Intraseasonal Forecasting of the 2009 Summer and Winter Australian Heat Waves Using POAMA

D. HUDSON, A. G. MARSHALL, AND O. ALVES
Centre for Australian Weather and Climate Research, Melbourne, Victoria, Australia

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ABSTRACT

Extreme heat waves occurred over much of southern and eastern Australia during the summer (27 January–8 February) and winter (14–31 August) of 2009. The summer heat wave resulted in many temperature records across southeastern Australia, as well as devastating bushfires in Victoria that caused losses of life and property. The winter heat wave primarily affected subtropical areas of eastern Australia and produced major disruptions to agricultural industries. In this study the ability of the Bureau of Meteorology’s dynamical seasonal prediction model, the Predictive Ocean Atmosphere Model for Australia (POAMA), to forecast fortnightly means for two periods corresponding to the heat waves (25 January–7 February and 15–28 August, respectively) is assessed. The forecasts are based on 10-member daily lagged-ensemble forecasts, initialized up to 30 days prior to the verification date. Ensemble mean and probabilistic forecasts are assessed. The paper forms part of a larger study investigating the use of POAMA for filling the current prediction capability gap between weather forecasts and seasonal outlooks for Australia. The most successful forecasts were initialized up to 2 weeks prior to the verification date, when POAMA demonstrated the ability to predict widespread warming over southeastern Australia for the summer event and over central and eastern Australia for the winter event. At these lead times, the ensemble mean forecast captured the midtropospheric subtropical anticyclonic anomaly over Australia that characterized both heat waves. The magnitude of the peak daytime warming in the ensemble mean forecast was, however, underpredicted, more so for the summer heat wave, and maximum warming occurred farther east than observed in both events. POAMA was able to predict temperature anomalies similar to those observed over the southeast in the ensemble initialized 0–9 days prior to the forecast verification date for the winter heat wave, thus being of potential benefit to the grain-producing regions of southeastern Australia.

1. Introduction

Heat waves occurred over much of southern and eastern Australia during the summer and winter seasons of 2009. The summer heat wave (27 January–8 February) was notable for both its intensity and duration, consisting of two major episodes of exceptionally high temperatures, from 27 to 31 January (27 January shown in Fig. 1a) and 6 to 8 February (7 February shown in Fig. 1b), that primarily affected northern and eastern Tasmania, most of Victoria and adjacent border areas of New South Wales, and southern South Australia (National Climate Centre 2009b). The heat wave peaked on 7 February (Fig. 1b) when many all-time daily minimum and maximum temperature records were set across the states of Victoria and South Australia. For example, Hopetoun (Victoria) reached a state record maximum temperature of 48.8°C [also believed to be the highest temperature ever recorded in the world so far south; National Climate Centre (2009b)], Renmark set a February record of 48.2°C for South Australia, and Melbourne’s maximum of 46.4°C well exceeded its previous all-time record set on 13 January 1939 (known as Black Friday). The beginning of several devastating bushfires in Victoria were marked on 7 February 2009 (known as Black Saturday), which resulted in losses of life and property; the weather conditions conducive to fire on that day were more extreme than those experienced during the Ash Wednesday fires of 16 February 1983 (Victorian Bushfires Royal Commission 2010).

The summer heat wave began with a high pressure system anchored over the Tasman Sea (Fig. 1c) and an intense tropical low off the northwest coast of Western
Australia in association with an active monsoon trough (not shown). This provided ideal conditions for a large-scale mass of hot air of tropical origin to form across the southern half of Australia (National Climate Centre 2009b). Trapped by the Tasman Sea high pressure system, the warm air was eventually pushed toward the southeast corner of the continent as a cold front moved over southern Western Australia, with the hot upper-level air mixed down to the surface in the associated turbulent winds (Fig. 1d). Although a weak cold front brought some relief to coastal areas between 31 January and 5 February, inland areas remained extremely hot until the Tasman Sea high finally moved away on 8 February. The 500–1000-hPa geopotential height thickness anomalies in Figs. 1c and 1d show the depth of warm air that developed over southern and southeastern Australia, with thickness anomalies in excess of 160 m occurring over most of Victoria at 1100 Australian Eastern Daylight Time (0000 UTC) on Black Saturday (Fig. 1d) prior to the extreme warming (Fig. 1b). These thickness anomalies were associated with a midtropospheric-level (500 hPa) anticyclone, dominating over southern and southeastern Australia.

The 2009 winter heat wave (14–31 August; see Fig. 2a) consisted of three episodes of extreme heat that primarily affected subtropical areas of Queensland, the southern Northern Territory, and northern New South Wales. The first of these occurred from 14 to 16 August and was the least extreme of the three episodes. The second hot spell occurred from 21 to 25 August, during which time many record high maximum and minimum temperatures were set, with the most dramatic extremes occurring on 23 and 24 August. For example, New South Wales set a state record high temperature for August of 37.8°C at Mungindi, and Brisbane set a new August record high of 35.4°C, both of which occurred on 24 August. New South Wales then set a state record high minimum temperature for August of 23.3°C at Lismore on the 25th of the month. The third record-breaking period of extremes occurred over 29–31 August and
primarily affected Queensland and the Northern Territory, with Queensland setting a state record high temperature for August when it reached 38.5°C at Bedourie on the 29th. The heat wave caused major disruptions to the agricultural industry, with many grain crops across central and southern Queensland failing from water stress due to the extreme weather in combination with poor winter rainfall (information online at http://www.agforceqld.org.au). Overall, August 2009 was Australia’s warmest on record, and the June–August period also set a new record for the highest average winter maximum temperatures over Australia (National Climate Centre 2009a).

The synoptic conditions were similar throughout all three major episodes of the winter heat wave; very warm and gusty north-to-northwesterly winds occurred over southern inland Queensland ahead of a surface trough and in association with coastal ridging from high pressure systems over the Coral and Tasman Seas (Bureau of Meteorology 2010) (Figs. 2b–d). The heat wave was characterized by a lack of cold outbreaks that normally bring air from the Southern Ocean to the Australian continent, with the strong northwesterlies further restricting the flow of cool, moist sea-breeze air to coastal locations. The heat wave was associated with an anticyclone over eastern Australia at the 500-hPa level and geopotential height (500–1000 hPa) thickness anomalies of up to 200 m (Figs. 2b–d), indicating that the episode was characterized by a deep layer of warm air that formed over eastern Australia (with large-scale subsidence of heat from aloft), rather than shallow advection of warm air from the tropics. The long-term societal benefits of predicting heat extremes beyond the synoptic (up to 1 week) time scale

FIG. 2. Maximum temperature anomalies (°C) for (a) 14–31 Aug 2009 (contour interval is 1°C) and mean sea level pressure (hPa, contours) and anomalous 500–1000-hPa geopotential height thickness (m, shading) for (b) 16, (c) 24, and (d) 29 Aug 2009 (mean sea level pressure contour interval is 2 hPa and thickness anomaly shading interval is 40 m). See section 2b for dataset details.
cannot be overstated. For example, prediction of heat extremes during summer may assist in timely bushfire warnings for high-risk communities, while prediction of winter extremes allows for grain farmers to manage the scheduling of planting, harvesting, maintenance, and fertilizer applications throughout the growing season. Availability of accurate forecasts on time scales beyond 1 week and shorter than a season will add to existing climate information and therefore assist in the development of better risk management strategies. Currently, at the Bureau of Meteorology (BoM), dynamical seasonal predictions are routinely produced with the Predictive Ocean Atmosphere Model for Australia (POAMA; Alves et al. 2003), which is a coupled ocean–atmosphere climate model and data assimilation system. Nine-month forecasts are produced every day. Recent work has begun to explore the potential for using POAMA for intraseasonal, or multiweek, forecasting for Australia (Hudson et al. 2011a; Marshall et al. 2011; Rashid et al. 2011). This would fill the current prediction capability gap between weather forecasts and seasonal outlooks for Australia.

In this study we assess the performance of POAMA in predicting both the summer and winter heat waves of 2009 at intraseasonal time scales, with a focus on fortnightly mean (2-week average) forecasts of circulation anomalies and daily maximum (Tmax) and minimum temperature (Tmin) anomalies over Australia for lead times of up to 30 days. Section 2 describes in more detail the POAMA forecast system, the forecast datasets, and the methodology. Section 3 examines the prediction of the summer and winter heat waves in POAMA, while section 4 presents a summary of the results with concluding remarks.

2. POAMA model, datasets, and methodology

a. POAMA model

POAMA version 1.5 uses the Bureau of Meteorology unified atmospheric model version 3 (BAM3; Colman et al. 2005; Wang et al. 2005; Zhong et al. 2006) and the Australian Community Ocean Model version 2 (ACOM2; Schiller et al. 1997; Schiller et al. 2002; Oke et al. 2005). BAM3 is a spectral transform model with triangular truncation 47 (T47; approximately 250-km resolution) and 17 vertical sigma levels (L17), and includes a mass flux convection scheme (Tiedtke 1989) with a CAPE relaxation closure (Nordeng 1994). The land surface component of BAM3 is a simple bucket model for soil moisture with a field capacity of 150 mm (Manabe and Holloway 1975) and has three active soil layers for temperature. ACOM2 is based on the Geophysical Fluid Dynamics Laboratory’s Modular Ocean Model version 2 (MOM2) and has a zonal resolution of 2° longitude and a telescoping meridional resolution of 0.5° equatorward of 8° latitude, gradually increasing to 1.5° near the poles. ACOM2 has 25 vertical levels, with 12 levels in the top 185 m and a maximum depth of 5 km. BAM3 and ACOM2 are coupled using the Ocean Atmosphere Sea Ice Soil (OASIS) coupling software (Valcke et al. 2000) with a coupling frequency of 3 h. Although no flux correction is applied, bias in the equatorial Pacific cold tongue is somewhat alleviated by using surface ocean currents in surface stress calculations that are applied to the ocean model (Zhao et al. 2010).

b. Data assimilation for initialization

Forecasts from POAMA are initialized from observed atmospheric and oceanic states. The ocean initial conditions are obtained from the ocean data assimilation scheme that is based on the optimum interpolation (OI) technique of Smith et al. (1991). Only temperature observations in the top 500 m are assimilated and SST is strongly relaxed to the observed analysis (Reynolds et al. 2002). The OI scheme is used to correct the ocean model background field every 3 days using a 3-day observation window. Corrections to ocean currents are calculated by applying the geostrophic relation to the temperature increments, in a similar way to the method described by Burgers et al. (2002). The atmosphere and land initial conditions are provided by the Atmosphere–Land Initialisation (ALI) scheme (Hudson et al. 2011b). ALI creates a set of atmosphere and land initial states by nudging zonal and meridional winds, temperatures, and humidity from the atmosphere model of POAMA (run prior to hindcasts or forecasts being made and forced with observed SSTs) toward an observationally based analysis. ALI nudges to the analyses from the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; Uppala et al. 2005) for the period 1980–August 2002, and to the BoM’s operational global numerical weather prediction (NWP) analysis thereafter. The scheme also generates land surface initial conditions that are in balance with the atmospheric conditions.

c. Hindcast generation

A hindcast dataset (retrospective forecasts) is required for skill assessment of the forecast system and for calibration of the forecasts. The hindcast dataset is a 10-member ensemble starting on the first day of every month for 1980 to 2006 (e.g., Hudson et al. 2011a; Lim et al. 2009; Wang et al. 2008; Zhao and Hendon 2009). The ensemble is generated through perturbing the atmospheric initial conditions by successively initializing...
each member with the atmospheric analysis 6 h earlier (i.e., the 10th member was initialized 2.25 days earlier than the 1st member). The ocean initial conditions are from the analyses provided by the ocean data assimilation scheme (section 2b) for the first of each month and are the same for each ensemble member.

Forecast skill is assessed using anomalies from the hindcast climatology. These anomalies are created by producing a lead-time-dependent ensemble mean climatology from the hindcasts. This climatology is a function of both start month and lead time, and thus a first-order linear correction for model mean bias is made (e.g., Stockdale 1997).

Model performance can be gauged by assessing the skill in predicting events in this hindcast dataset. This has been done to some extent by Hudson et al. (2011a) and is not the focus of the current paper. However, we do include an assessment of the correlation skill in predicting Tmax and Tmin anomalies in this hindcast data (1980–2006) in the January–March and July–September forecast start months, respectively, since these periods are relevant to the case studies. Correlation measures the linear correspondence between the ensemble mean forecast anomalies and observed.

d. Real-time forecasts

In the POAMA real-time system, a 9-month forecast is produced each day starting from the latest assimilated initial conditions. Uncertainties in the initial conditions are therefore taken into account using a daily lagged approach. In this study a 10-member ensemble is generated from forecasts that include the one starting on the forecast issue date and those from the initial conditions for the previous 9 days. For the summer heat wave, our verification fortnight is the period from 25 January to 7 February 2009, and for the winter heat wave it covers 15–28 August 2009. Our definition of forecast lead time is based on the days included in the ensemble relative to the beginning of the verification period. For example, for the summer heat wave we define a “0–9-day lead” as the ensemble with the most recent member having a start date of 25 January and the newest member initialized on 16 January. Similarly, a 7–16-day lead is defined as the ensemble with the most recent member initialized on 18 January and the earliest member initialized on 9 January (and so on). It is important to note that the daily lagged approach, although acceptable for the seasonal forecasting for which the system was designed, is not optimal for intraseasonal forecasting. The large lags in the initial conditions of the ensemble members are likely to have a negative impact on the skill of the forecasts. The next version of POAMA (version 2) will have a specific intraseasonal component, where the ensemble forecast will be generated using perturbed initial conditions. It is also clear that there is a difference between the real-time and hindcast ensemble generation techniques in POAMA-1.5. This is not ideal, since the real-time forecast anomalies are created using the hindcast climatology (see the following section). The real-time forecast system has not been running for a sufficiently long enough period of time to use the real-time system climatology. We will be addressing this issue in the next version of POAMA (version 2), such that the ensemble generation method will be consistent between the hindcast and real-time systems.

e. Verification of the real-time forecasts

For the verification, we compare the ensemble mean forecast anomalies of Tmax, Tmin, mean sea level pressure, and 500-hPa geopotential height to their respective observed values. The anomalies are calculated using the hindcast climatology. Since this climatology is only based on forecasts from the first of every month, linear interpolation is used to obtain the forecast climatology for the desired real-time forecast start date. In addition, we include probabilistic verification by examining the percentage of ensemble members forecasting Tmax–Tmin anomalies above the upper tercile (both heat waves were associated with temperatures in the upper tercile). The tercile threshold is not a particularly extreme measure of the heat experienced, but given our limited ensemble size (10 members), we felt that a more extreme threshold would not be reliably resolved. The tercile thresholds are obtained from the hindcast dataset using anomaly data from all 10 ensemble members of the hindcast set, and for both the model and the observed results we use all years (1980–2006). Linear interpolation is used to obtain the thresholds for the desired real-time forecast start date.

Probabilistic verification is also obtained with a probability density function (PDF) analysis. Here, we examine the distribution of Tmax and Tmin anomalies, averaged over the verification fortnight and geographical regions of interest, for the model hindcast and observed datasets (1980–2006), and for the case study 0–9-day lead-time ensemble. The geographical regions of interest are

(i) “southern Australia” (Fig. 11, top left),
(ii) “southeastern Australia” (Fig. 11, top right), and
(iii) “eastern Australia” (Fig. 16 top left).

This analysis tests the effectiveness of the 0–9-day lead-time ensemble forecast relative to the observed outcome as well as both the observed and modeled climatologies.
f. Observed data

We use the BoM National Climate Centre gridded daily analyses of Tmax and Tmin for the observed data. These gridded analyses are produced from quality-controlled station data by the application of a three-pass Barnes successive-correction analysis (Mills et al. 1997). They are available on a 0.25° grid, but for this study have been averaged onto the POAMA model’s T47 grid. For mean sea level pressure and geopotential height we use data from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis 1 dataset (Kalnay et al. 1996), which uses a “frozen” data assimilation–forecast system to provide global, quality-controlled datasets on a 2.5° × 2.5° latitude–longitude global grid. Anomalies are calculated for Tmax, Tmin, mean sea level pressure, and 500-hPa geopotential height using the respective observed climatologies for the period 1980–2006.

3. Heat wave prediction in POAMA

a. Hindcast skill

Hudson et al. (2011a) document the skill of POAMA in predicting the first and second fortnight (average of days 1–14 and 15–28, respectively) of the forecast for precipitation and temperature anomalies over Australia. They found that the skill of forecasting maximum temperature in the second fortnight is focused over eastern and southeastern Australia, particularly during the austral spring (September–November, SON). Over these regions during spring, the forecast of the second fortnight from the model performs generally better than forecasts of persistence of observed, better than persistence of the forecast of the first fortnight (average days 1–14), and better than climatology. The model generally shows less skill in forecasting minimum temperature in the second fortnight compared to maximum temperature. Here, we provide an indication of the skill of POAMA during and around the months corresponding to the summer and winter heat wave case studies, respectively.

Figure 3 shows the correlation skill for minimum temperature anomalies in the first and second fortnights from POAMA hindcasts starting on the first of the month for January–March 1980–2006 (i.e., n = 81). As a baseline of comparison, the skill of persistence of observed conditions is also shown (Figs. 3c and 3d). A persistence forecast is calculated by persisting the average of the observed fortnight immediately prior to the forecast start date. For the first fortnight, POAMA’s skill is generally higher than that obtained from persistence of observed and is highest over southern Australia. The degradation of skill in the second fortnight is clear. Correlations in the second fortnight are highest over the northeast (Fig. 3b) and in this region they are higher than those obtained for persistence (Fig. 3d).

The correlation skill for the maximum temperature anomalies in January–March months is shown in Fig. 4. POAMA’s skill in the first fortnight is highest over eastern, southeastern, and parts of Western Australia. The largest gains in correlation skill over persistence of observed are over southeastern and southern Australia (Figs. 4a and 4c). In the second fortnight POAMA’s skill is focused over southern-central, northeastern, and southeastern Australia (Fig. 4b), and beats persistence of observed in these regions (Fig. 4d).

For the period corresponding to the winter heat wave case study, the skill of forecasting temperature in the July–September forecast start months (1980–2006, n = 81) is assessed and the correlation results for Tmin anomalies are shown in Fig. 5. Skill is highest over northern and parts of eastern Australia in both the first and second fortnights (Figs. 5a and 5b). In the second fortnight, however, the skill from persistence of observed is higher than that obtained from POAMA over central Australia and much of northwestern Australia. In particular, correlations over central Australia are significantly different from zero for persistence of observed (Fig. 5d) but not for POAMA (Fig. 5b).

Predictions of Tmax anomalies in July–September are generally more skillful than those for Tmin (Fig. 6). In contrast to Tmin, POAMA’s skill for Tmax is focused more over the southern half of Australia. In the second fortnight there is a relatively high level of correlation skill over southeastern Australia, particularly over New South Wales, and this skill exceeds that obtained from persistence of observed (Figs. 6b and 6d).

b. Summer heat wave: January–February 2009

We now assess the forecast minimum and maximum temperatures during the fortnight of 25 January–7 February for the summer heat wave of 2009. Figure 7 shows minimum temperature anomalies from observed (Fig. 7a), persistence of observed (Fig. 7b; average of observed fortnight 11–24 January), and from the POAMA ensemble means at lead times of 0–9 days (Fig. 7c; forecast start dates range from 16 to 25 January), 7–16 days (Fig. 7d; forecast start dates range from 9 to 18 January), 14–23 days (Fig. 7e; forecast start dates range from 2 to 11 January), and 21–30 days (Fig. 7f; forecast start dates range from 26 December to 4 January). Observed nighttime temperature anomalies in excess of 5°C occur over much of the southern and southeastern Australian regions. POAMA ensemble mean forecasts at 0–9- and 7–16-day lead times clearly outperform the persistence forecast over these regions, with the model Tmin anomalies...
being in better agreement with those observed. The 14–
23- and 21–30-day lead-time ensemble forecasts, however, 
appear to be fairly similar to the persistence forecast; 
at these longer lead times the Tmin predictions from 
POAMA are in better agreement with observations 
along much of the southern coast (particularly from 
Adelaide to Melbourne where the persistence forecast 
anomalies are negative), but are slightly worse than 
the persistence forecast elsewhere over southern and 
southeastern Australia. This is consistent with the model 
result of Fig. 3; at this time of year there is more skill in 
the first fortnight than that obtained from the persist-
ence forecast, and degradation of skill in the second 
fortnight.

As expected, the prediction of Tmin anomalies over 
southeastern Australia improves closer to the verifica-
tion period (i.e., with decreasing lead time). Even at the 
shortest ensemble lead times, however, the ensemble 
mean forecast underestimates the peak warming by at 
least 50%; nighttime ensemble mean temperature anom-
aliies peak spatially at about 2°C for the 7–16-day lead 
time ensemble and at about 2.5°C for the 0–9-day lead 
time ensemble (Fig. 7). Further, peak anomalies emerge over 
eastern Australia in the 7–16-day lead-time ensemble 
forecasts before shifting into the southeastern corner of 
the continent (more in line with those observed) in the 
0–9-day lead time ensemble. These results demonstrate 
the impacts of the initial conditions on both the intensity 
and location of the predicted warming in the lead up to 
the event.

We present a similar analysis for maximum tempera-
ture during the 2009 summer heat wave (Fig. 8). Maxi-
mum observed daytime temperature anomalies also peak 
over the southern and southeastern Australian regions, 
with the largest anomalies observed along the eastern half 
of the southern coastline. Contrary to the skill measures
in Fig. 4, however, POAMA forecasts of Tmax over the southeast do not beat persistence of observed at longer lead times (Figs. 8d–f). This is probably a reflection of the longevity of this extreme event. The 0–9-day lead-time ensemble mean forecast is comparable to the persistence forecast over the southeast (Figs. 8b and 8c). The ensemble mean clearly underestimates the peak observed Tmax anomaly by at least 70%; daytime temperature anomalies peak around 2.5°C at both the 0–9- and 7–16-day forecast leads, compared with observed warming in excess of 8°C (Fig. 8). Qualitatively, predicted Tmax anomalies appear to be similar to the Tmin anomaly forecasts; peak anomalies emerge over eastern Australia in the 7–16-day lead time forecasts before shifting into the southeastern corner of the continent in the 0–9-day lead forecasts.

We relate the temperature forecasts discussed above to the ability of POAMA to predict circulation anomalies associated with the heat wave. A subtropical anticyclonic anomaly at the 500-hPa level is observed during the target fortnight, dominating southern and southeastern Australia (Fig. 9a). The persistence forecast does not capture the strength or position of this mid-tropospheric anticyclonic anomaly (Fig. 9b). In contrast, POAMA’s 0–9-day lead-time ensemble does better than persistence in representing both the spatial pattern and magnitude of the anomaly (Fig. 9c). However, the high pressure anomaly is weaker than observed in both the 0–9- and 7–16-day lead-time ensemble forecasts and is shifted farther east, centered over New Zealand rather than the Tasman Sea. An eastward-shifted, weaker mid-tropospheric high pressure in POAMA compared to observed would result in weaker adiabatic heating from large-scale subsidence and is consistent with the weaker and more localized warming over Australia in the forecasts (Figs. 7 and 8).

At the surface, a negative pressure anomaly was observed over the southern half of the continent (Fig. 10a), indicative of the strong anomalous northwesterly flow advecting heat from northern Australia to the southern and southeastern Australian regions during the heat wave (see also Figs. 1c and 1d). As was found for the 500-hPa
level, the persistence forecast does not reproduce the intensity or location of this broad-scale surface feature, nor do the POAMA forecasts (Fig. 10). Instead, the 0–9- and 7–16-day lead time ensemble forecasts produce a relatively weak negative pressure anomaly that is again shifted farther east than that observed, occurring over much of New South Wales and southern Queensland (Figs. 10c and 10d). The positioning of this low is such that the associated northwesterly anomalous flow on its eastern flank appears to bring warm inland air from the north to eastern Australia for the 7–16-day lead-time forecasts and to southeastern Australia for the 0–9-day lead-time forecasts, consistent with Figs. 7 and 8. Moreover, the negative pressure anomaly in the model appears as more of a regional feature over the southeast, rather than a broad feature spanning the breadth of the continent as is observed (Fig. 10). Thus, the anomalous flow over much of southern Australia tends to be easterly to south-easterly in these model forecasts, in contrast to the observed strong northwesterly anomaly (Fig. 10), and hence the predicted heat wave is restricted to southeastern Australia and appears weaker than that observed.

For the 14–23- and 21–30-day lead-time forecasts, the circulation anomalies over southern Australia (Figs. 9e,f and 10e,f) are consistent with the lack of predicted warming at these lead times (Figs. 7 and 8).

The temperature forecasts shown thus far are created using the ensemble mean, so it may not be too surprising that they underestimate the observed warming. It is therefore informative to consider the probabilistic forecasts that utilize the ensemble information. We have examined the POAMA-predicted probability of maximum temperature falling in the upper tercile for each forecast ensemble, compared with that observed for the fortnight of 25 January–7 February. Much of southeastern Australia experienced maximum temperatures in the upper tercile in this fortnight (not shown). Encouragingly, in the 0–9- and 7–16-day lead-time ensembles, the probabilistic forecast is consistent with observed, indicating forecast probabilities ranging between 60% and 70% over eastern and southeastern Australia (not shown). The spatial patterns of these maximum forecast probabilities are similar to those from the ensemble mean maps (Figs. 8c and 8d).
We examine the ensemble information further within the context of a PDF analysis that places the forecast from the individual ensemble members within the context of the hindcast and observed climatologies and the observed outcome. Figure 11 presents PDFs of fortnightly averaged maximum and minimum temperature anomalies averaged over southern Australia and southeastern Australia for the target fortnight 25 January–7 February. These plots show that the observed temperature anomaly for each region during the 2009 heat wave (vertical dashed line) falls in the positive tail of the temperature distributions for POAMA 9-month hindcasts over the period 1980–2006 (gray bars) and for observations over the same period (black bars). The text at the top of each plot indicates that less than 1% of the POAMA hindcasts exceed the observed Tmin and Tmax values for 2009. We therefore surmise that the extreme temperatures of the 2009 heat wave are “exceptionally unlikely” to occur in the POAMA hindcast climatology [using the parlance of Solomon et al. (2007) for probabilities less than 1%]. Moreover, for this unusual summer heat wave, none of the observations over the 1980–2006 base period exceed that observed for the target fortnight, further highlighting the extreme nature of the event. Temperature distributions for the 0–9-day lead-time ensemble of anomaly forecasts for the heat wave (open bars) are centered near 0°C for the southern Australian region, and near 2°C for the southeastern Australian region, consistent with the ensemble-averaged anomalies shown in Figs. 7 and 8. Within each ensemble, individual forecasts reach a maximum temperature anomaly of 4°C (in all figure panels except Tmin over southern Australia, which peaks at 3°C; open bars), and no individual forecast member in the 0–9-day lead-time ensemble is able to capture the intensity of the 2009 summer heat wave over southern and southeastern Australia. However, with the exception of Tmax for southern Australia, the POAMA forecasts show a shift in the probabilities when compared to the hindcast climatology. This shift indicates an increase in the likelihood of extreme high temperature events (i.e., events in the right tail of the climatological distribution) and may be significant within the context of risk management. For example, risk managers may be more interested in knowing the probability of a rare event...
occurring rather than the most likely outcome. These results highlight the potential use of probabilistic forecasts from POAMA as a tool in quantifying the risk of extreme weather.

c. Winter heat wave: August 2009

Finally, we assess the ability of POAMA to forecast minimum and maximum temperatures during the fortnight of 15–28 August for the winter heat wave of 2009. Figure 12 shows minimum temperature anomalies from observed (Fig. 12a), persistence of observed (Fig. 12b; average of observed fortnight 11–24 January), and from POAMA (10-member ensemble mean) at lead times of (c) 0–9 days (forecast start dates range from 16 to 25 January), (d) 7–16 days (forecast start dates range from 9 to 18 January), (e) 14–23 days (forecast start dates range from 2 to 11 January), and (f) 21–30 days (forecast start dates range from 26 December to 4 January). The contour interval is 0.5°C and grid boxes with anomalies >±0.5°C are shaded.
to 1 August), and 21–30 days (Fig. 12f; forecast start dates range from 16 to 25 July). Observed Tmin anomalies in excess of 5°C occur over central Australia, primarily affecting southwest Queensland, the northernmost reaches of South Australia, and the southern half of the Northern Territory. The POAMA ensemble mean also produces a strong warming signal across central Australia for the 0–9-day lead-time ensemble mean forecasts, but with approximately half of the observed peak magnitude. (Recall that POAMA also underpredicted peak Tmin anomalies by about 50% for the summer heat wave.) The warming around the New South Wales and Victorian coastal areas, however, is similar to that observed, falling within the range 0.5°–2°C. Moreover, predicted Tmin anomalies for the 0–9-day lead ensemble forecast clearly outperform the persistence forecast everywhere over the continent except for the southwest. POAMA therefore produces a reasonable spatial forecast of the Tmin anomaly at lead times up to 9 days. At longer lead times the model ensemble forecasts improve upon the persistence forecast over northwestern Australia and New South Wales only, and the magnitude of the warming is greatly underpredicted over most of the continent. Nonetheless, the spatial characteristics of the predicted Tmin anomalies

FIG. 8. As in Fig. 7, but for maximum temperature anomalies (°C).
FIG. 9. As in Fig. 7, but for 500-hPa geopotential height anomalies (m) over the Southern Hemisphere. The contour interval is 20 m and anomalies greater than ±20 m are shaded.

a) Target observed fortnight 25Jan–7Feb2009
b) Persistence of observed

c) POAMA: 0–9 days lead
d) POAMA: 7–16 days lead

e) POAMA: 14–23 days lead
f) POAMA: 21–30 days lead
again appear reasonable, with peak anomalies in excess of 1°C occurring over central and eastern Australia for the 7–16-day lead-time ensemble. Indeed, POAMA predicts significant nighttime warming over New South Wales and southern Queensland even in the 21–30-day lead-time ensemble.

Figure 13 presents a similar analysis for maximum temperature anomalies during the winter heat wave. Observed Tmax anomalies peak farther east than the observed Tmin anomalies, with the largest daytime warming exceeding 7°C over southern Queensland. POAMA achieves greater success forecasting Tmax anomalies.
anomalies for this event than for the summer heat wave, both in terms of the intensity and the spatial characteristics of the warming. The peak magnitude for the 0–9-day ensemble (>4.5°C) is around 65% of that observed, compared with only 30% of that observed for the summer heat wave. POAMA also predicts anomalous daytime warming across central-eastern Australia at both the 0–9- and 7–16-day leads, agreeing reasonably well with that observed, although the peak anomaly in the ensemble mean is shifted farther east and closer to the coast than that observed. Moreover, the predicted warming over much of southeastern Australia for the 0–9-day lead-time ensemble appears to be similar to that observed. Interestingly, the persistence forecast produces peak anomalies that are centered over southwestern Australia; thus, the model-predicted Tmax anomalies in the 0–9- and 7–16-day lead time ensembles also outperform persistence of observed with respect to the spatial distribution of the warming. For the 14–23- and 21–30-day forecast leads, the maximum predicted warming

FIG. 11. The PDFs of fortnightly averaged (middle) Tmax and (bottom) Tmin anomalies averaged over (left) southern and (right) southeastern Australia for the target fortnight of 25 January–7 February. Plots show observations over the 1980–2006 base period (black bars, $n=27$), POAMA hindcasts over the 1980–2006 base period (gray bars; using the 9-month forecasts, $n=2160$), and 10 POAMA forecasts for the 2009 summer heat wave (open bars, $n=10$) made at daily intervals for lead times 0–9 days (start dates 16–25 Jan 2009). Observed temperature anomalies for 2009 are represented by a vertical dashed line. At the top of each plot is the percentage of 1980–2006 POAMA hindcasts that exceed the 2009 observed value. The PDF for each dataset is normalized by its maximum number of counts per bin. (top) Locations of southern and southeastern Australia.
is displaced farther south over southeastern Australia; as for the summer heat wave, improved prediction of Tmax anomalies closer to the verification period demonstrates the impacts of the initial conditions on both the intensity and location of the warming in the lead up to the event.

We relate the temperature forecasts discussed above to the ability of POAMA to predict circulation anomalies associated with the winter heat wave. As for the summer heat wave, the circulation over Australia during the winter heat wave was dominated by a subtropical high pressure anomaly at the 500-hPa level (Fig. 14a) and a continental-scale negative pressure anomaly at the surface (Fig. 15a) associated with a surface trough (Fig. 2). The strong negative pressure anomalies observed to the south of Australia reflect the preponderance of low pressure systems during each major episode of the heat wave (Figs. 2b–d, 14a, and 15a).
The negative mean sea level pressure anomalies (and strong pressure gradient) observed over Australia (Fig. 15a) are indicative of the anomalous gusty northwesterly flow over Queensland that inhibited the passage of cool air from the Southern Ocean and the Tasman and Coral Seas to the Australian continent. The persistence forecast produces a westward-shifted surface (Fig. 15b) and midtropospheric (Fig. 14b) pressure pattern that is consistent with the westward shift in the maximum temperature anomaly (centered over southwestern Australia; Fig. 13b), relative to that observed. The persistence forecast also does not capture the strong pressure gradient that was observed (Figs. 14b and 15b). The 0–9-day lead-time ensemble does well in capturing the location of the midtropospheric anticyclonic anomaly over eastern Australia, although it is slightly weaker than observed (Fig. 14c). This anomaly is still evident in the 7–16-day lead-time ensemble (Fig. 14d), consistent with the temperature forecasts seen in Figs. 12d and 13d. The 0–9- and 7–16-day lead-time ensembles produce relatively weaker than observed surface negative pressure anomalies, located over southern Australia (stronger in the east), rather than being of a more continental scale (Fig. 15). The model-predicted pressure gradient is also weaker.
FIG. 14. As in Fig. 12, but for 500-hPa geopotential height anomalies (m) over the Southern Hemisphere. The contour interval is 20 m and anomalies greater than ±20 m are shaded.

a) Target observed fortnight 15–28Aug2009
b) Persistence of observed

c) POAMA: 0–9 days lead
d) POAMA: 7–16 days lead

e) POAMA: 14–23 days lead
f) POAMA: 21–30 days lead
than that observed (Fig. 15); thus, weaker than observed surface northwesterly flow in the model forecasts is likely to account in part for the underestimated intensity of the eastern Australian warming at these lead times.

It is interesting to note that on the hemispheric scale, the observed midlatitude circulation for the target fortnight is dominated by a three-wave pattern, with large high pressure anomalies centered southeast of Australia (60°S, 170°W), South America (60°S, 30°W), and South

Fig. 15. As in Fig. 12, but for mean sea level pressure anomalies (hPa). The contour interval is 0.5 hPa and anomalies greater than ±0.5 hPa are shaded.
Africa (55°S, 70°E) (Fig. 14a). Encouragingly, POAMA seems somewhat able to capture this pattern in the 0–9-day lead-time ensemble (Fig. 14c). Of interest is that Argentina also experienced extreme heat toward the end of August and many new daily maximum temperature records were set. For example, Buenos Aires set a record of 34.4°C on 30 August (WMO 2010). These results suggest that the August heat wave in Australia might have been part of a larger hemispheric-scale event, with large-scale forcing perhaps resulting in Rossby wave generation. However, it is beyond the scope of this paper to investigate the nature and source of the forcing and the mechanism for the development of the subtropical midtropospheric anticyclone that dominated Australia.

In terms of the probabilistic prediction of the maximum temperature falling in the upper tercile, POAMA predicted probabilities that exceeded 70% in a northwest-southeast orientation over much of the continent for the 0–9-day lead-time ensemble (not shown), again demonstrating a relatively successful forecast at these lead times, since most of Australia (except for western regions of Western Australia) experienced maximum temperatures in the upper tercile in this fortnight. Probabilities greater than 60% were predicted over much of eastern Australia for the 7–16-day lead-time ensemble, and over southeastern Australia for the 14–23- and 21–30-day lead-time ensembles (not shown). Figure 16 presents PDFs of fortnightly averaged maximum and minimum temperature anomalies averaged over eastern Australia (left column) and southeastern Australia (right column) for the target fortnight 15–28 August. As for the summer heat wave, these plots show that the observed temperature anomalies for each region (vertical dashed line) fall in the positive tail of the temperature distributions for POAMA 9-month hindcasts over the period 1980–2006 (gray bars) and for observations over the same period (black bars). The text at the top of each plot for the southeast (i.e., SEAUST; right column) indicates that 9% and 3% of the POAMA hindcasts exceed the 2009 observed Tmax and Tmin values, respectively (compared with <1% of hindcasts for the summer heat wave; Fig. 11). Thus, over southeastern Australia, the extreme temperatures of the winter heat wave are more likely to occur in the POAMA hindcast climatology than the extremes of the summer heat wave. This is also true for the likelihood of each event in the observed climatology, with around 7% (Tmax) and 3% (Tmin) of the observations over the 1980–2006 base period exceeding the observed values for the target fortnight (as may be inferred from Fig. 16), compared with 0% for the summer heat wave. Over eastern Australia, however, where the winter warming was more extreme than over the southeast, the peak temperatures have a relatively small likelihood of occurring in the POAMA hindcast climatology (<2%). It may come as little surprise, then, that POAMA achieves greater success forecasting temperature anomalies over southeastern Australia than over eastern Australia for the 2009 winter heat wave. We noted earlier that both the predicted nighttime warming over much of southeastern Australia (Fig. 12c) and the predicted daytime warming around southeastern coastal areas (Fig. 13c) appear similar to observed for the 0–9-day lead-time ensemble. This encouraging result is reflected in Fig. 16; temperature distributions for the 0–9-day ensemble over southeastern Australia (right column; open bars) are centered near 3°C for Tmax and 1.5°C for Tmin, similar to the observed values over this region (vertical dashed lines). In contrast, for the eastern Australian region (left column; open bars), only one POAMA forecast in the 10-member ensemble captures the intensity of the observed warming (Tmax ~ 6°C and Tmin ~ 4°C). However, over both regions for Tmax and Tmin, the POAMA forecasts for the 2009 event exhibit a shift in the probabilities compared to the hindcast climatology toward a more extreme event.

4. Summary and conclusions

We have assessed the ability of the POAMA dynamical prediction system to forecast minimum and maximum temperature and circulation anomalies during the fortnight of 25 January–7 February for the 2009 summer heat wave, and during the fortnight of 15–28 August for the 2009 winter heat wave. The circulation over Australia during both heat waves was characterized by a midtropospheric (500-hPa level) subtropical anticyclonic anomaly and a surface negative pressure anomaly.

For the summer heat wave, observed Tmin anomalies in excess of 5°C and Tmax anomalies in excess of 8°C occurred over much of southern and southeastern Australia. POAMA was able to reproduce anomalous warming over southeastern Australia up to 2 weeks prior to the summer heat wave, although the intensity of the warming was underpredicted by up to 70% in the ensemble mean forecast and the location of the peak warming was farther east than that observed. While the observed circulation signal consisted of a negative sea level pressure anomaly spanning the southern half of the continent, the POAMA ensemble mean predicted a relatively weak negative pressure anomaly that appeared as more of a regional feature over southeastern Australia. This gave rise to the prevalence of easterly and southeasterly anomalous flow over much of southern Australia in contrast to the observed strong northwesterly flow, thus restricting the anomalous warming to southeastern Australia with less intensity than that observed. In addition, at the 500-hPa
level, although POAMA’s 0–9-day lead-time ensemble captured the anticyclonic anomaly over Australia, it was weaker than observed and was shifted farther east. However, at this lead time POAMA performed better than the persistence forecast in capturing the anticyclonic anomaly. There was a notable degradation in forecast skill at lead times greater than 2 weeks, consistent with the model showing less skill in the second fortnight (compared with the first fortnight) for POAMA hindcasts starting on the first of the month for January–March over 1980–2006. Our PDF analysis showed that the extreme temperatures of the 2009 summer heat wave were exceptionally unlikely to occur in both the POAMA hindcast climatology and in the observed climatology, thus highlighting the extreme nature of the event.

For the winter heat wave, observed Tmin anomalies in excess of 5°C and Tmax anomalies in excess of 7°C occurred over central and eastern Australia. Despite again underpredicting the peak Tmin anomalies by about 50% for the 0–9-day lead-time ensemble mean, POAMA achieved greater success forecasting the magnitude of Tmax anomalies for this event than for the summer heat wave. While the peak magnitude for the 0–9-day ensemble exceeded 4.5°C for the winter heat wave (underpredicting that observed by around 35%), the predicted warming over much of southeastern Australia at these short leads

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Fig. 16. As in Fig. 11, but for (left) eastern and (right) southeastern Australia for the target fortnight of 15–28 August. Plots show observations over the 1980–2006 base period (black bars, $n = 27$), POAMA hindcasts over the 1980–2006 base period (gray bars; using the 9-month forecasts, $n = 2430$), and 10 POAMA forecasts for the 2009 winter heat wave (open bars, $n = 10$) made at daily intervals for lead times 0–9 days (start dates 6–15 Aug 2009).
was similar to that observed. The spatial distribution of the anomalous warming was also reproduced reasonably well in POAMA’s 0–9- and 7–16-day lead-time ensembles, outperforming the persistence forecast in terms of the pattern of the event. The 0–9-day lead-time ensemble captured the 500-hPa hemispheric circulation reasonably well, including the location of the midtropospheric anticyclonic anomaly over eastern Australia, although it was weaker than observed.

We conclude that the most successful forecasts for the 2009 summer and winter heat waves were made up to 2 weeks prior to the beginning of each event, and that there was a notable degradation in forecast skill at longer lead times out to 30 days. Of particular interest is the fact that, although POAMA underpredicted the magnitude of the peak warming in each event, similar to observed warming was forecast over southeastern Australia for the winter heat wave in the 0–9-day lead-time ensemble. Our PDF analyses further showed that the extreme temperatures over the southeast were more likely to occur in the POAMA hindcast climatology for the winter heat wave than for the summer heat wave. For the winter heat wave, the warming was, however, more extreme over eastern Australia than over the southeast, and the peak temperatures over the east had a relatively small likelihood of occurring in the POAMA hindcast climatology. It is therefore of interest to postulate whether POAMA could be expected to achieve higher skill forecasting extreme temperatures for a winter heat wave concentrated over southeastern Australia.

The 0–9-day lead-time ensemble forecast can only be issued on day 0 (i.e., 0-day lead time); therefore, it is of interest to know how POAMA forecasts compare to NWP forecasts, even though a fortnight forecast is still beyond the range of a weather forecast. For example, it is not clear if a POAMA fortnight forecast is better or worse in general than a persisted NWP 1-week forecast. It is likely that in the case of a persistent event, such as these heat waves, the weather forecast could be more skillful than POAMA, because NWP initialization of the atmospheric model is better, NWP models are run at considerably higher resolutions than POAMA and there is no lagged ensemble in NWP (i.e., use of “old” initial conditions). A comparison of the POAMA forecasts with NWP forecasts is beyond the scope of this paper, but is planned for future versions of POAMA.

This study has been conducted with POAMA version 1.5, which was not designed for the purpose of intra-seasonal forecasting and has deficiencies in this regard. The daily lagged ensemble of the real-time system, in particular, is not optimal for short-term forecasts. Such large lags in the atmospheric initial conditions of the ensemble members are likely to impact negatively on the skill. The next version of POAMA (version 2) will have a specific intraseasonal component, including a real-time system that does not incorporate a lagged ensemble approach. Instead, an ensemble forecast will be generated once per week using perturbed initial conditions. Of course, an even better approach would be to generate an ensemble more frequently than once per week, providing more continuous forecast updates and more flexibility with the forecast issue date, but present computing resources do not permit this. Enhancements to the ensemble generation and initialization strategy for POAMA-2 are expected to lead to further improvements in forecast skill. Despite the deficiencies of the current system, POAMA has demonstrated some skill in predicting the 2009 heat waves at lead times greater than a week. This is particularly true for the temperature anomalies over the southeast in the 0–9-day lead ensemble for the winter heat wave, which is thus of potential benefit to the grain-producing regions of southeastern Australia.

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REFERENCES


National Climate Centre, 2009a: Exceptional winter heat over large parts of Australia. Bureau of Meteorology Special Climate Statement 18, Melbourne, VIC, Australia, 13 pp.


