict El Niño and La Niña in the Pacific, seasonal forecasts for regional rainfall in this Pacific region are extremely good. The long duration of ENSO events means they have the potential to be predictable on seasonal time scales of several seasons, thus assisting local governments in planning activities and implementing risk reduction strategies for floods and droughts caused by climate extremes. This provides a sound basis for using dynamic models like POAMA to develop seasonal forecasts for the region and during the transition from statistical models, which will be eventually phased out, as they cannot account for all aspects of climate change and contain only short historical analogues to predict future rainfall.

This study has described various aspects of POAMA and the hindcast forecasts which show that POAMA has good skill to predict many aspects of tropical Pacific climate. We have showed POAMA can simulate regional climate with both extremes of the rainfall associated with El Niño and La Niña events by verifying POAMA with CMAP and Reynolds SST data using regression analyses and hindcast correlation skill. The overall high correlation between predicted rainfall and the gridded analyses of CMAP across the Pacific region indicates good potential for improved seasonal forecasting using this dynamical forecast model for many of the countries in the PASAP project. At a station level, there is generally a good correlation between rainfall and the Niño 3.4 index, where much of the skill resides in POAMA for predicting SSTs and therefore rainfall variations across the region. The impacts of rainfall at two stations was assessed to show the strong impact on rainfall associated with the extremes of the ENSO and also to show the varying onset and termination dates of this impact. Many models are able to simulate many features associated with the ITCZ and the SPCZ, but often lack the correct rainfall width, intensity and also the alignment of the SPCZ over the southwest Pacific region (Brown et al. 2011). However, as we have shown, POAMA does have the ability to replicate many of these features, and provides a good basis for future seasonal forecasting products. To further investigate the rainfall skill in POAMA, hit rates were calculated from the combined lower and upper terciles. These hit rates show the highest skill occurs in the austral spring (SON) and summer (DJF), with lower skill in MAM and JJA. As most El Niño and La Niña events tend to be locked in by the early austral spring (SON), this means POAMA has good skill and potential to forecast the seasonal rainfall changes associated with these events and therefore provide reliable seasonal forecasts to predict drought or increased rainfall across the tropical Pacific, and also to many station locations and districts within Pacific islands countries. Improved reliability of the seasonal forecasts can be obtained by calibrating the raw forecasts. We have shown the 'Inflation of Variance' technique described by Johnson and Bowler (2009) can improve the reliability of seasonal forecasts in the lower and upper tercile associated with drought or extreme rainfall, and can also make these forecasts less emphatic, with higher reliability across all of the forecast probability ranges.

Due to the success of these regional forecasts using the POAMA coupled model, the forecasts for the partner Pacific Island nations became routinely available in September 2011 and are delivered via a subscription webpage:
http://poama.bom.gov.au/experimental/pasap/index.shtml. The PASAP web page development is described in detail in Charles and et al (2011). Forecast products include tercile forecasts at stations and maps of ensemble mean rainfall anomalies. Forecast skill based on hindcast performance is also directly available so that users will have a clear indication of forecast reliability and accuracy. Equally important as to the development of skilful predictions with the

model and the timely provision of the forecasts through the web page, in-country training for understanding and using the forecasts has been provided (and will continued to be provided) via a number of in-country workshops, which have been well attended by forecasters and climate service personnel from the partner National Meteorological Services.

Since commencement of this project, the POAMA1.5b system has been upgraded to POAMA2.4, which has slightly improved skill for predicting El Niño and also improved reliability due to an improved ensemble generation strategy. POAMA1.5b has been superseded by POAMA2.4 for the delivery of real time predictions for this PASAP project by end of 2011. While POAMA2.4 is a clear improvement over POAMA1.5b, we expect the practical forecast skill for the Pacific region to be similar to that documented here. The PASAP project will be continued under the Pacific-Australia Climate Change Science and Adaptation Planning Programme (PACCSAP), which will focus research in three main areas of seasonal forecasting of climate extremes, specifically tropical cyclones in the western Pacific, sea surface temperature extremes and associated coral bleaching, and sea level changes in the Pacific region.

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