Seasonal Forecasting in the Pacific Using the Coupled Model POAMA-2

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ABSTRACT

The development of a dynamical model seasonal prediction service for island nations in the tropical South Pacific is described. The forecast model is the Australian Bureau of Meteorology’s Predictive Ocean–Atmosphere Model for Australia (POAMA), a dynamical seasonal forecast system. Using a hindcast set for the period 1982–2006, POAMA is shown to provide skillful forecasts of El Niño and La Niña many months in advance and, because the model faithfully simulates the spatial and temporal variability of rainfall associated with displacements of the southern Pacific convergence zone (SPCZ) and ITCZ during La Niña and El Niño, it also provides good predictions of rainfall throughout the tropical Pacific region. The availability of seasonal forecasts from POAMA should be beneficial to Pacific island countries for the production of regional climate outlooks across the region.

1. Introduction

As part of the Australian government’s Australian Agency for International Development (AusAID) International Climate Change Adaptation Initiative, the Pacific Adaptation Strategy Assistance Program (PASAP) has provided assistance to 14 Pacific island nations and East Timor 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 has supported the Australian Bureau of Meteorology (BoM) in developing improved seasonal climate prediction services for the 15 countries across the region (Fig. 1). Although the main motivation for the PASAP program is to assist Pacific island nations in adapting 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 have been based on the Seasonal Climate Outlook for Pacific island Countries (SCOPIC) model, which is derived from statistical relationships between sea surface temperature (SST) variations, primarily those associated with El Niño–La Niña, and the local climate in the Pacific. He and Barnston (1996) have previously reported on similar statistically based seasonal forecasts 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 of handling nonstationary climate, better predicting extremes, and forecasting 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, Predictive Ocean–Atmosphere Model for Australia (POAMA). This paper is organized into the following sections. Section 2 describes the POAMA forecast system, the seasonal hindcasts for the period (1982–2006) 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 POAMA model, is reviewed in section 3. Analysis of forecast skill including probabilistic forecasts, an assessment of a current statistical model, and a demonstration of some forecast products from POAMA is 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.

2. POAMA model and verification data and methods

a. POAMA model

The POAMA seasonal forecast system has been developed at the BoM to provide seasonal climate forecasts for the Australian and global community. It is a coupled ocean–atmosphere climate model that uses the Bureau of Meteorology Research Centre Atmospheric Model (BAM3.0) for the atmosphere (Colman et al. 2005; Wang et al. 2005; Zhong et al. 2006) and the Australian Community Ocean Model version 2 (ACOM2) for the ocean, which is based on the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model, version 2 (MOM2; Schiller et al. 2002). The first operational version of POAMA was POAMA-1, which ran from 2002 to 2007, and was subsequently replaced by version POAMA-1.5b in 2007. At the end of 2011, further updates resulted in the multimodel version POAMA-2.4 (POAMA-2 herein). POAMA-2 has an improved ocean data assimilation scheme compared to the earlier version, with the latest upgrade focused on improved forecast initialization, rather than changes in the model physics.

The atmospheric model BAM3.0 is a spectral transform model that uses a nominal grid spacing of 2.5° × 2.5° (72 × 144 grid points), with 17 vertical levels (Colman et al. 2005). Shortwave radiation is parameterized using Lacis and Hansen (1974) and longwave radiation using a modified Fels–Schwarzkopf scheme (Schwarzkopf and Fels 1991). It uses a mass flux cumulus parameterization (Tiedtke 1989), which has been shown to simulate fundamental features of the Madden–Julian oscillation (Zhang et al. 2006) and cloud formation based on the statistical condensation scheme of Smith (1990). Surface boundary layer parameterizations and vertical diffusion are based on Louis (1983). Gravity wave drag is calculated using the scheme by Palmer et al. (1986). The land surface component uses a simple bucket model for soil moisture after Manabe and Holloway (1975). Further details of the BAM3.0 model can be found in Colman et al. (2005) and Wang et al. (2005). The ocean model ACOM2 (based on MOM2) has the highest resolution in the tropics, with a grid
spacing of 2° in the zonal direction and 0.5° in the meridional direction at the equator, which increases to 1.5° at the poles. There are 25 levels in the ocean, with 12 levels between 185 m and the surface (Schiller et al. 2002; Schiller and Godfrey 2003; Oke et al. 2005). The higher resolution at the equator has been shown to improve ocean dynamics and El Niño–Southern Oscillation (ENSO) behavior, as well as associated teleconnections (Hudson et al. 2010). Further details on the ACOM2 (MOM2) can be found in Pacanowski (1995), Schiller (1999), and Schiller and Godfrey (2003).

The atmospheric model of the POAMA-2 system is initialized with an atmosphere and land initialization scheme (ALI) that generates realistic atmospheric and land initial conditions that capture the observed intraseasonal atmospheric state. Improvements in initializing the atmospheric state result in higher skill for predicting Niño-3 and Niño-3.4 indices compared to the earlier POAMA system, whose atmospheric model is initialized with conditions generated from Atmospheric Model Intercomparison Project (AMIP) type simulations (Hudson et al. 2010). ALI produces atmosphere–land surface initial conditions by nudging the BAM3.0 atmospheric model once per day toward the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; Uppala et al. 2005) for the period 1982–2002 and to the global analyses from the BoM’s numerical weather prediction system for 2002–06 and for the real-time forecasts. The atmosphere and the ocean are coupled by the Ocean Atmosphere Sea Ice Soil model (OASIS), described by Valcke et al. (2000).

POAMA-2 uses a new advanced ocean initialization scheme provided by the POAMA Ensemble Ocean Data Assimilation System (PEODAS), which is based on an ensemble Kalman filter (Yin et al. 2011). The implementation of PEODAS is an improvement over the previous system, POAMA-1.5b, as it assimilates both ocean temperature and salinity observations into the model every 3 days. The system also generates an ensemble of initial ocean states generated by perturbing the wind and surface fluxes. This ensemble of initial states is used to calculate background error covariances for temperature, salinity, and currents and to make ensemble forecasts (Yin et al. 2011).

Hindcasts and forecasts from the POAMA-2 system use three slightly different model configurations (in order to sample uncertainty due to model error), each with a set of 10 members, initialized on the first of each month and run for 9 months, with hindcasts generated for 1982–2006. The differences in the three model versions in the atmosphere and ocean physics are summarized in Table 1. In POAMA-2.4b, the flux correction was applied to reduce the climatological bias in the coupled model. This adjusts the shortwave radiation, total heat flux, and wind stress to be closer to the observed datasets, and, consequently, the large cold and warm biases in the tropical Pacific are substantially reduced (Lim et al. 2010). This approach of using three slightly different model versions helps to address model uncertainty (Wang et al. 2011), and to increase forecast reliability (Langford and Hendon 2011; Langford and Hendon 2013). Improved data assimilation in POAMA-2 using temperature and salinity in PEODAS has also improved the ocean dynamics, such as the thermocline depth and zonal velocity, as well as the mean sea level pressure compared to POAMA-1 (Yin et al. 2011). An example of the rainfall skill at various lead times over the Pacific and Indian Ocean regions is shown in Lim et al. (2009).

![Table 1. Summary of the main atmosphere and ocean physics in the three models of POAMA-2.](http://journals.ametsoc.org/waf/article-pdf/28/3/668/4652127/waf-d-12-00072_1.pdf)
b. Verification data

Seasonal rainfall hindcasts from POAMA-2 are verified against available station records in the Pacific and the gridded monthly analyses from the Climate Prediction Center (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 data from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis. Monthly rainfall records from 14 stations in 10 Pacific island countries were obtained from the National Climate Centre at the BoM and the Pacific Climate Change Science Program (PCCSP). The stations were selected based on geographical coverage and availability of complete or nearly complete monthly rainfall records covering the period from 1982 to 2006. At many stations, monthly rainfall records date back to 1950 or earlier. Station locations and mean annual rainfall from CMAP are shown in Fig. 1.

SST forecasts from POAMA-2 are verified against the analyses from the Reynolds optimal interpolation version 2 dataset (OLv2; Reynolds et al. 2002) for January 1982–December 2006. The Niño-3.4 SST index (SST averaged from 5°N to 5°S and 170° to 120°W) is used to monitor El Niño conditions in the Pacific. The composite evolution of SST around each of the rainfall stations during El Niño–La Niña is formed using the average of the analyzed SST in 10° latitude × 10° longitude boxes around each rainfall station.

c. Verification and analysis methods

Forecasts are verified for four standard seasons: austral summer [December–February (DJF)], autumn [March–May (MAM)], winter [June–August (JJA)], and spring [September–November (SON)]. Forecast anomalies from the POAMA-2 model are formed relative to the model’s hindcast climatology, which is a function of lead time (LT) and start month for the period 1982–2006. Anomalies of the verification data are formed relative to the climatology for the same 1982–2006 period. The analysis is conducted over the tropical western Pacific domain (10°N–30°S, 135°E–140°W) and using rainfall data from 14 stations from some key Pacific island nations who are participating in PASAP (Fig. 1).

Along with the standard verification techniques using correlation and normalized root-mean-square error (NRMSE; RMSE normalized by the standard deviation of the observation) based on the ensemble mean forecast, probabilistic forecasts are also verified using the combined hit rate for predicting rainfall in the lower and upper terciles. Probabilistic forecasts from POAMA-2 are computed using the number of individual ensemble members out of the total ensemble (30) that fall into each tercile category. The tercile thresholds for the forecasts and verification are based on the hindcast and observed climatologies, respectively, and are computed by cross validation, whereby the thresholds are calculated by leaving out the target year.

Rainfall forecasts from the POAMA-2 have also been calibrated to the CMAP data using the inflation of variance method (IOV; Johnson and Bowler 2009). This calibration results in more reliable forecasts. This technique optimally adjusts the ensemble variance to be equal to the observed variance while maintaining the original correlation of the ensemble mean with the observed. This calibration results in a reduction of the mean square error (MSE) in the forecast. The technique is applied and validated using the “leave one out” method (i.e., where each target year is removed from both the observed and POAMA-2 prior to computing calibration and climatologies). For the verification of the gridded model forecasts against station data, the nearest model grid point to the station from POAMA-2 is used. We also include attribute diagrams (Wilks 2006) of POAMA-2 forecast rainfall to show the reliability of the forecasts before and after calibration.

We also briefly compare to the statistical seasonal forecasts from SCOPIC, which have been described by Abawi et al. (2005a,b). SCOPIC is a portable software package that has been utilized since 2002 in the Pacific islands for seasonal forecasting and water resource management. Forecasts in SCOPIC are generated for specific stations by using seasonal rainfall data (predictands) and the monthly Southern Oscillation index (SOI) or a few SST empirical orthogonal functions (EOFs) as predictors. We compare the tercile hit rates between SCOPIC and POAMA at a few select station locations.

Finally, we include an example of forecast products for two representative stations (Bonriki International Airport in Tarawa, Kiribati, and Nadi International Airport in Fiji) in order to demonstrate the practicable application of using the dynamical coupled model seasonal forecast system in the region.

3. Basis for seasonal prediction

a. El Niño–La Niña rainfall anomalies

The climate over the tropical Pacific Ocean is largely determined by the mean position of the intertropical convergence zone (ITCZ) over northern and central equatorial latitudes and the South Pacific convergence

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zone (SPCZ) over the southwest Pacific Ocean. The mean annual rainfall from CMAP across the tropical Pacific is shown in Fig. 1, where the mean location of the ITCZ and the SPCZ can be seen. The ITCZ is formed by converging southeasterly and northeasterly trade winds, resulting in deep convection and high rainfall amounts. The ITCZ is generally most active in austral winter and remains north of the equator east of ~180° all year round (Meehl 1987; Barry and Chorley 2003). 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 toward Fiji, Tonga, and the Cook Islands (Vincent 1994; Barry and Chorley 2003). The SPCZ is characterized 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 and New Zealand region (Barry and Chorley 2003). The SPCZ is also more active in the austral summer (Meehl 1987; Vincent 1994). El Niño and La Niña are the main sources of interannual variability in the ITCZ and SPCZ.

The seasonal pattern of rainfall anomalies during El Niño–La Niña is displayed in Fig. 2, which shows the regression of the CMAP rainfall analyses onto the standardized 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 the equatorward shift of the ITCZ is most prominent in austral autumn and winter. In the SPCZ region in the southwest Pacific, there is a 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. This highlights both the challenge and the importance of accurately predicting the east–west and north–south excursions of the ITCZ and SPCZ during El Niño and La Niña years.

For the island stations near the equator and the date line, [e.g., Betio (Tarawa) and Funafuti, Tuvalu], the correlation of rainfall with the Niño-3.4 SST index is strongly positive in all seasons, as anticipated from Fig. 2, with a correlation over all months of 0.71 at Tarawa. For other island stations in the southwest Pacific and SPCZ region, the correlations are generally negative (less rainfall in El Niño years) and strongest in austral summer (DJF) and autumn (MAM) and weakest in the austral winter (JJA).

Two stations were selected from the 14 stations to represent these different impacts of El Niño and La Niña on rainfall across the Pacific region. Tarawa is indicative of locations near the equator, where rainfall varies in phase with El Niño (Fig. 2). In contrast, Nadi airport is representative of stations in the SPCZ region, where rainfall varies out of phase with El Niño (Fig. 2).

Monthly SST and rainfall data from El Niño and La Niña years were selected from 1982 to 2006 and composites were constructed. We include four classical El Niño years (1982–83, 1986–87, 1987–88, and 1997–98), where the maximum surface warming is in the eastern equatorial Pacific, and four La Niña years (1984–85, 1988–89, 1998–99, and 1999–2000), defined by the Niño-3.4 monthly index as being about >0.8 or <−0.8 respectively. We also have examined four El Niño events whose maximum warm SST anomaly was shifted toward the date line [i.e., Modoki El Niño, warm-pool El Niño or
of the local SST variation is much weaker than in the Niño-3.4 region farther to the east.

Nadi airport (Fig. 3b), in contrast to equatorial Tarawa, exhibits a pronounced seasonal cycle of rainfall, with a distinct wet season (>200 mm month$^{-1}$) that peaks in February and a dry season (<100 mm month$^{-1}$) centered on July–August. 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. Also in contrast to Tarawa, the local SST anomaly is opposite to the Niño-3.4 anomaly, but again with an amplitude that is much smaller than for Niño-3.4.

b. POAMA-2 prediction of El Niño rainfall patterns

To skillfully predict rainfall in the Pacific, 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 (Hendon et al. 2009; Zhao and Hendon 2009) have documented the good forecast skill of POAMA-1.5b at short lead times (i.e., up to about 3–4 months) for predicting SST anomalies associated with El Niño, including details of the east–west variation in the pattern of the SST anomaly. The skill of POAMA-2 in predicting the tropical Pacific SST is displayed in Fig. 4. The skill is assessed by the correlation of predicted SST with observations for the four standard seasons at zero lead (LT = 0) for POAMA-2 (e.g., hindcasts for DJF were initialized on 1 December). The highest forecast skill is found in the equatorial central and eastern Pacific as a result of the increased predictability associated with El Niño behavior (Barnston and Ropelewski 1992). The correlation skill is highest ($r > 0.8$) over the equatorial region in austral spring (SON; Fig. 4d) and summer (DJF; Fig. 4a). Regions of high skill also extend into the northwest and
southwest Pacific at different times of the year. The high skill in the southwest Pacific and the SPCZ 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 Coral Sea is low during austral summer (Fig. 4a), thus suggesting the prediction of regional climate in this region during the peak of the wet season will be challenging.

We now demonstrate that POAMA-2 can also simulate the rainfall anomalies associated with El Niño–La Niña. We do this by creating similar regressions as in Fig. 2, but using POAMA-2’s simulated rainfall at LT = 0 and POAMA-2’s standardized Niño-3.4 SST index. The regressed rainfall anomalies from POAMA-2 are shown in Fig. 5. 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. However, there are a couple of notable exceptions. The magnitude of the predicted rainfall anomalies are generally overemphasized and too zonally orientated. Negative rainfall anomalies extend to just east of Papua New Guinea, which is a feature not present in the observations.

Nonetheless, the overall pattern and magnitude of the rainfall anomalies associated with ENSO in the prediction model is in good agreement with the observed behavior. Therefore, the combination of good predictions of El Niño–related SST variations and good simulation of the El Niño–related rainfall anomalies should
4. Rainfall forecast skill

a. Correlation using ensemble mean predictions

The ensemble mean prediction of the seasonal rainfall anomaly at \( LT = 0 \) is verified against CMAP rainfall using correlation (Fig. 6). 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). A secondary, weaker region of high skill is evident in the southwest Pacific on the southwest side of the climatological SPCZ. El Niño rainfall anomalies in the SPCZ region 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), the time of lowest forecast skill for local SST (Fig. 4a). This suggests that local rainfall in this region is primarily controlled by remote SST. The forecast skill for rainfall in the SPCZ region is lowest in austral winter (JJA). However, this is the dry season and so forecasted rainfall and associated impacts are generally lower.

Some indication of the ability of POAMA-2 to predict rainfall at the station level throughout the Pacific is provided by verifying POAMA-2 against station records (Fig. 6). The predicted rainfall at the station location is simply given by selecting the closest grid point from POAMA-2 to the station location. Forecast correlation at each station is indicated by the filled dots in Fig. 6, 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), although 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-2, such as at Tarawa during all seasons. Stations generally with a low correlation \(<0.4\) are located in regions with a low correlation between CMAP and POAMA-2, such as Rotuma, Fiji, and Funafuti in austral summer (DJF). A summary of the correlation between station rainfall and POAMA-2 predictions is presented in Table 2 for the

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**TABLE 2.** Summary of the correlation of predicted rainfall from POAMA-2 at \( LT = 0 \) with observed rainfall across the Pacific region for the period 1982–2006. Statistically significant correlations at the 5% level \((r \geq 0.4)\) by two-tailed Student’s \( t \) test with 25 independent samples) are boldfaced.

<table>
<thead>
<tr>
<th>Region</th>
<th>DJF</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equatorial region</td>
<td>0.58</td>
<td>0.41</td>
<td>0.58</td>
<td>0.63</td>
</tr>
<tr>
<td>SPCZ region</td>
<td>0.48</td>
<td>0.36</td>
<td>0.28</td>
<td>0.48</td>
</tr>
<tr>
<td>Southwest Pacific region</td>
<td>0.38</td>
<td>0.43</td>
<td>0.56</td>
<td>0.55</td>
</tr>
</tbody>
</table>
equatorial (Tarawa and Funafuti), SPCZ (10 stations), and southwest Pacific (Port Vila, Vanuatu, and Port Moresby, Papua New Guinea) regions. POAMA-2 rainfall forecasts exhibit the highest correlation with station rainfall at Tarawa during all seasons. The highest skill for this station occurs in austral winter (JJA), the season for which skill is lowest at most other stations. Due to Tarawa’s equatorial location, it does not have a dry season like many of the other Pacific island groups farther south. Nabouwalu in Fiji and Port Vila also have moderate to high correlations in all seasons (>0.4). These stations, located near 18°S, have a strong seasonal cycle in rainfall, which is closely 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, the dry season. In contrast, the correlation values are low (≤0.35) at Rotuma, Honiara (Solomon Islands), Funafuti, and Apia (Samoa), and these stations are located in a narrow zone of low skill along the edge of the SPCZ (Fig. 6). Suva (Fiji) also has low correlation values, especially in austral summer (DJF), most likely due to its location on the southeast side of the island of Viti Levu. This site is exposed to the moist southeasterly trade winds all year round and is, therefore, less dependent on conditions in the equatorial Pacific.

In summary, the overall high correlation skill between predicted rainfall and CMAP across the Pacific region indicates good potential for improved seasonal forecasting using POAMA-2 for many island countries in the PASAP project. Predictive skill is highest in the equatorial and SPCZ regions during the wet season (DJF), and to a lesser degree in austral spring (SON) and autumn (MAM). This seasonality in skill is seen for both gridded rainfall and at the station level.

b. Probabilistic forecast of tercile rainfall and calibration

The ability of POAMA-2 to provide probabilistic (tercile) forecasts of rainfall over the tropical western Pacific domain (10°N–30°S, 135°E–140°W) and at the 14 stations is evaluated. 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 using a three-category contingency table, similar to the 2 × 2 contingency table described by Wilks (2006).

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. Figure 7a shows the attributes (or reliability) diagram of POAMA-2 probabilistic rainfall forecasts at LT = 0 for combined lower and upper tercile rainfall results over the tropical western Pacific domain during the four major seasons. Perfect reliability of forecasts is indicated by the diagonal line. The forecasts falling in the shaded areas are considered to be reliable forecasts as they
TABLE 3. Summary of the hit rates (%) for combined upper and lower tercile rainfall forecasts across the Pacific region from POAMA-2 hindcasts at LT = 0 verified against CMAP for the period 1982–2006. Columns annotated U and C represent uncalibrated and calibrated forecasts, respectively. Statistically significant values with a confidence interval at the 95% level (|z| = 1.96) are boldfaced.

<table>
<thead>
<tr>
<th>Region</th>
<th>DJF U</th>
<th>DJF C</th>
<th>MAM U</th>
<th>MAM C</th>
<th>JJA U</th>
<th>JJA C</th>
<th>SON U</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Equatorial</td>
<td>55</td>
<td>48</td>
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</tr>
<tr>
<td>SPCZ region</td>
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<td>34</td>
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<td>23</td>
</tr>
<tr>
<td>Southwest Pacific region</td>
<td>45</td>
<td>39</td>
<td>36</td>
<td>27</td>
<td>36</td>
<td>19</td>
<td>40</td>
<td>28</td>
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</tbody>
</table>

To improve the forecast reliability, the POAMA-2 forecasts were calibrated using the CMAP observations and the IOV method after Johnson and Bowler (2009). The calibration was cross validated using a leave-one-out approach. The resultant calibrated forecast outcome is plotted in Fig. 7b. Calibration improves the reliability of the forecasts (now closer to the diagonal line), but at the expense of reduced sharpness (more forecasts are similar to climatological forecasts, a probability of 0.33).

Accuracy of the probabilistic forecasts is assessed using a combined hit rate for the lower and upper tercile over the entire tropical western Pacific domain for the four major seasons. The average hit rates over the broad western Pacific domain are 42% and 34% for uncalibrated and calibrated data, respectively. Both are above the climatological hit rate of 33.3%. We note that the hit rate for the calibrated forecast drops because of cross validation using a relatively short record length. At the station level, a summary of the hit rates for the four standard seasons at the 14 Pacific island stations is given in Table 3. Results are provided for uncalibrated and calibrated forecasts. Skillful hit rates exceeding the climatological expected hit rate are achieved at most stations in most seasons, with the highest hit rates occurring at stations with the highest correlation skill. Tarawa has particularly high hit rate values, with all uncalibrated and calibrated values being statistically significant at the 95% level (not shown). Overall, DJF has the highest average hit rate, followed by SON and JJA, and then MAM, with the lowest average hit rate. The average hit rates calculated for all stations and seasons for uncalibrated and calibrated data are 40% and 29% respectively.

We also assess forecast accuracy using the RMSE of the ensemble mean forecasts over the tropical western Pacific domain and at the 14 stations. The RMSE is normalized by the observed standard deviation so that NRMSE < 1 is indicative of a skillful forecast. Averaged over the entire tropical western Pacific domain and using all start months, the NRMSEs are 1.08 and 0.86 for the uncalibrated and calibrated data, respectively, indicating that calibration resulted in a more skillful forecast over the region as a whole. A summary of the NRMSEs for ensemble forecasts of both uncalibrated and calibrated data at the station locations is provided in Table 4. The benefit of calibration is clearly seen, with a dramatic reduction in NRMSEs for the calibrated forecasts. The average NRMSE values for all stations and seasons are 1.31 and 0.89 for uncalibrated and calibrated data, respectively. Therefore, the IOV calibration has produced a reduction in the NRMSE to less than 1, resulting in a more skillful forecast.

c. POAMA-2 and SCOPIC skill assessment

As mentioned earlier, many of the Pacific countries currently use the statistical software named SCOPIC for seasonal forecasting at a number of stations within each country. The average hit rates for the 14 stations for the combined lower and upper terciles calculated from SCOPIC are similar to POAMA-2 (uncalibrated), with average tercile hit rates for all stations of 46% and 40%, respectively, again if the same period (1982–2006) and lead time (0) are considered. Further assessments are planned between POAMA-2 and SCOPIC in the near future to assess the skill of each seasonal forecast system.

d. Example forecast products

An expected outcome of the PASAP project is the provision of routine forecast products for the Pacific
island countries. Here, we demonstrate using the POAMA-2 hindcast two typical forecast products (probabilistic forecast rainfall at the station locations and the calibrated ensemble mean rainfall anomaly across the western Pacific) that will be available in real time. The first example is the rainfall tercile forecast for DJF 1999 at Tarawa (Fig. 8a) and at the Nadi airport (Fig. 8b). The standardized Niño-3.4 SST index (from Reynolds SST) was $-1.5$, indicating that 1999 was a La Niña year. At Tarawa, the probability of rainfall being in the lower tercile was predicted to be 100% (dark gray bar) and remained the same after calibration (light gray bar). The verifying analysis (black bar) was in the lower tercile, as correctly predicted. Similarly, at the Nadi airport, the probabilities of being in the upper and middle tercile were 97% and 3%, respectively, for the uncalibrated forecast. Calibration reduced these probabilities to 67% in the upper tercile and 33% in the middle tercile. The verifying analysis was in the upper tercile (green bar) and therefore the forecast scored correctly.

The second example is a forecast of the calibrated ensemble mean rainfall anomaly in the Pacific region for DJF 1999 (Fig. 9b). This forecast is verified against CMAP (Fig. 9a). The strong La Niña signal evident in the observed rainfall is well represented in this forecast, with the pattern and magnitude of the forecast anomaly agreeing well with the verification (acknowledging that the ensemble forecast does not account for forecast spread/uncertainty). Rainfall is suppressed in the ITCZ and the SPCZ has shifted westward. The locations of Tarawa and the Nadi airport discussed above are shown to highlight the opposite rainfall anomalies at these stations at this time. These two example forecast products and additional forecast products are made available
to the partner Pacific island nations through a subscription to a Web site (described below).

5. Discussion and conclusions

We have demonstrated the feasibility of making seasonal climate predictions for the tropical western Pacific using the POAMA-2 coupled model forecast system. Because of the strong impacts of El Niño in the region and the good ability to predict El Niño and its impacts in the Pacific, seasonal forecasts for regional rainfall in this Pacific region are extremely good. In fact, one could argue that this Pacific region has the highest seasonal climate predictability of anywhere on the planet because of the direct impacts of ENSO. Due to the success of these regional forecasts using the POAMA-2 coupled model, the forecasts for the partner Pacific island nations became routinely available in September 2011 and are delivered via a subscription Web site (http://poama.bom.gov.au/experimental/pasap/). Forecast products include probabilistic tercile rainfall 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 to the development of skillful predictions with the model and the timely provision of the forecasts through the Web pages is in-country training for understanding and using the forecasts. This 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.

Downscaling to the station level using dynamical models is an issue, and model grid sizes ~ 200 km cannot possibly replicate important subscale factors such as orography and the local effects on wind speed, temperature, and rainfall. However, we have shown POAMA-2 is skillful in most regions and seasons in the Pacific region. A number of studies have already shown the benefit of using dynamical downscaling methods in the Pacific region to improve rainfall and temperature forecasts, such as in Fiji and Australia (Lal et al. 2007; McGregor et al. 2008; Katzfey et al. 2011). The implementation of these techniques into future seasonal forecasting schemes is a plausible objective that has yet to be realized. In the longer term, increased resolution of the dynamical seasonal forecasts models should overcome some of the limitations of predicting regional climate variations with POAMA-2 and will also be able to account for anthropogenic factors that may influence rainfall and temperature.

Based on the success of this initial project, a number of ongoing projects have been undertaken. These include exploration of predicting extreme SST events in the Pacific that may, for instance, be related to episodes of coral bleaching. Prediction of sea level, which is also strongly modulated by El Niño and La Niña and has large impacts on the daily lives of many populations throughout the Pacific, is also being developed. Seasonal prediction of tropical cyclones across the western Pacific is also being investigated. A detailed study is under way to compare the skill of seasonal forecasts from POAMA-2 and the Seasonal Climate Outlooks for Pacific island Countries (SCOPIC) statistical model in the Pacific region. Progress on these projects will be reported in due course. In the medium term, POAMA-2 will be succeeded by POAMA-3, which will be based on the Australian Community Climate and Earth-System Simulator (ACCESS).

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