Why are Temperature Forecasts from the Australian Digital Forecast Database Poorer on Summer Afternoons?

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Temperature forecast grids from the Australian Digital Forecast Database have been routinely verified since 2013. It was noted that forecast accuracy, determined using root mean square error (RMSE), tends to be poorer for summer afternoon forecasts for each Australian state. Temperature forecast grids for Western Australia were examined to investigate possible reasons behind the reduced accuracy. A suspected flaw in the verification process was confirmed and was found to slightly increase RMSE. Increases in summer afternoon forecast errors associated with coastal sea breezes and rainfall together with systematic bias were also identified as contributory factors to the increased RMSE. In view of these findings, a number of refinements to the verification process are proposed with the aim of improving future forecast accuracy.

Introduction

The Next Generation Forecast and Warning System, NexGenFWS, is an initiative to modernise forecast operations at the Bureau of Meteorology (BoM). A key component of the NexGenFWS is the Australian Digital Forecast Database (ADFD), which provides a nationally consistent set of official forecasts grids (BoM 2015) issued twice a day with nominal base times of 00UTC and 12UTC. A progressive rollout of NexGenFWS began in 2008 and was completed in 2014 (BoM 2014).

The NexGenFWS allows the visualisation of a variety of gridded and site-based forecast guidance sources that include numerical weather prediction (NWP) model output, the BoM's consensus forecasts, and observations. Forecasters can inspect, select and blend guidance sources via an interactive graphical user interface. The interface also allows forecasters to apply their own edits to the resulting grids using a variety of tools. The end product of this process is the ADFD grids. ADFD forecasts are issued as sets of grids at hourly intervals, typically out to 168hrs. Figure 1 shows an example of a 00UTC 30hr surface temperature forecast grid (hereafter referred to as a 30hr grid) issued on December 4th 2013.

The range of guidance sources available in the NexGenFWS means that there is no single model driving all ADFD forecast grids. That said, the BoM's gridded Operational Consensus Forecast (OCF) guidance often provides the basis for ADFD surface temperature grids. This system produces weighted average forecasts of gridded meteorological fields from an ensemble of bias-corrected NWP models run locally and from overseas centres (BoM 2012). OCF temperature grids are down-scaled to a 2.5′×2.5′ (approximately 5km×5km) grid spacing and then temporally interpolated to hourly frequency (BoM 2008). Upon ingest into the NexGenFWS OCF grids are bilinearly interpolated to the ADFD grid and a basic topographic adjustment is also applied to the resulting temperatures based on the standard adiabatic lapse rate multiplied by the height difference between the topography that the OCF is based on (also ingested into the NexGenFWS and bilinearly interpolated) and the NexGenFWS's own topography grid.

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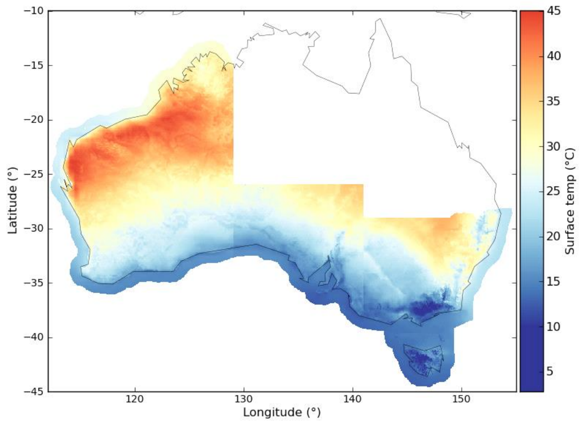
Figure 1 ADFD 30hr surface temperature forecast grid from the Dec 4th 2013 00z issue. The grid is a composite of state grids and has a resolution of 0.05° x ~0.06°. As of late 2013, Queensland and the Northern Territory were not part of the ADFD. This grid is valid for December 5th 06UTC which corresponds to local times from 2pm in the west to 5pm in eastern states.



The ingested OCF grids represent one possible starting point for forecasters to create ADFD surface temperature grids. A second option, likely the most commonly used (M. Foley, pers. comm.), involves an additional guidance source, site OCF (Woodcock and Engel, 2005), which is the site-based counterpart to the gridded OCF system. In this option maximum and minimum surface temperature grids are derived by determining maxima/minima from the gridded OCF hourly grids. These two new grids are then adjusted to match maxima and minima from the site OCF system at grid points which correspond to the observation sites for which the site OCF system produces forecasts. The adjustments to the grids are spread in space around site OCF locations. These steps are automated. Forecasters may then manually apply a 'rescaling' tool to adjust the hourly OCF surface temperature grids to allow for the changes made to the maxima and minima. A third option available to forecasters is simply the use of NWP model output grids. These grids also undergo bilinear interpolation to the ADFD grid and topographic correction. Factors such as differing regional forecasting policy between the Australian states, forecaster preference, and the weather regime at the time may well influence which of these options are employed on any given day. A further complexity is the capability for forecasters to apply their own edits to the final product.

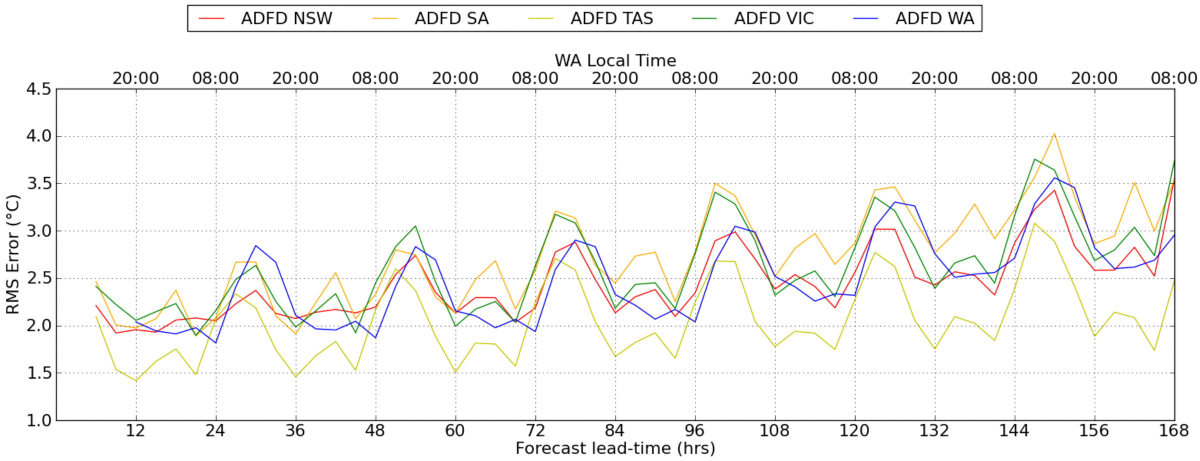
The progression from NWP grids, to OCF grids, to ADFD grids is sometimes referred to as a 'value chain' of gridded products at the BoM. Thus, verification of the ADFD grids is of considerable interest to provide an objective measure of forecast quality along this chain. (Projects to investigate other elements of the value chain are either anticipated or already underway.) Furthermore ADFD grids are also used to generate downstream products such as text forecasts and map displays (BoM 2014) reinforcing the need for verification.

To meet this need a routine verification process for ADFD state and national forecast grids was established in the Bureau National Operations Centre, formerly the National Meteorological and Oceanographic Centre. This verification process became operational in November 2013 and is currently carried out on three surface parameters: temperature, dew point temperature and wind speed. These parameters are verified daily in near real time against observations from automatic weather stations. Nearest-neighbour sampling was used to match grid points to observation locations (experimenting with bilinear interpolation led to near identical results to one decimal place).

The verification metrics calculated are bias and root mean square error (RMSE) and are averaged over the set of observation locations available in each of the following states: New South Wales, South Australia, Tasmania, Victoria and Western Australia (WA). The grids for Victoria and Tasmania have a resolution of 0.02°x~0.03°. All other grids have a resolution of 0.05°x~0.06°. Queensland and the Northern Territory are not yet verified. In the case of surface temperature, no height correction for the observation locations is carried out as part of the verification process. The reason for this is the absence of an appropriate ADFD topography grid (I. Senior, pers. comm.). However, a manual exercise to investigate the effect of height corrections in this study found no change to the results to one decimal place.

Following commencement of the routine ADFD verification process, unexpectedly large RMSEs were noted for afternoon temperature forecast grids (T. Hart, pers. comm.). This is illustrated in Figure 2 which shows the December 2013 mean of the daily RMSEs for 00UTC ADFD temperature forecast grids, for forecast lead times out to 168hrs. The five Australian states verified as of December 2013 are represented by different coloured lines. All states, to some extent, exhibit a 'spike' in RMSE for ~30hr grids and for grids at subsequent 24hr intervals. These forecast lead times correspond to local valid times between 2 and 5 pm. The afternoon RMSE spike is the emphasis of much of the discussion that follows.

Figure 2 December 2013 mean of daily RMSE for ADFD temperature forecast grids versus forecast lead-time. Different coloured lines represent different Australian states. Grids have a nominal 00UTC base-time. Local WA valid time is also shown along the top of the plot (for South Australia add two-and-a-half hours, for other states add three hours).



Characterising the RMSE Spike

The first RMSE spike in Figure 2, for ~30hr grids, is most pronounced for WA. For this reason, WA ADFD 00UTC issue grids were chosen to investigate possible causes of this feature. Figure 3 is a reproduction of the averaged December 2013 RMSEs for WA from Figure 2 but also includes WA RMSEs averaged for June 2013. For December, the mean RMSE for 24hr grids (valid at 8am) is 1.8°C. For 30hr grids (valid at 2pm) this increases sharply to 2.8°C then falls, almost as sharply, to 2.1°C for 36hr grids (valid at 8pm). This pattern repeats with an increase in RMSE being observed for each subsequent 24 hour forecast lead-time increment. The June average RMSE for 24hr grids, 1.8°C, is very similar to the December average. However, for the 30hr grids, instead of a sharp increase, the average RMSE actually drops to 1.7°C - around one degree less than in December. At 36hrs, the RMSE increases again to 2°C. Again, this is very similar to the value for December 36hr grids.

For intervening months (not shown) the RMSE of the 24hr grids shows some variation in the range 1.5°C - 1.9°C but no obvious trend. However, for the 30hr grids, from August onwards, a progressive increase is seen for each month up to the aforementioned value of 2.8°C for December. From January 2014 the RMSE begins to fall again. Thus there is a marked seasonal variation in RMSE for 30hr grids (and grids at additional 24hr increments) which, at its summer peak, results in the RMSE spike in Figure 2 and Figure 3.

Figure 3 also shows forecast lead time plots of bias (forecast - observation) for June and December 2013. A diurnal pattern is evident which, like the corresponding RMSE plots, is dominated by a spike for ~30hr grids and at subsequent 24 hourly intervals. The December bias spikes (>1°C) indicate a tendency to over-forecast afternoon temperatures. Minima are observed for 21hr (11pm) grids and at subsequent 24 hourly intervals and show negligible bias for the first few forecast days at least. Bias was also found to exhibit a seasonal variation as shown by the June bias lead time plot where a broadly similar bias pattern was obtained but it was 0.5-1.0°C more negative than for December.

Seasonal variations in verification metrics for ADFD temperature grids are not without precedent. The bar chart in Figure 4 (from the BoM intranet verification portal) shows monthly averages of RMSE for ADFD next day forecasts for maximum/minimum daily temperature. RMSEs are averaged across five locations in WA. It can be seen that there is a qualitative consistency with the June and December RMSEs for the 30hr temperature forecast grids in Figure 3 with maximum temperature forecast RMSEs (strong red bars) larger in summer (~2°C for December) than in winter (~1°C for June).

Quantitative differences between the RMSEs are attributed to the fact that the comparison is between instantaneous temperature in Figure 3 and maximum temperature in Figure 4 and also to differences in how the verification was performed in each case. In addition to the BoM's ADFD grids, forecast lead-time plots of temperature RMSE exhibiting afternoon increases similar to Figure 3 have also previously been reported elsewhere (Shaw et al., 2004, Colorado State University, 2014). No discussion around the nature of the increased afternoon RMSEs was given, however.

Figure 3 RMSE and bias (forecast - observation) for ADFD WA temperature forecast grids for June and December 2013 versus forecast lead-time.

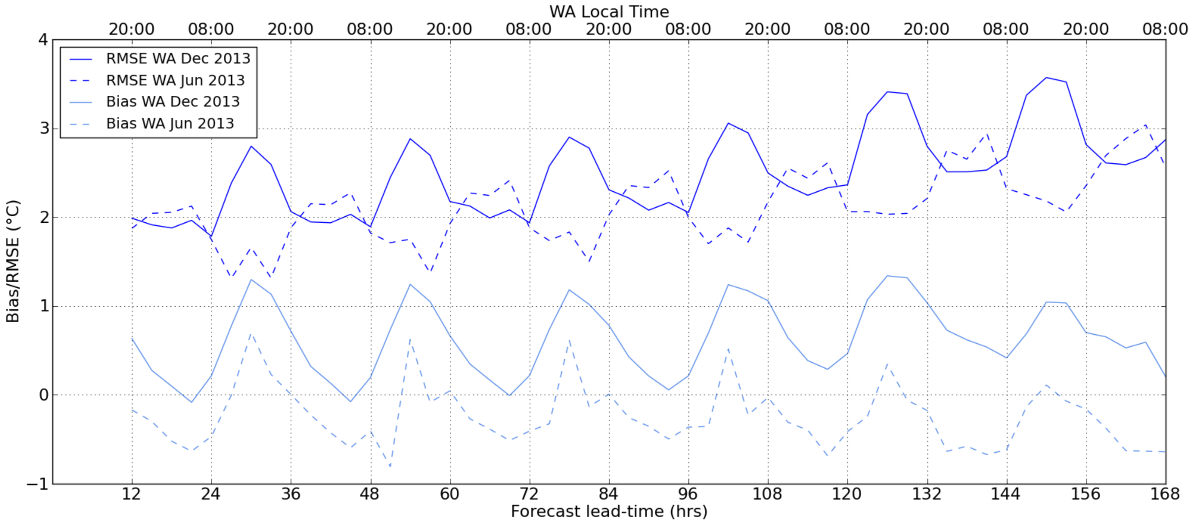
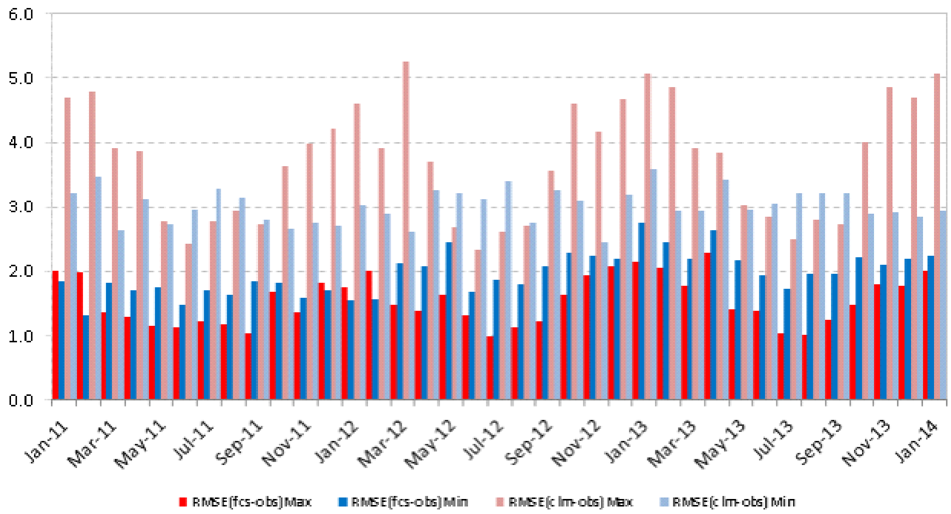


Figure 4 Monthly averages of daily RMSE in ADFD next day forecasts of maximum (strong red) and minimum (strong blue) temperature spatially averaged for five sites in WA: Port Hedland, Geraldton, Perth, Albany and Kalgoorlie. Monthly averages of RMSE for climatological forecasts of max (light red) and min (light blue) temperature for the same five sites are also shown for comparison. The time-series spans 2011 to 2013.



In what follows it will be shown how through stratification of the above verification metrics the RMSE spike associated with December afternoon temperature forecast grids is partly due to a flaw in the current verification process and also an increase in forecast errors. A contribution to the RMSE spike from the aforementioned forecast bias is also described. Finally the seasonal nature of the afternoon spike, which becomes a 'dip' in June, is discussed.

Stratification of RMSE and Bias

The biases and RMSEs presented thus far are aggregated statistics. That is, daily area averages (determined from the forecast errors at individual observation locations across WA each day) from which the monthly average has then been calculated. These provide a broad view of overall performance. However, there exists a tension between the need to present large amounts of information on routine forecast accuracy in a manner that it easily understood and (in doing so) introducing the risk of presenting misleading results (Hamill & Juras 2006). With this in mind, whilst aggregated scores are important, the importance of stratification to identify reasons behind the poorer summer afternoon results must also be highlighted. Thus, to further investigate the December RMSE spike the aggregated statistics were broken down to their component contributions, with a focus on 24hr grids (valid at 8am) and 30hr grids (valid at 2pm).

Figure 5 Time series of daily RMSEs for WA ADFD 24hr (green) and 30hr (yellow) temperature forecast grids for December 2013. The dates on the x-axis are valid dates. Horizontal dashed lines indicate monthly means.

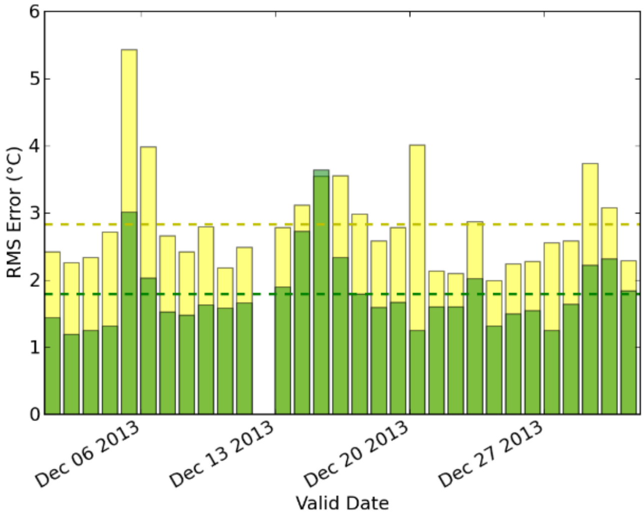


Figure 5 provides a view of the temporal variation in RMSE in December 2013, by showing daily RMSEs calculated for ADFD WA 24hr and 30hr temperature forecast grids. The previously discussed monthly average in each case is also shown by the dashed lines. (Note no grids were available for the December 12th issue.) From Figure 5 it is clear that there is substantial variation in RMSE from day to day. For 24hr grids daily RMSEs vary from 1.2-3.5°C. For 30hr grids the range is larger, 2.0-5.4°C with above average daily RMSEs occurring for the following valid dates/periods: 6-7th, 15-18th, 21st, and 30-31st December. These days/periods were found to coincide with either rain events, the presence of a west coast trough or a combination of both. The period at the end of the month, for example, incorporated the rainfall associated with tropical cyclone *Christine* which made landfall near Whim Creek in the Pilbara and also a west coast trough.

Figure 6 and Figure 7 provide a view of the spatial variation in forecast error for December 2013 24hr and 30hr grids, respectively. The coloured circles on these 'error maps' indicate observation locations.

The colours of the points show the bias for December between the nearest ADFD grid point value and the observed value at that location. Positive values (red) indicate that the forecast value tends to be greater than the observed value. Verification of the 24hr and 30hr grids from the December issued grids for WA resulted in between 100 and 200 grid point/observation pairs depending on the number of reported observations for a given day. The locations exhibiting the five largest errors are labelled. Detail regarding these locations is included in Table 1 for the 24hr grids and Table 2 for the 30hr grids. Note the magnitudes of the 30hr grid errors in Table 2 are all greater than those for the 24hr grid errors in Table 1. Figure 5, Figure 6 and Figure 7 (with Table 1 and Table 2) provide the basis for much of this study.

Figure 6 Forecast bias (°C) between nearest grid points and observation locations averaged from the ADFD WA 24hr temperature forecast grids from December 2013. The forecast grids correspond to 8am local time the day following the forecast issue. The five biases of greatest magnitude are labelled.

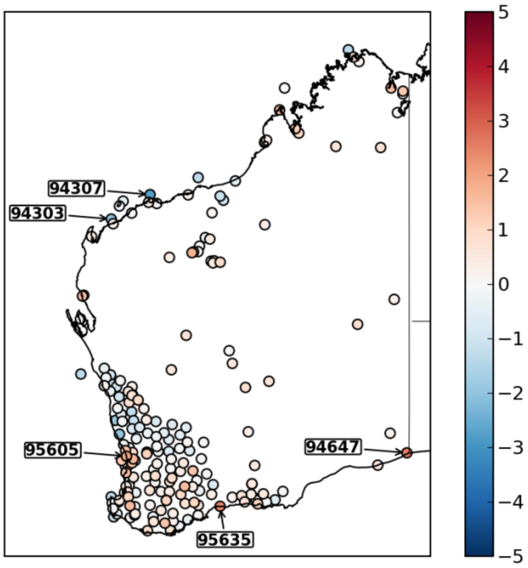


Figure 7 As per figure 6 except for 30hr ADFD temperature forecast grids. The forecast grids correspond to 2pm local time the day following the forecast issue.

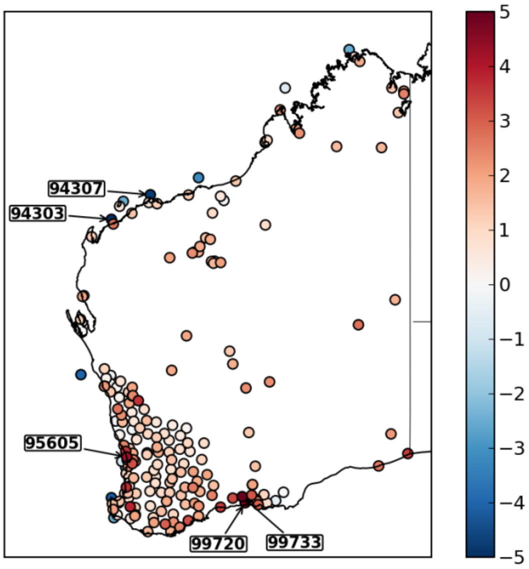


Table 1 The five observation locations with the largest biases depicted in Figure 6.

WMO ID	*Station Name*	*Bias (°C)*
94647	Eucla	2.5
95635	Hopetoun North	2.4
95605	Hillary's Boat Harbour	2.0
94303	Thevenard Island	-2.0
94307	Legendre Island	-2.8

Table 2 The five observation locations with the largest biases depicted in Figure 7. DAFWA signifies that the observation stations at these locations are operated by the Department of Agriculture and Food, Western Australia.

WMO ID	*Station Name*	*Bias (°C)*
99733	Cascade (DAFWA)	5.4
99720	Coomalbidgup (DAFWA)	4.8
95605	Hillary's Boat Harbour	4.2
94307	Legendre Island	-4.8
94303	Thevenard Island	-5.4

A Flaw in the Verification Process: Islands

A number of island-based observation locations feature amongst the large forecast errors in Table 1 and Table 2. These locations are part of a group shown in Figure 6 and Figure 7 distinguished by their negative biases (blue colour). The inclusion of island-based observation locations is a known limitation of the current ADFD grid verification process. Whilst including such locations in the verification process is not in itself a problem, in the absence of a land-sea mask for the ADFD grids (I. Senior, pers. comm.) there exists the possibility that the nearest-neighbour ADFD grid point determined by the verification software may be a marine grid point rather than a land grid point. This inability to discriminate such cases represents a flaw in the verification process since land and sea surface temperatures can differ greatly. As mentioned in the introduction using bilinear interpolation instead of the nearest neighbour approach to match grid points to observations made practically no difference to the verification results to one decimal place.

For WA, eleven instances of land-based observation locations being matched to marine grid points were identified, representing on average ~7% of the total number of reporting observation locations used by the verification process. With the exceptions of Cape Naturaliste (WMO id 94600) and Cape Leeuwin Lighthouse (WMO id 94601) these locations are islands and are hereafter collectively referred to as 'island' locations. The largest error, which was in excess of 10°C, was identified for Legendre Island where an observed temperature of 36.1°C was matched to a grid point forecasting 25.5°C for January 1st at 06UTC. The impact of island locations on the overall bias and RMSE for December is shown for 24hr and 30hr grids in Table 1Table 3.

Table 3 highlights the negative bias associated with island observation locations. The statistical significance of these stratification results (and all subsequent results) was demonstrated using a two-sample t-test (p-value << 0.01 in all cases). The more strongly negative island bias at 30hrs is attributed to the greater increase in observed temperature on land compared to over water as morning progresses into afternoon. For mainland locations, a positive bias is obtained. Again this is more pronounced for 30hr grids. Table 3 also shows that the RMSE of the December 24hr grids is insensitive to this stratification step to one decimal place but, for the 30hr grids the RMSE is greater for island observation locations. In summary, island locations make a near negligible contribution to the bias/RMSE of the 24hr grids. By contrast, in the 30hr grids a larger bias associated with mainland locations is, to some extent, masked by the more strongly negative bias of island locations. Also, whilst the RMSE is unchanged to one decimal place, a modest reduction from 2.83 to 2.75°C (~3%) was, in fact, obtained by excluding island locations.

Table 3 Stratification of bias and RMSE (°C) for 24hr and 30hr WA ADFD temperature forecast grids from December 2013 based on whether observation locations are island locations or not. The mean observed temperature (°C) is provided in parentheses.

Forecast Grid (Hrs)	*Bias/RMSE (°C)*		
	Islands	Mainland	Total
24	-1.0/1.8 (25.2)	0.3/1.8 (23.7)	0.2/1.8 (23.8)
30	-3.0/3.6 (27.8)	1.6/2.8 (30.6)	1.3/2.8 (30.4)

Island stratification, could be regarded as simply one way of 'slicing and dicing' the sample data. However, the exclusion of island observation stations matched to marine grid points from the calculation of verification statistics actually fixes a flaw in the current ADFD verification process. Implementing it could be accomplished in at least two ways. The existing verification software caters for the application of masks so the creation of a suitable land-sea mask is one possible solution. An alternative approach would be to add the island observation stations to a 'black list' to be excluded from the calculation of verification scores.

Given the Wind is Coming off the Sea, What is the Temperature Error?

The three largest biases in Table 2 for December afternoons are for coastal mainland observation locations. The days that contributed most to these monthly biases, in general, coincided with the presence of a west coast trough. These days included the periods in mid and late December identified in Figure 5 for which above average daily RMSEs were calculated. The west coast trough arises due to heating of the land during the warmer months of the year and is characterised by hotter temperatures from the continental interior to the east of the trough line and cooler temperatures from maritime air to the west. The position of the trough relative to the coast tends to be closely coupled with the onset and strength of sea-breezes (BoM 2010; C. Lethlean, pers. comm.; Sturman and Tapper 2005). Forecasting the location and intensity of the trough, which is further complicated by the passage of frontal systems to the south of WA, is therefore important in the forecasting of cooler temperatures due to sea-breezes. Consequently, the role of sea-breeze-related forecast errors was investigated as a possible contributor to the December afternoon RMSE spike.

15 December 2013 provides an example of a west coast trough and coastal sea-breeze conditions. Figure 8 shows the WA portion of the Bureau National Operations Centre mean sea-level pressure analysis chart valid at 15 December 2013 at 06UTC. The heat-trough is indicated by the dashed blue line. Also marked on the chart but difficult to discern are observed wind direction/speed and temperatures. These are consistent with sea-breezes along the west and south-west coast. Figure 9(a) shows the 30hr grid from the December 14th ADFD issue valid at the same time as the analysis chart in Figure 8. Relatively lower forecast temperatures are evident along the coast at a number of locations including the southwest of the state. Figure 9(b) shows the corresponding forecast error map. Despite the forecast of lower coastal temperatures in Figure 9(a), Figure 9(b) shows that temperatures were still significantly over-forecast in the southwest and on the west coast around Perth. A small number of locations were under-forecast further along the south coast.

Figure 8 A section of the Bureau National Operations Centre Australian mean sea-level pressure analysis chart showing WA valid for December 15th 2013 at 06UTC, 2pm in WA.

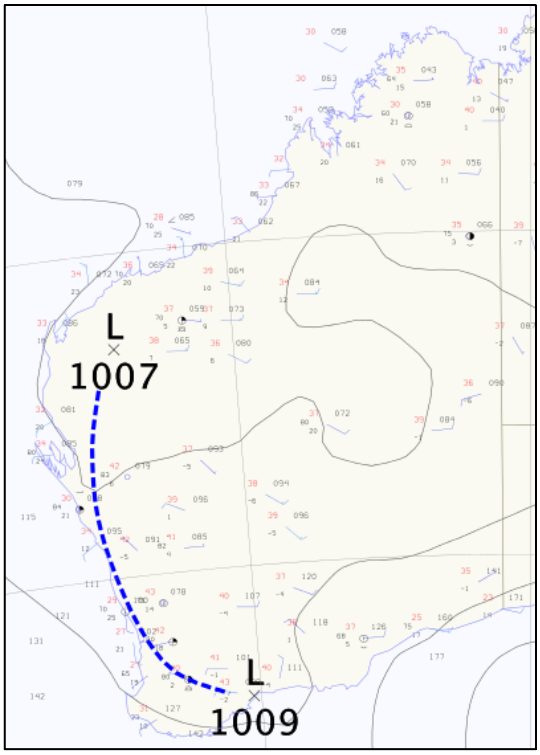
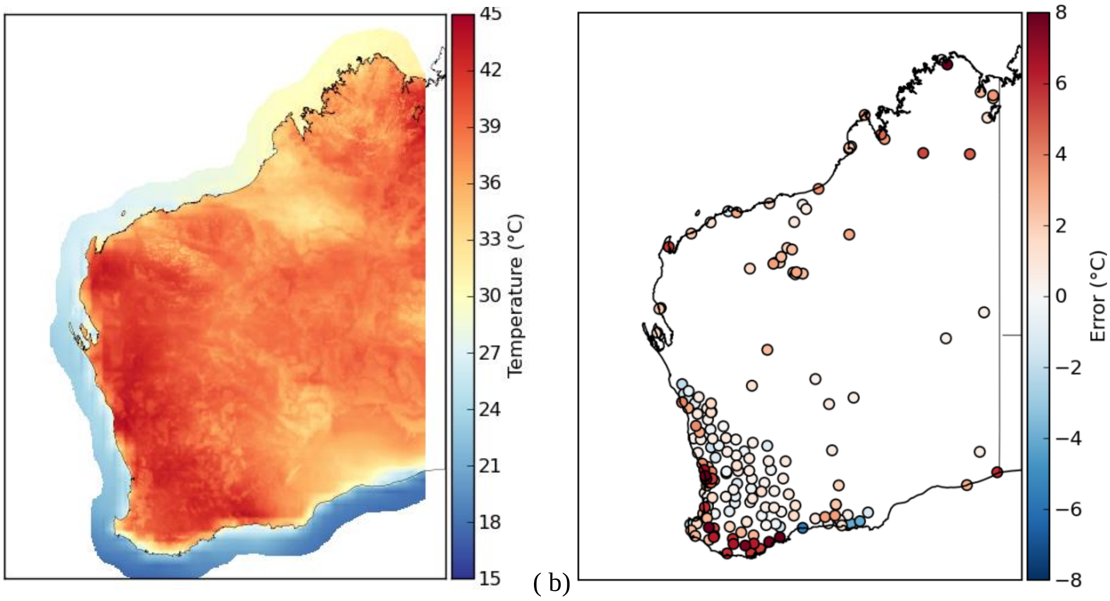


Figure 9 (a) ADFD 30hr surface temperature forecast grid for WA from the Dec 14th 2013 00UTC issue valid at 06UTC on December 15th 2013. (b) Forecast errors in °C for the grid in (a) comparing the grid points nearest to the observation locations with the observed temperatures.



(a) (b)

To quantify the impact of these forecast errors on the overall RMSE for WA a set of 71 coastal observation locations including observation locations within 10km of the WA coast line and the more prominent errors in Figure 9b was derived. This allowed the mainland observation locations previously defined to be further stratified into coastal (37%) and inland (63%) locations. This is a somewhat crude approach since not all coastal locations necessarily experience sea breezes at

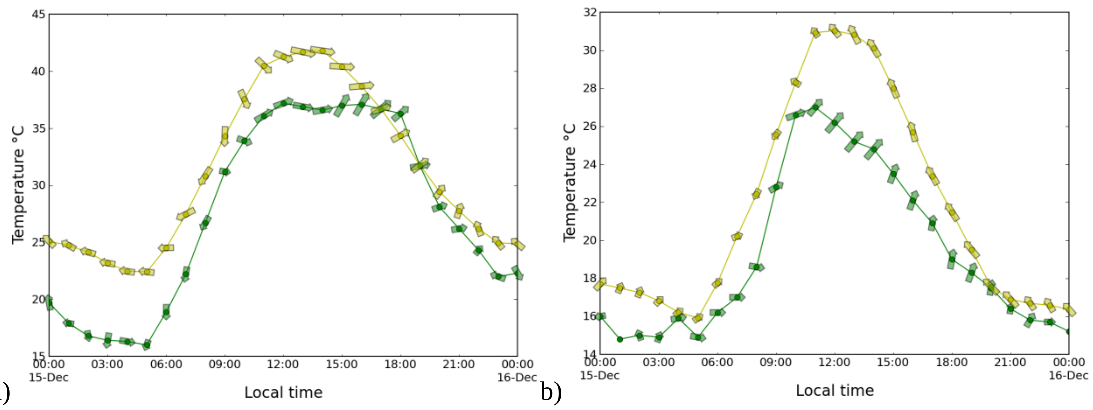
2pm whilst some inland locations may well do. A more appropriate analysis might also incorporate observed wind direction to determine whether flow was onshore. Nevertheless, performing this exercise highlighted a significantly greater bias for temperature forecasts at coastal locations for the December 14th 30hr grid (3.1°C) compared to inland locations (1°C) and a substantially increased coastal RMSE (4.4°C) compared to inland locations (1.9°C). For a more representative data sample, this stratification approach was extended to the whole of December for both 24hr and 30hr grids using the same set of observation locations. The results are shown in Table 4. It can be seen that the bias and RMSE of the 24hr grids were largely insensitive to this stratification. However, the 30hr grids exhibited a higher bias/RMSE at coastal locations compared to inland locations. In particular, comparing the overall mainland RMSE, 2.8°C, to the value for inland locations, 2.5°C, in Table 4 provides a measure of the contribution that coastal locations make to the RMSE spike associated with the 30hr grids.

Table 4 Stratification of bias and RMSE (°C) for 24hr and 30hr WA ADFD temperature forecast grids from December 2013 based on whether mainland observation locations are coastal or inland locations. The mean observed temperature (°C) is provided in parentheses.

Forecast Grid (Hrs)	*Bias/RMSE (°C)*		
	Coastal	Inland	Total
24	0.4/1.8 (23.4)	0.3/1.8 (23.9)	0.3/1.8 (23.7)
30	1.9/3.1 (28.3)	1.5/2.5 (32.2)	1.6/2.8 (30.6)

The increased temperature forecast errors at coastal locations for the 30hr grids, valid at 2pm, as compared to the 24hr grids, valid at 8am, are consistent with difficulties in accurately forecasting sea-breezes which, whilst not confined to afternoons are certainly more likely after 8am. To further investigate the possible role of sea-breeze forecasting errors for this case further analysis was carried out on the errors shown in Figure 9b, focusing on (24) locations for which the temperature forecast error exceeded 5°C. This involved examining wind speed and direction at these locations as well as temperature. The forecast lead time plots in figure 10 for Perth and Albany Airports on December 15th summarise reasonably well the findings of this analysis for the west and south coasts, respectively.

Figure 10 Observed temperatures (green) and forecast (yellow) temperatures at the grid points closest to a) Perth and b) Albany airports on December 15th 2013. Forecast temperatures are taken from the 16-40hr grids from the December 14th issue. Observed and forecast wind directions/speeds are also shown by the orientation and size of the arrows. An arrow pointing vertically upwards represents southerly wind flow. The absence of an arrow indicates calm conditions. Four arrow sizes, from small to large, represent wind speeds of up to 2, 4, 6, and 8 m/s, respectively.



a) b)

For Perth Airport, Figure 10a shows the development of a WSW breeze late morning, which then shifted south-westerly mid-afternoon. Associated with the onset of the WSW breeze was a slowing of the surface heating rate. This resulted in a temperature maximum of ~37°C around midday, a temperature which was, more or less, maintained throughout the afternoon. By contrast, the ADFD wind direction grids, for the grid point closest to Perth Airport, forecast light early morning easterly winds, becoming northerly mid-morning, westerly by mid-afternoon and finally south-westerly. Temperature forecast grids showed a rather higher than observed overnight minimum proceeded by a heating rate roughly similar to the observed rate. An abrupt reduction in heating rate followed and was coincident with the emergence of a strengthening westerly component in forecast wind direction. A maximum of ~42°C was forecast for 2pm.

For both forecast and observations a shift to an onshore wind direction was associated with a slowing of the heating rate in the lead up to the maximum temperature. However, the forecast wind shift and the timing of the forecast temperature maximum were late. This may be due to a timing error in the forecast position of the west coast trough which may, in reality, have shifted eastward earlier in the day or may even have been east of Perth all day. Such an explanation could account for the general over-forecasting of temperature throughout the morning and afternoon, the late forecast temperature maximum and the disparities between forecast and observed wind direction in Figure 10a. A verification exercise to investigate possible linkages between large errors in hourly temperature grids and large errors in maximum (minimum) temperature grids such as in figure 10 where both the maximum and 2pm temperatures were over-forecast could be useful. A further note on maximum temperature forecasts relates to the OCF grids often used to produce the ADFD maximum/minimum temperature grids. Analysis of the OCF guidance valid on December 15th indicated maxima around Perth that were higher than the observed values but lower than the values in the final ADFD grids. This suggests that the previously described post-processing steps and/or forecaster editing may have contributed to greater forecast errors in the ADFD grids.

Turning to the south coast, Figure 10b shows that a light westerly breeze developed early in the morning at Albany Airport and shifted to the south-west by late morning. This shift coincided with a cessation in surface heating and a temperature maximum of ~27°C at 11am which fell steadily throughout the remainder of the day. The ADFD wind direction grids at the grid point closest to this location forecast light predominantly south-westerly early morning breezes becoming south-easterly mid to late morning and then increasing in strength. The forecast temperature showed a similar overnight temperature minimum to the observed value and a similar but more sustained surface heating rate up to midday resulting in a maximum of ~31°C. The timing of the forecast maximum was coincident with the forecast of a strengthening of the late morning south-easterly breeze. The subsequent forecast fall in temperature during the afternoon was initially much slower than the observed rate leading to the large forecast error at 2pm. Whilst the forecast wind shift to a south-easterly onshore flow is at odds with the observed shift to the south-west the reduced sensitivity of the forecast temperature to the onshore wind change is possibly of greater note.

These findings, for a limited data sample, are not intended as a definitive explanation for the relatively larger temperature bias and RMSE of coastal land in ADFD 30hr grids as compared to 24hr grids for WA from December 2013. Nonetheless they provide possible reasons as to how coastal sea-breeze-related forecast errors could contribute to bias/RMSE, such as, the late timing of sea breeze onset and incorrectly forecasting the impact on temperature following sea-breeze onset. What could cause a late onset of the sea-breeze and a less than anticipated cooling effect? One possibility is the model guidance upon which the ADFD grids are based. Resolving sea breezes at all requires model grid spacing of around 20km (Avissar et. al, 1990). Subsequent reviews of sea-breeze modelling have shown studies using grid spacing in the 2-10km range (Abbs and Physick, 1992) and more recently at grid spacing of around 1km (Crosman and Horel, 2010). By comparison the finest of the OCF ensemble members for this study was ~12km, although OCF temperature grids are then down-scaled to a 5km grid. In this case, such coarse grids might be expected to lead to a weaker representation of the temperature gradient across the coastline than was actually the case resulting in weaker pressure gradients and therefore a weaker sea-breeze and a reduced cooling effect. Another possible source of these errors may be forecaster edits in the ADFD grids. Routine provision of error maps like Figure 7 in near real-time for both the OCF and ADFD grids could help better understand these errors and their source and, as a result, better inform the ADFD grid generating process. The addition of routine verification of wind direction, which is not currently supported by the verification software, may also be beneficial in this regard.

Given Rain, What is the Temperature Error?

The error map in Figure 7 for 30hr forecast grids highlighted systematic errors for December 2013 associated with island and coastal land locations by indicating monthly bias by location. A different approach still based on spatial distribution but showing only the largest single error at each location for the December 30hr grids provided an alternative perspective on forecast errors. This exercise highlighted 39 forecast errors in excess of 10°C (0.8% of the data sample). The five largest of these are shown in Table 5.

Table 5 The locations of the five largest forecast errors and valid dates from the December 2013 30hr WA ADFD grids. BHP and DAFWA signify that the observation stations at these locations are operated by BHP Billiton and the Department of Agriculture and Food, Western Australia, respectively.

WMO ID	*Station Name*	*Dec 2013Valid Date*	*ADFD (°C)*	*Obs (°C)*	*Error (°C)*
94457	Warburton Aerodrome	30th	43.2	24.9	18.3
94449	Laverton Aerodrome	6th	33.1	16.6	16.5
99302	Yarrie (BHP)	14th	39.8	24.6	15.3
95635	Hopetoun North	16th	33.4	18.5	15.0
99720	Coomalbidgup (DAFWA)	16th	40.0	25.3	14.7

The three largest of these errors were found to coincide with rainfall within one hour of the forecast valid time at inland locations. In fact 24 of the 39 large errors were found to be associated with rain at inland locations. Eleven were non-rain-related errors at coastal locations, including the fourth and fifth entries in the table and these fell in to the previously discussed 15th-18th December period associated with a west coast trough. Regarding 24hr grids only one error in excess of 10°C was identified and this was not rain-related.

December 21st serves as an example of a day where RMSE was strongly influenced by (localised) rainfall. This is one of the December periods discussed in relation to figure 5 for which a larger than average RMSE was calculated (4.0°C). Figure 11(a) shows the forecast errors from the December 20th grid issue valid at Dec 21st 06UTC. It can be seen that a cluster of locations in the Pilbara show particularly large forecast errors (> 12°C). These large forecast errors are also shown in Figure 11(b), superimposed upon an MTSAT thermal infrared (11.5 - 12.5 µm) satellite image for the same valid time. Figure 11b shows these locations to be cloud covered. The WA regional forecasting centre archive includes a brief report for December 21st 2013 which reported that: *"Thunderstorms which developed over the inland, western Pilbara produced a severe gust at Coondewanna, northwest of Newman…"* In fact all of the locations in Figure 11(b), one of which is Coondewanna, recorded rainfall within 1 hour of 06UTC.

A forecast lead time plot for temperature at one of the locations in the Pilbara cluster, Fortescue Dave Forrest Airport, for December 21st 2013 is shown in Figure 12. Forecast temperatures were determined from the 16-40hr grids from the December 20th WA ADFD grid issue using the grid point nearest to the actual location. Also plotted are the observed temperatures and observed hourly rainfall amounts at that location. It can be seen that substantial rainfall between 1 and 2 pm was associated with a rapid drop in observed temperature that was not captured in the ADFD temperature forecast.

Interestingly, examination of the ADFD surface precipitation grids for this day indicated a rainfall prediction of 0.25mm for this grid point for the period between 11am and 2pm. In this case, the forecast rainfall amount is quite different to the observed amount but it may be worthwhile investigating additional cases to determine whether the precipitation grids (despite their limited three-hourly resolution) could be used to inform the hourly temperature grids. Any benefits in doing so would also need to be weighed up against the effort required and the relatively low number of locations that appear to be affected by localised rainfall, however.

Figure 11 (a) Forecast errors (°C) for the WA ADFD 30hr temperature forecast grid from the December 20th grid issue valid at Dec 21st 06UTC, (b) The five large forecast errors from (a), clustered in the Pilbara, are shown superimposed upon an MTSAT thermal infrared (11.5 - 12.5 µm) satellite image for the same valid time.

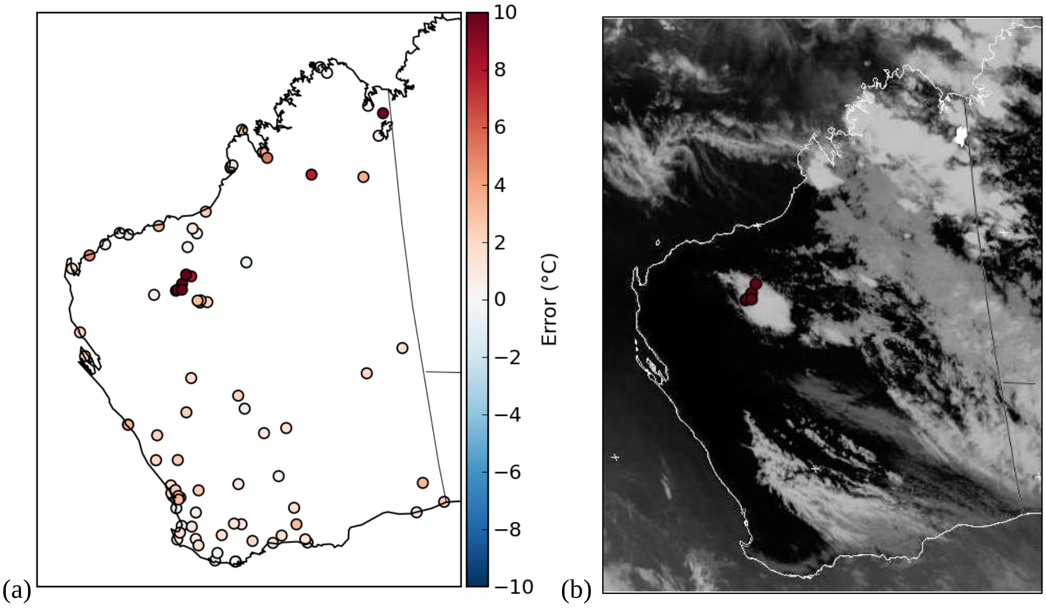
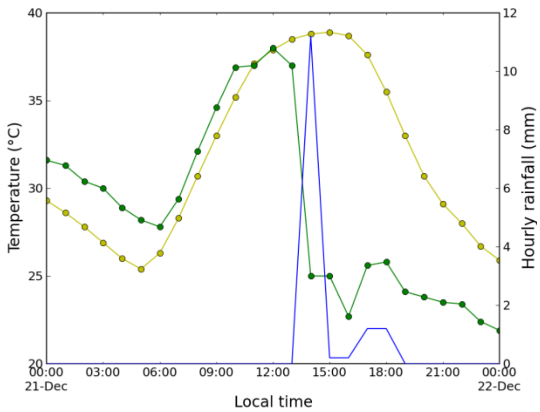


Figure 12 Observed temperatures (green), observed hourly rainfall amounts (blue) and forecast temperatures (yellow) for Fortescue Dave Forrest Airport December 21st 2013, local time. Forecast temperatures are taken from the 16-40hr grids from the December 20th WA ADFD issue using the grid point closest to the location.



To determine how rain-affected locations impacted the RMSE on this day mainland locations were stratified according to whether rain was observed at each location in the hour preceding the valid time of the 24hr and 30hr grids from the December 20th WA ADFD grid issue. For the 24hr grid, a single rain-affected location was identified exhibiting a modest temperature bias and RMSE of 1.5°C. The bias/RMSE for dry locations was 0.1°C/1.2°C. For the 30hr grid, shown in Figure 11a, five locations were identified all from the previously discussed Pilbara cluster. The bias/RMSE at these locations was substantial, 12.8°C/12.9°C, compared to the values for dry locations, 1.7°C/2.7°C. In other words, the five rain-affected locations increase the RMSE for the December 20^{th} 30hr grid from 2.7°C to 4°C, that is, from a value slightly below the monthly average RMSE to one of the worst values for the month. Whilst this demonstrates how rainfall, if not forecast, can have a significant impact on temperature forecast errors it also highlights another limitation of the current verification process which relies upon an unevenly distributed observation network. In this case a cluster of locations subject to possibly the same localised rain event contributed multiple large forecast errors to the overall RMSE calculation.

A similar pattern of results was found by extending the stratification to the whole of December for both 24hr and 30hr grids. These results are shown in Table 6. It can be seen that bias and RMSE were greater for rain-affected locations (~2%

of all mainland locations in both cases). This was particularly so for the 30hr grids which exhibited a rain-affected RMSE of 6.3°C in contrast to 2.6°C for dry locations. Compared to the mainland RMSE of 2.8°C, the figure of 2.6°C for the dry locations provides a measure of the influence of afternoon rain on the RMSE spike associated with the 30hr grids.

Table 6 Stratification of bias and RMSE for 24hr and 30hr WA ADFD temperature forecast grids from December 2013 based on whether mainland observation locations are rain-affected or not. The mean observed temperature (°C) is provided in parentheses.

Forecast Grid (Hrs)	*Bias/RMSE (°C)*		
	Rain	No Rain	Mainland
24	2.1/2.8 (23.7)	0.3/1.7 (23.7)	0.3/1.8 (23.7)
30	5.8/6.3 (25.3)	1.5/2.6 (30.7)	1.6/2.8 (30.6)

A simple explanation for the difference in forecast error between 30hr and 24hr grids for rain affected-locations is that observed temperatures at 2pm showed greater sensitivity to rain than at 8am. If, therefore, rain occurred at a particular location that was not forecast (or was forecast but with a timing or location error), a larger forecast error would be expected for the afternoon than for the morning. Additionally, although slightly more overall rainfall events were observed in WA in the hour before 8am compared to the hour before 2pm in December, convective thunderstorms tend to be more frequent during afternoons than mornings at this time of year (Severe Thunderstorm Directive 2013/2014, Western Australia Regional Office, BoM). If these phenomena are sufficiently localised that they (and any associated rainfall) are not resolved by the ADFD grids, their increased afternoon frequency could lead to more large rain-related forecast errors at 2pm. The verification of maximum (minimum) temperature suggested in the discussion on sea-breezes may also be interesting in this scenario. Whereas possible linkages between the large errors in 2pm temperature and maximum temperature forecasts were highlighted in Figure 10, in Figure 12 the temperature forecast for 2pm was poor due to a thunderstorm but the maximum temperature forecast was quite good.

An inability to adequately forecast convective rainfall is a likely source of these temperature forecast errors. Like the sea-breezes discussed previously the ability to forecast convective rainfall depends on, amongst other things, model resolution. Studies in this area report grid spacing ranging from the 4km to sub-km scales (Stensrud 2006; Warner 2011), that is, much finer than the grid spacing of the guidance used to generate the ADFD grids. Analysis of the OCF guidance that was available to forecasters to generate the ADFD temperature grids verified in Figure 12, suggests that the rainfall-related temperature drop was not captured by the OCF guidance either. This is consistent with the assertion in Engel and Ebert that differences associated with transient small-scale weather cannot be resolved in OCF.

Forecast Bias

It has been previously mentioned that the ADFD 30hr grids exhibited a larger positive bias than the 24hr grids for December. Interestingly, preliminary verification of the gridded OCF guidance that often provides the starting point for generating the ADFD grids does not demonstrate this bias. In fact 24hr and 30hr grids for December 2013 appear largely unbiased (perhaps reassuring given that the OCF grids are bias-corrected). This raises the possibility that, if the OCF grids are the main source of guidance for this period, the bias in the 30hr ADFD grids is introduced as part of the automated post-processing and/or the possibility of forecaster edits to the grids described in the introduction. Of course, it is possible that forecasters may have employed alternative guidance in the form of NWP output which *does* contain afternoon biases. This is an area of ongoing study.

Even though the origins of this bias remain the subject of investigation, it is instructive to consider how this bias affects RMSE. RMSE can be decomposed in to a bias component and a variance component. The square of the RMSE, the mean square error (MSE), can be written as:

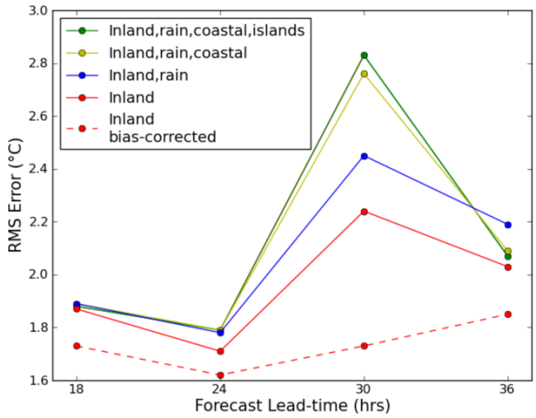
$$MSE = bias^2 + variance(forecast\text{-}observation) \quad (1)$$

The variance term is sometimes called the bias-corrected MSE. Bias-correction reduced the mainland RMSE for December 24hr grids from 1.8 to 1.7°C. The 30hr grids experienced a larger reduction: 2.8 to 2.2°C. This indicated that the RMSE spike associated with the December 30hr grids included a significant component due to increased systematic bias in addition to the variance term that includes forecast errors such as those described in the previous section. Stratification of observation locations to exclude island locations from the bias/RMSE calculations has already been described as a valid modification to the existing verification process. The subsequent application of bias correction of the RMSE may also be a worthwhile modification to emphasise the varying contribution that bias makes to the RMSE of 24hr and 30hr grids (and other lead times at 24hr increments).

The Net Effect: Stratification, Bias Correction and June

The net effect of the stratification exercise and bias correction on the 30hr RMSE spike is summarised in Figure 13. RMSEs for December as a whole are shown pre-stratification and following stratification to account for island, coastal land locations and rain-affected locations. It can be seen that the 30hr grids are more sensitive to the effects of the stratification process than the 24hr grids and the RMSE spike is thus significantly reduced as a result of the stratification process.

Figure 13 Forecast lead time plots (up to 36hrs) showing the effect of island, coastal land and rain-affected observation locations on the RMSE calculation for December 2013 WA ADFD grids. The effect of bias correcting the RMSE is also indicated.



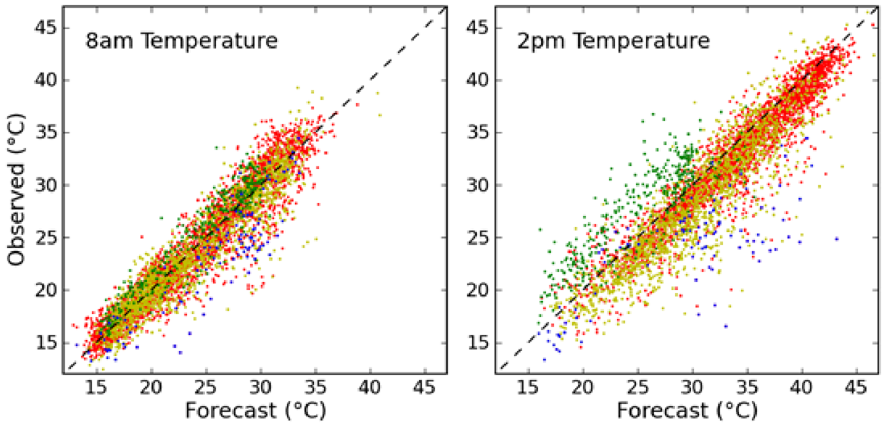
The contributions to the RMSE spike in the 30hr grids identified by the stratification process are collectively attributed to surface heating. Generally surface heating will lead to warmer afternoon temperatures compared to morning temperatures. The small RMSE contribution identified for island locations is an example of this. Here, island-based observation locations warmed more quickly over the course of the morning than the marine grid points against which they were erroneously matched. More substantial RMSE contributions were found for coastal and rain-affected mainland locations where temperatures in the 30hr grids tended to be over-forecast compared to the 24hr grids. This was also attributed to surface heating which can enhance factors such as sea-breezes and convective thunderstorms that mitigate against high temperatures. The cooling effects of these features do not appear to be adequately captured in the ADFD grids. Inadequate resolution of the underlying model guidance may contribute to this.

The final step, bias correction of the RMSE, results in very similar values of 1.6 and 1.7°C for the 24hr and 30hr grids, respectively. These findings suggest that the identified flaw in the verification process, difficulties associated with forecasting sea-breezes and convective thunderstorms, and systematic bias significantly contribute to the December RMSE spike associated with ADFD 30hr grids for WA.

In

Figure 14 scatter plots of forecast versus observed WA December 2013 temperatures for 24hr grids, valid at 8am, and 30hr grids, valid at 2pm, complement the errors summarised in Figure 13. Previously the RMS error was decomposed into a bias term and a variance term. The increased bias at 2pm is shown by the tendency for data points to lie below the dashed diagonal line. The increase in variance at 2pm is indicated by the greater spread of data both along the diagonal and away from the diagonal.

Figure 14 Scatter plots of forecast versus observed temperatures in WA, December 2013 at 8am and 2pm, respectively. Island locations (green), rain-affected locations (blue), dry coastal locations (yellow) and dry inland locations (red) are highlighted.



Consider first the observed temperatures. The temperature distribution of rain-affected locations was found to be very similar at 8am and 2pm (in the range ~13 to ~34°C). However, the overall temperature range at 2pm extends to rather higher temperatures (~47°C) than 8am (~39°C) with the higher 2pm temperatures dominated by dry, inland locations. By contrast the lower end of the overall temperature range is similar for both 8am and 2pm (~12 and ~13°C, respectively) though, at 2pm, these lower temperatures contain a greater proportion of coastal locations. The result of this is an increased overall temperature range at 2pm of ~33°C compared to ~27°C at 8am and a correspondingly larger temperature variance at 2pm compared to 8am. The effect of variance on RMSE can be qualitatively demonstrated using the idea of a climatological forecast. A climatological forecast for the 2pm temperature would result in a larger RMSE than a climatological forecast of the 8am temperature because, in this case, RMSE is simply the square root of the observed temperature variance. Thus, the spread in the observations alone plays a role in the larger 2pm RMSE (see Murphy 1988, equation 9) and is, in a sense, a measure of the difficulty associated with forecasting the situation.

Of course how well the forecasts match the observations ultimately determines the overall RMSE. In terms of temperature range the ADFD forecasts are quite well matched to the observed temperatures. However, it is evident that there is a greater departure from the diagonal, i.e. reduced correlation between forecasts and observations, in the 2pm temperatures compared to 8am temperatures. Island, rain-affected, and coastal locations all contribute – for reasons already discussed – and lead to an increase in overall RMSE compared to the RMSE of inland locations. The visual representation of these differing temperature regimes at 2pm and the differing difficulty in forecasting them is a reminder of the earlier caution from Hamill and Juras to take care when aggregating locations for verification.

The same analysis carried out for December 2013 was also performed for the June 2013 30hr grids, to investigate the relatively low RMSE of 1.7°C for June afternoons in Figure 3. Results were found to be somewhat similar to those for December 24hr grids. The RMSE of 1.7°C for the June 30hr grids was insensitive to island stratification. The similar RMSE of 1.8°C for the December 24hr grids was also insensitive to island stratification. In terms of coastal versus inland locations the June 30hr grids exhibited an RMSE of 1.8°C for coastal land and 1.5°C for inland locations. For the December 24hr grids the RMSE was found to be 1.8°C for both coastal and inland locations. Stratification to discern the effect of rain on the RMSE of June 30hr grids resulted in an RMSE of 2.8°C for the rain affected locations and 1.5°C for dry locations. For the December 24hr grids, rain-affected locations also had an RMSE of 2.8°C and dry mainland locations an RMSE of 1.7°C. Applying these stratification steps sequentially together with bias correction led to a final figure of 1.2°C for dry inland locations for the June 30hr grids compared to 1.6°C for December 24hr grids.

The similarity in the results for the June 30hr grids and the December 24hr grids, may allow the same arguments used to account for the lower RMSE of the December 24hr grids to also explain the June 30hr grids when making a comparison with the December 30hr grids. That is, reduced surface heating, leading to a tendency for lower temperatures in general and a reduced role for sea-breezes and convective thunderstorms in June at 2pm as compared to December at 2pm. The result of this is a narrower observed 2pm temperature range of ~26°C for June 2013 compared to that for December 2013 at 2pm, which is consistent with the earlier suggestion relating larger forecast errors to a broader observed temperature range. The range of observed 2pm June temperatures for dry, inland locations, in particular, although similar to that for December 8am temperatures at these locations was found to be predominantly concentrated between 15-25°C in contrast to the more even spread of the December 8am temperatures (red data points, left hand panel,

Figure 14). This may account for the lower RMSE associated with dry, inland locations determined for the June 30hr grids as compared to the December 24hr grids.

Summary

A verification system was operationally implemented at the BoM in 2013 to routinely verify a number of ADFD weather forecast grids for each available Australian state. It was noticed that surface temperature forecast grids for summer afternoon showed substantial increases, or 'spikes', in the monthly mean of daily RMSEs. WA was selected to investigate reasons for the RMSE spikes since it displayed the most significant spike in RMSE between the 24hr forecast grids (valid at 8am local time) and the 30hr forecast grids (valid at 2pm local time) for December 2013. The RMSE spike in the 30hr grids was found to be seasonal in nature. For 2013, a minimum was identified for June and a maximum in December. A corresponding seasonally varying afternoon spike was also observed for bias.

The RMSE spike associated with the December 30hr temperature grids was in part due to a number of errors that were driven by a tendency for increased surface heating by 2pm, when the 30hr grids were valid, compared to 8am when the December 24hr grids were valid. This heat led, unsurprisingly, to generally higher temperatures at 2pm but also, indirectly, to cooler temperatures at certain locations that were not adequately captured in the ADFD grids.

Firstly, a small contribution to the RMSE spike arose from a flaw in the verification process whereby a small number of (mainly) island-based observation locations were identified as being erroneously paired with marine grid points. Errors in the 24hr grids for these locations were relatively small as land and sea temperatures at this time, 8am, tended to be similar. However, the flaw became significant for the 30hr grids because, by 2pm, much higher island temperatures were observed whereas the forecast temperature of the marine grids points had increased only slightly, resulting in substantial negative biases.

Secondly, a tendency to over forecast temperatures at coastal locations was identified as being due to difficulty in forecasting the cooling effect of sea-breezes. Sea-breeze-related forecast errors were more of a factor in the 30hr grids, valid at 2pm, than the 24hr grids, valid at 8am, since the required coastal temperature gradient for a sea-breeze would tend to be greater in the afternoon than the morning. The sea-breeze forecasting difficulty may be due to insufficient resolution in the model guidance that informs the ADFD grids but forecaster editing of the ADFD grids may also play a part.

Thirdly, a tendency to over forecast temperatures at locations affected by rainfall is likely due to some rain events being too localised to be represented in the ADFD grids or simply not being forecast at all. This meant that their cooling effect was not captured in the temperature grids. Such errors were found to be relatively small in the 24hr grids with forecast temperatures generally only slightly higher than the observed 8am temperature at rain-affected locations. For the 30hr grids such errors were much larger because forecast temperatures tended to be much higher for 2pm than 8am whereas observed temperatures at rain-affected locations were, on average, little changed from 8am. In addition to a general increase in the magnitude of forecast errors, higher afternoon temperatures may also lead to increased numbers of unforecast/unresolvable rain events in the form of convective thunderstorms and therefore an increased frequency of large rain-related forecast errors. Insufficient resolution of the model guidance used to generate the ADFD grids is a likely cause of these errors.

Additionally, a larger bias in the 30hr grids, compared to a near negligible bias for the 24hr grids, also contributed significantly to the RMSE spike. The source of this bias is under investigation but does not appear to be related to the OCF model guidance that often forms the basis of the ADFD temperature grids.

The same arguments applied to explain the differences between December 24hr and 30hr grids were also applied to account for much of the difference between the RMSE of the June 30hr grids and December 30hr grids.

As a result of this study a modification to the verification process to fix the island-related flaw is anticipated. The fix should apply not just to temperature but all surface parameters that are verified. Pairing this change with the production of forecast lead time plots for bias-corrected RMSE should also be considered to highlight differing contributions made by bias to the RMSE at different lead times. Further enhancements to the presentation of verification results could include the routine provision of timely forecast error maps which may assist in reducing the forecast errors described. The addition of wind direction grids to the verification process may also be beneficial. A useful future feature of the ADFD grids themselves could be the provision of a forecast range or forecast confidence intervals based on feedback of the forecast errors described here (M. Foley, pers. comm.). Natural extensions of this work include determining whether the findings for WA are applicable to other Australian states, extending the study to include maximum and minimum temperatures and also further investigation of the varying temperature bias in the ADFD grids.

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