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The science behind the Queensland bushfire and heatwave event

Informing the 2018 Queensland Bushfires Review

Commissioned by the Office of the Inspector-General Emergency Management, Queensland

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Consultant Meteorologist- May 2019

Version	Release history	Date
1.0	Initial release of document	1/4/2019
2.0	Revisions following client discussions	8/4/2019
2.1	Minor revision	15/15/2019

Publisher:
Bushfire and Natural Hazards CRC

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ACKNOWLEDGMENTS

During the preparation of this report the advice from Neil Burrows and James Gould contributed to the final product. The comments on the draft of this report from Sarah Mizzi and Richard Thornton from the Bushfire and Natural Hazard Cooperative Research Centre were greatly appreciated, as was the on-going support from Sarah during the project. Discussions with staff from the Inspector General Emergency Management, Queensland and Queensland Fire and Emergency Services were important in the shaping of the final report.

This work was commissioned by the Inspector-General Emergency Management, Queensland.

EXECUTIVE SUMMARY

The Queensland Inspector General of Emergency Management review into the bushfires over Queensland in late 2018 has led the Bushfire and Natural Hazards Cooperative Research Centre (BNHCRC) to task three work packages addressing a range of issues. This report comprises Work Package 1, which has the objective to provide a scientific/meteorological explanation for and description of the drought and heatwave conditions that gave rise to the bushfires that occurred in Queensland during 24 November to 4 December 2018 (the Critical Period).

This has been a time-limited analysis and so is based on data that were accessible and analyses that could be conducted within the constraints of the project schedule.

This report comprises five main sections following the Introduction (Section 1):

- Section 2 describes the current and antecedent conditions over Queensland to the end of June 2018 when the Northern Australia Seasonal Bushfire Assessment (NASBA) was prepared, and summarises this outlook.
- Section 3 documents rainfall, temperature, humidity, soil moisture, and soil moisture conditions and anomalies from climatology from the end of June 2018 up to and including the Critical Period.
- Section 4 presents and discusses the Bureau of Meteorology (BOM) seasonal outlooks issued twice per month through July-October, and leading to the Critical Period.
- Section 5 discusses aspects of the heatwave period, including a review of the dynamics and processes leading to the heatwave, the BOM heatwave forecasts, and aspects of the weather and climate experienced during the heatwave, and its climatological context.
- Section 6 provides some synthesis of the material presented in the preceding sections and points to some directions where research efforts may usefully enhance knowledge and are likely to provide improved guidance in operational planning.

Climate anomalies over Queensland prior to and during June 2018

Prior to June 2018 there had been a long period of below average rainfall and above average temperature over Queesnsland, and this had led to widespread well below average soil moisture conditions, particularly on parts of the coast. With the (then) current seasonal outlooks suggesting higher than normal probabilities of above median temperature and below median rainfall over Queensland, together with an assessment of fuel state, the NASBA highlighted the Capricornia and Central Coasts as areas of above normal bushfire potential for the coming fire season.

Climate and weather anomalies June-December 2018

Through most of the period between the end of June and the Critical Period temperatures remained above average, rainfall below average, and atmospheric humidity below average. Only a rainfall event over southeastern Queensland in the second half of October interrupted this pattern.

Also notable through this period were the sustained deficits of various humidity measures. One measure calculated in this report, and designed to test how unusual

was this *sustained* period of deficit, was the accumulated deficit from climatology of the daily Keetch-Byram Drought Index, computed from the approximate end of the wet season. At a number of station locations with long-term records (eg Cairns, Mackay and Rockhampton) the accumulated deficit was the third highest in the more than 75 years of records at these stations.

Other assessments of humidity deficit (soil moisture, atmospheric humidity) as well as those described above, also indicated sustained dryness over parts of coastal Queensland leading to the Critical Period. While these measures have not been assessed in a climatological context in this report, and noting that there are undoubtedly strong relationships between some of these measures, investigation into how these sustained, rather than simply episodic, large deficits, affect fuel state may prove worthwhile.

Seasonal Outlooks August-December 2018

The BOM seasonal outlook issued at the time of preparation of the NASBA was for above average probability of above median temperature and below median rainfall over most of Queensland through the outlook period.

Subsequent outlooks, issued twice per month, were very consistent with this trend. Verifying climate anomalies suggest that these outlooks were overall qualitatively correct.

The Heatwave and the Critical Period

During the Critical Period extreme heatwave conditions were widely experienced on and near the Queensland coast, extending from near Bundaberg to Lockhart River. During this period a number of maximum temperature records were broken, some by very large amounts (eg 5.4C at Cairns Airport). It was also noted that at a number of locations the previous highest record was exceeded on several days during the heatwave, highlighting the severity of the event.

Also unprecedented were the Catastrophic FFDI values experienced at Rockhampton on 28 November. While temperature, humidity, and drought factor were all at values that would contribute to large values of FFDI, the most unusual factor was the wind speed on that day, where a sustained period over 40km/hr was experienced, and the 3pm wind speed of 51.8 km/hr was only exceeded once in the period of anemometer records, during the passage of TC Marcia in February 2015. Further, these winds were from the western quadrant – climatologically highly unusual.

The factors that lead to heat waves are discussed, and larger scale circulation anomalies that are generally present leading up to heat waves were identified over Queensland in the months leading to the critical period. These include a mid-tropospheric anticyclone, slow moving near surface systems, and pronounced soil moisture deficit. All three factors allow accumulation of heat in the lower layers of the atmosphere. The final ingredient is a weather system that acts to advect the pool of hot air to a more benign environment. All factors were identified in this event, but their morphology differs in some ways from those reviewed in cases of mid-latitude heatwaves, and so some studies of other north Queensland heatwaves may prove instructive.

The mean temperature over Queensland has been increasing in recent years, and there is some indication that there has also been a trend for increasing heatwave frequency on the Queensland coast. Other independent studies have also shown indications of a trend to increasing fire weather over southern Queensland, but more research in this area, particularly addressing trends in extremes, is needed. In addition, while heatwave conditions do not in themselves define extreme fire weather, they do provide several of the ingredients that contribute to extreme fire weather. Studies of the relationship between fire weather and heatwave conditions in Queensland coastal environments, both in past heatwaves and based on future projections, may prove instructive.

Both the Bureau of Meteorology seasonal outlooks and the shorter period fire weather outlooks and forecasts (more detail in the Bureau of Meteorology submission to this enquiry) provided useful guidance as to conditions subsequently experienced, with, as is often the case with extreme events, increasing specificity as lead-times decrease. However, increasing the warning time for forecasts of the most extreme conditions is desirable. The use of ensemble forecast systems that provide a range of probable outcomes, including worst-case scenarios, can aid risk assessment. While the seasonal forecasts and medium range forecasts are based on ensembles of forecasts, this is not yet available at the highest resolution, short timescale. The Bureau of Meteorology is developing such a system, and its progress and potential should be monitored.

1. INTRODUCTION

The Inspector General Emergency Management, Queensland Government, (IGEM) have been tasked by the Minister for Fire and Emergency Services to conduct a review in light of the significant bushfires and heatwave that impacted Queensland communities late November- early December 2018. The purpose of the review is to ensure a robust approach informed by lessons learned and best practices is taken to drive continuous improvement across all stakeholders and all aspects of Queensland's disaster management system and recovery arrangements.

As part of this review, the Bushfire and Natural Hazards Cooperative Research Centre (BNHCRC) has tasked three work packages addressing a range of issues. This report comprises Work Package 1, with the objective to provide a scientific/meteorological description of the drought and heatwave conditions that gave rise to the bushfires that occurred in Queensland during November-December 2018.

The project aims to understand the science behind the events, including:

- A scientific analysis and explanation of the drought and heatwave conditions that gave rise to the bushfire incident.
- The extent to which drought, heatwave and associated fire danger / behaviour were predictable and within the range of historical conditions.
- How both the heatwave and bushfire events fit with current assessment of bushfire risk in Queensland?
- What the predictors/indicators of such events were?
- What can be done to focus on addressing these predictor/ indicators more in future years?
- What is the predictability of fire weather in a general sense?

The requirements of this Work Package are to focus on conditions leading to and including the Critical Period (23/11/2018 to 4/12/2018) but to have a broad geographic perspective (IGEM, personal communication).

This report has five main sections and a Summary following this Introduction, with Sections 3 and 5 in particular having a number of subsections.

- Section 2 describes the current and antecedent conditions over Queensland at the time (June 2018) when the Northern Australia Seasonal Bushfire Assessment (NASBA) was prepared, and summarises this outlook.
- Section 3 documents rainfall, temperature, humidity, soil moisture, and soil moisture conditions and anomalies from climatology in the period leading up to and including the Critical Period.
- Section 4 presents and discusses the Bureau of Meteorology (BOM) seasonal outlooks issued twice per month through June-October, together with verifying rainfall and temperature anomalies over Queensland.
- Section 5 discusses aspects of the heatwave period, including a review of heatwave dynamics and processes leading to the heatwave, the BOM heat wave forecasts, and aspects of the weather and climate experienced during the heatwave, and its climatological context, including wind, humidity, and vertical atmospheric stability.

- Section 6 provides some synthesis of the material presented in the preceding sections, particularly in the context of the questions posed above, and points to some directions where efforts may usefully enhance knowledge and potentially provide improved guidance to operational planning.

2. THE NORTHERN AUSTRALIAN SEASONAL BUSHFIRE ASSESSMENT

The NASBA was prepared in June 2018 in Townsville (see BNHCRC 2018).

The rainfall decile maps from the Australian Water Availability Project (AWAP, Jones et al 2009) for 12, 9, 6, 3, and 1-month periods leading into June 2018 (Fig. 1) showed very persistent rainfall deficits throughout these periods along the coast from (broadly) Gladstone to Townsville (a map showing locations of meteorological observation locations and forecast districts over Queensland is shown in Appendix 1), and extending in a broad area inland to the southwestward.

There had also been a lengthy period of many years of above average annual temperatures across all of Queensland, as seen in the "financial year" annual temperature anomaly time series in Fig. 2, with this period being chosen here as it was current at the time of the NASBA workshop. There are only two 12-month periods since June 1999 when there has been a negative temperature anomaly over Queensland, and the warmest 10 years in the record all occurred in this century.

The 3-monthly maximum temperature anomalies (Fig. 3) were above average over almost the entire state, with the greatest anomalies in the southwest. Decile rankings showed these to be above average to well above average through most of the state, with the most extreme values near the New South Wales (NSW) border. Vapour pressure (humidity) anomalies also show a negative (drier than normal) anomaly over most of the state at both 9am and 3pm (Fig. 4). These vapour pressure anomalies are broadly consistent with the below average rainfall through this period.

Based on the underlying rainfall deficit, and the seasonal outlook that indicated low probabilities of above median rainfall and high probabilities of above median temperature, together with fuel assessments, the NASBA concluded (in part) ***"Above normal fire potential is expected for these forested areas along the Central Coast, Whitsundays and the Capricornia…."***.

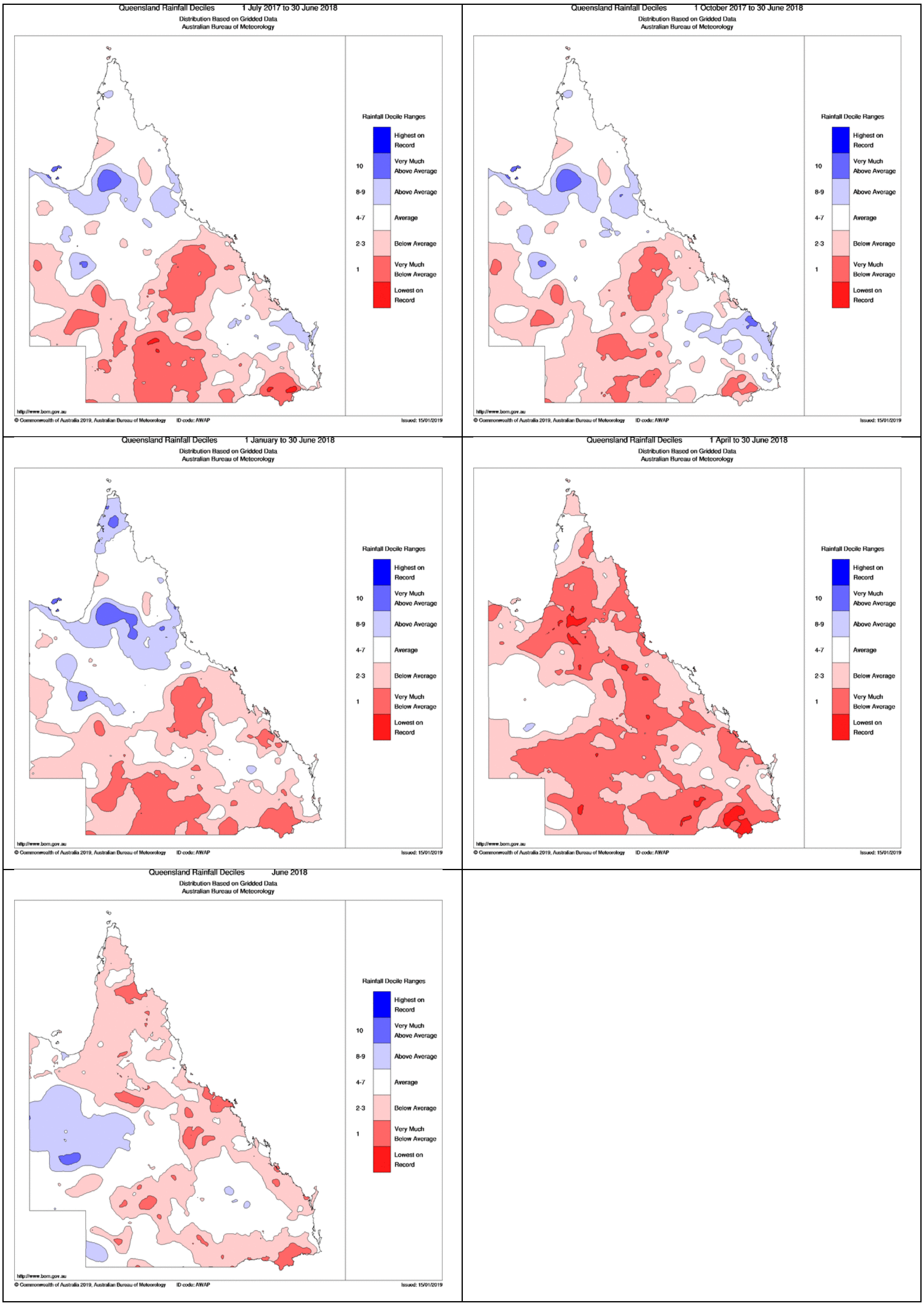

Figure 1. From left to right, top to bottom: 12-month, 9-month, 6-month, 3-month, and 1-month rainfall deciles to 30 June 2018 from BOM AWAP analyses.

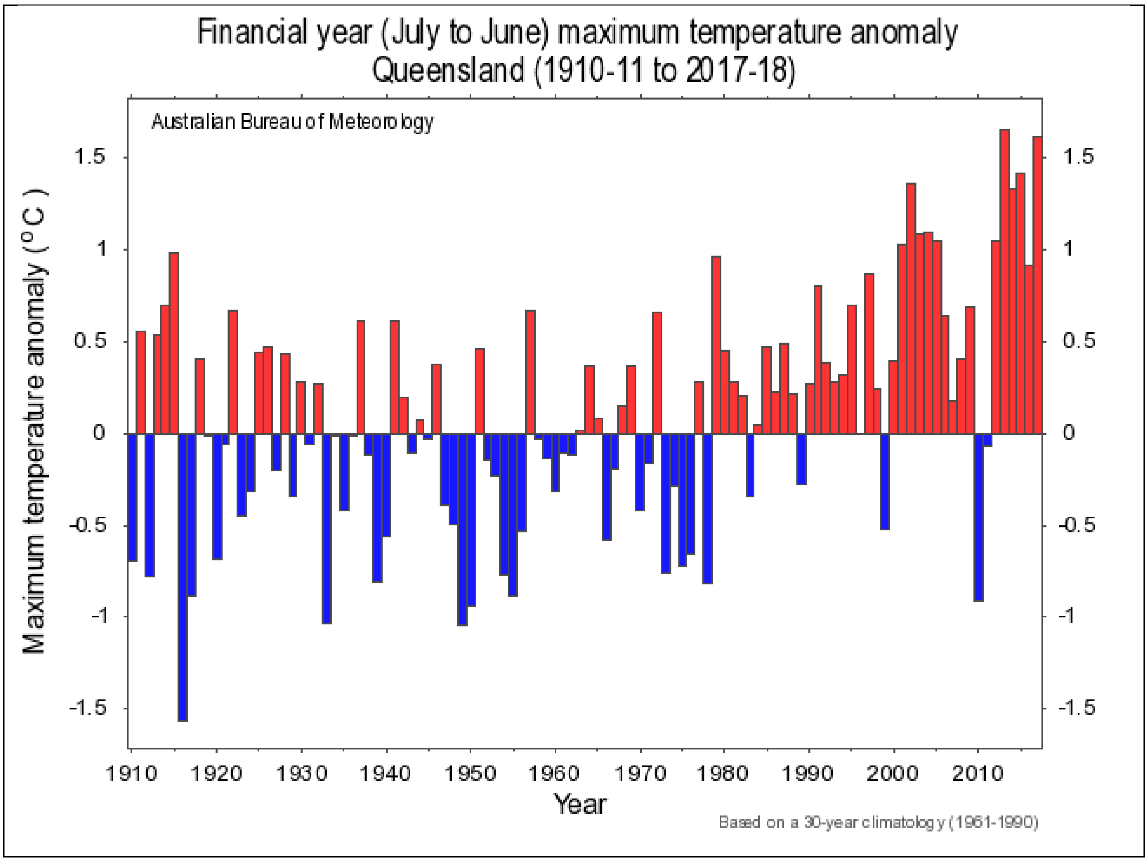

Figure 2. Maximum temperature anomalies over Queensland by July-June years from 1910-11 to 2017-18.
(http://www.bom.gov.au/climate/change/#tabs=Tracker&tracker=timeseries)

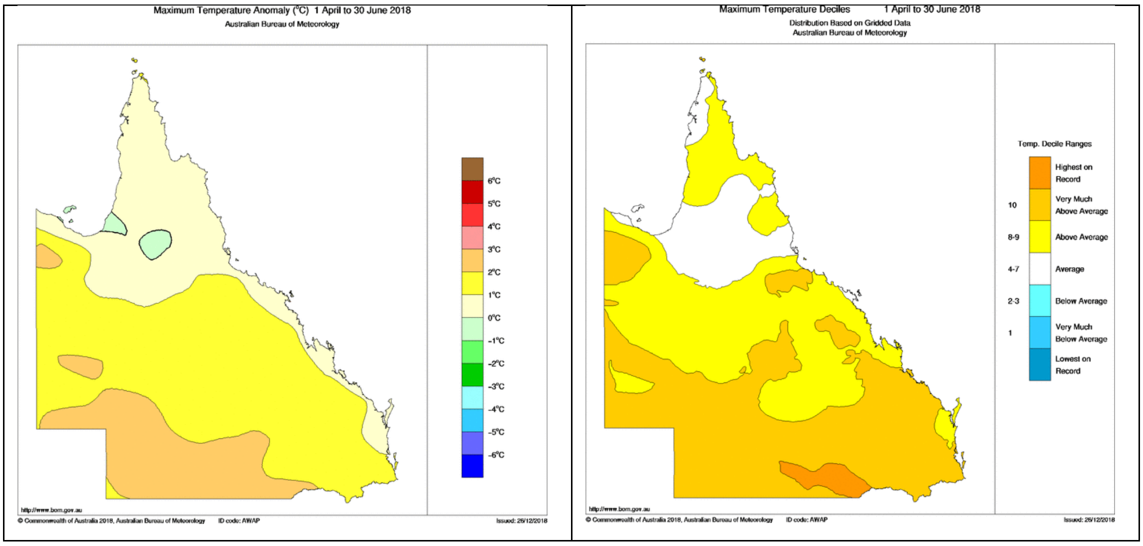

Figure 3. Maximum temperature anomaly (left) and decile ranking (right) for the 3-months to 30 June 2018 from BOM AWAP analyses.

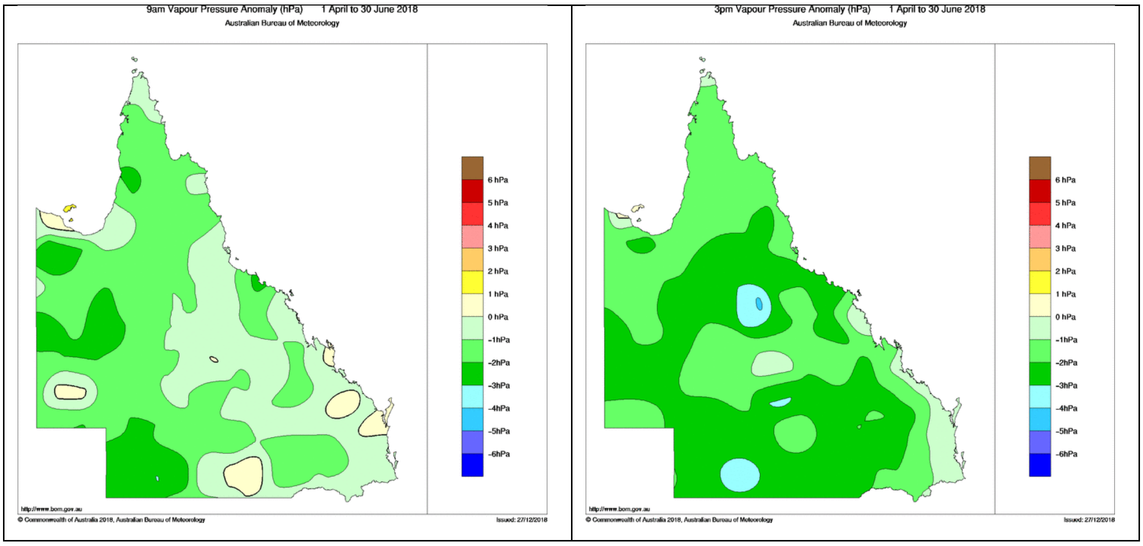

Figure 4. Vapour pressure anomalies at 9am and at 3pm for the three months to 30 June 2018 from BOM AWAP analyses.

Also in the NASBA was the comment "*Soil moisture is generally close to the long-term average,* ***except for areas inland from Proserpine, Collinsville, Mackay and south to Rockhampton, where soil moisture is below average*"** (my emphasis). While no evidence for that statement was shown in their report, Fig. 5 shows the upper zone and the root-zone soil moisture anomaly for June from the Australian Landscape Water Balance (AWRA-L) model[1] (Frost et al 2018). The AWRA-L model has three soil layers (upper: 0–10 cm, lower: 10–100 cm, and deep: 1–6 m). Shallow rooted vegetation has access to subsurface soil moisture in the upper and lower soil stores only, while deep rooted vegetation also has access to moisture in the deep store.

There is an area of very much below average root zone soil moisture extending from north of Mackay southwards to near Bundaberg, and well inland, with large areas in the lowest 1% of June values (1911-2018). Another narrow area of very much below average root-zone soil moisture extends from north of Townsville through Cairns close to the coast.

[1] http://www.bom.gov.au/water/landscape/#/sm/Relative/ accessed 13/2/2019

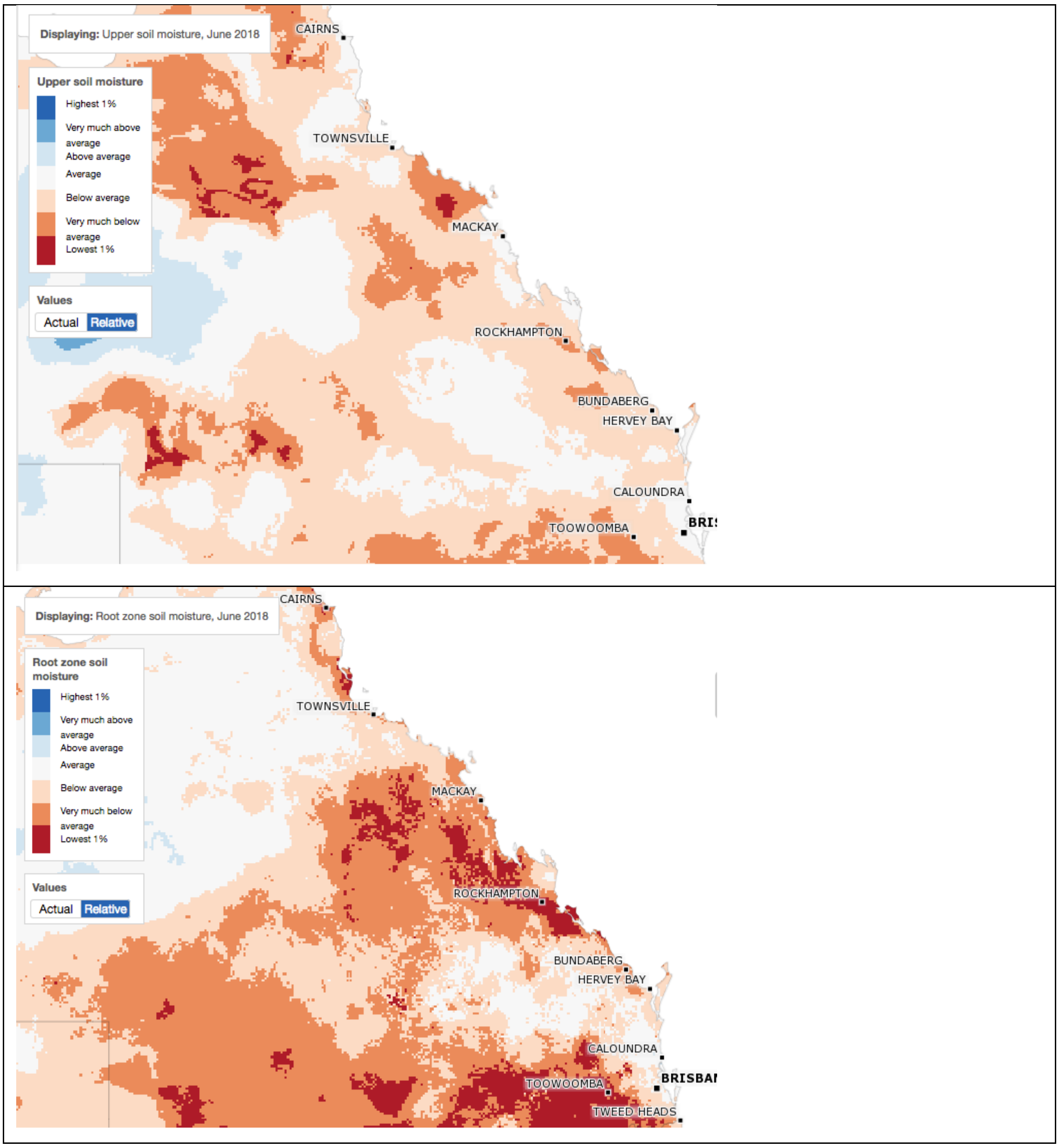

Figure 5. Upper Zone and Root Zone soil moisture anomaly for June 2018 from the AWRA-L landscape water balance model.

The NASBA graphical outlook is shown as Fig. 6, with the areas of above normal fire potential highlighted in red.

A point to be remembered is that the seasonal rainfall and temperature outlooks that inform the NASBA are valid for the 3 calendar months from their time of issue. The outlook current at the time of preparation of the NASBA was for the 3-month period August-October, and so did not extend to include the Critical Period. The consistency of subsequent seasonal outlooks that led to and included the Critical Period are presented and discussed in Section 4 of this report.

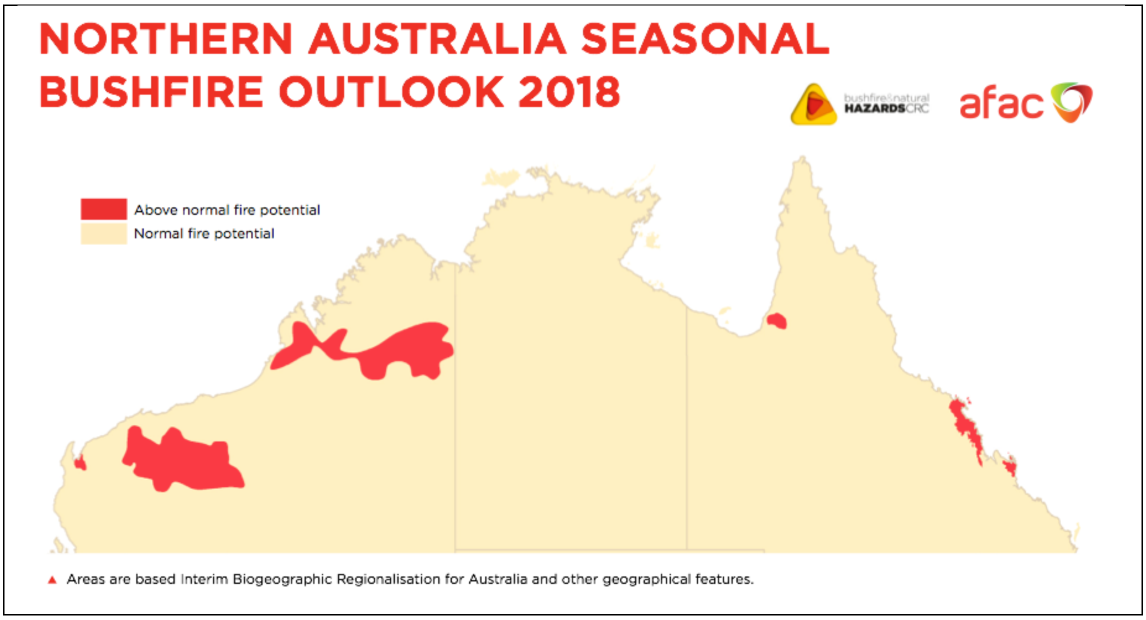

Figure 6. The Northern Australia Bushfire Assessment map for 2018 (BNHCRC 2018). Areas of above normal bushfire potential are shaded red.

KEY POINTS : SECTION 2

- There were marked rainfall and soil moisture deficits over Queensland for a lengthy period to the end of June 2018.
- The seasonal outlook indicated probable below normal rainfall and above normal temperature for the August-October period.
- The NASBA identified Capricornia and the Central Coast as regions of above normal bushfire potential.

3. CLIMATE ANOMALIES JUNE-NOVEMBER 2018

3.1 Rainfall Anomalies

Figure 7 shows the 3-month and 6-month deciles to the end of November 2018, and Fig.8 shows the rainfall deciles for each month from July-November.

The 6-monthly accumulated rainfall deciles to the end of November (Fig. 7) show below (decile 2-3) to very much below (decile 1) average rainfalls along the coast from Bundaberg to Townsville, and inland of the divide from Weipa to central Queensland. The 3-monthly deciles show a similar pattern, but rainfall in October over southeast Queensland reduces the amplitude somewhat. However, the coastal regions near Mackay and Townsville continue to show very much below average rainfalls.

The monthly decile maps (Fig. 8) show generally below to well below average rainfall over the coastal region north of Bundaberg, although in July there is some above average rain north of Townsville, and in August near Cooktown. October shows an area of above average rainfall over southeast Queensland, and this extends northwards along the ranges: however, between Bundaberg and Townsville the coastal region has only around average rainfall.

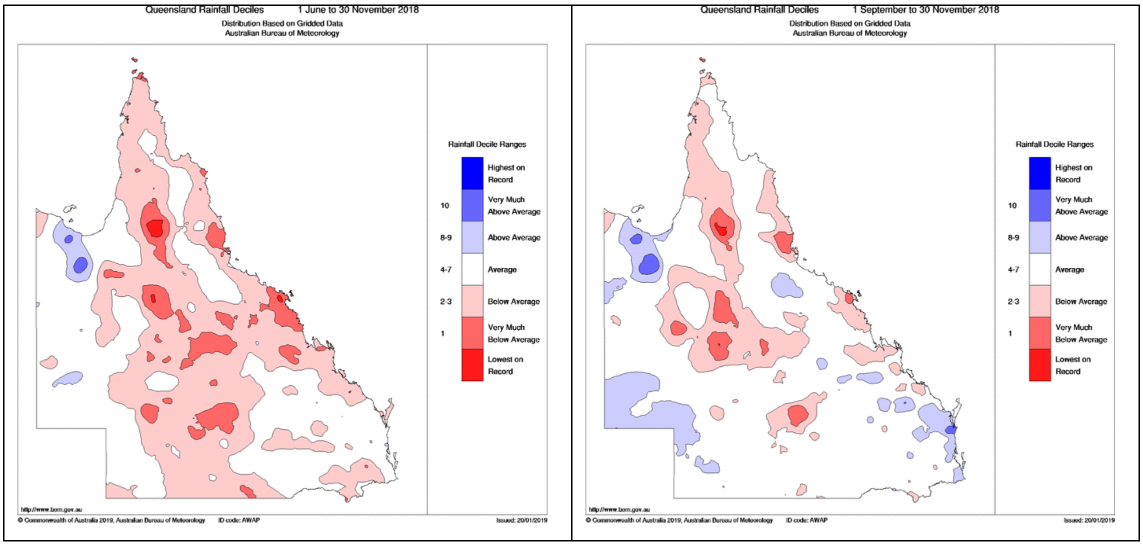

Figure 7. Six-monthly and 3-monthly rainfall deciles to the end of November 2018, from the BOM AWAP rainfall analyses.

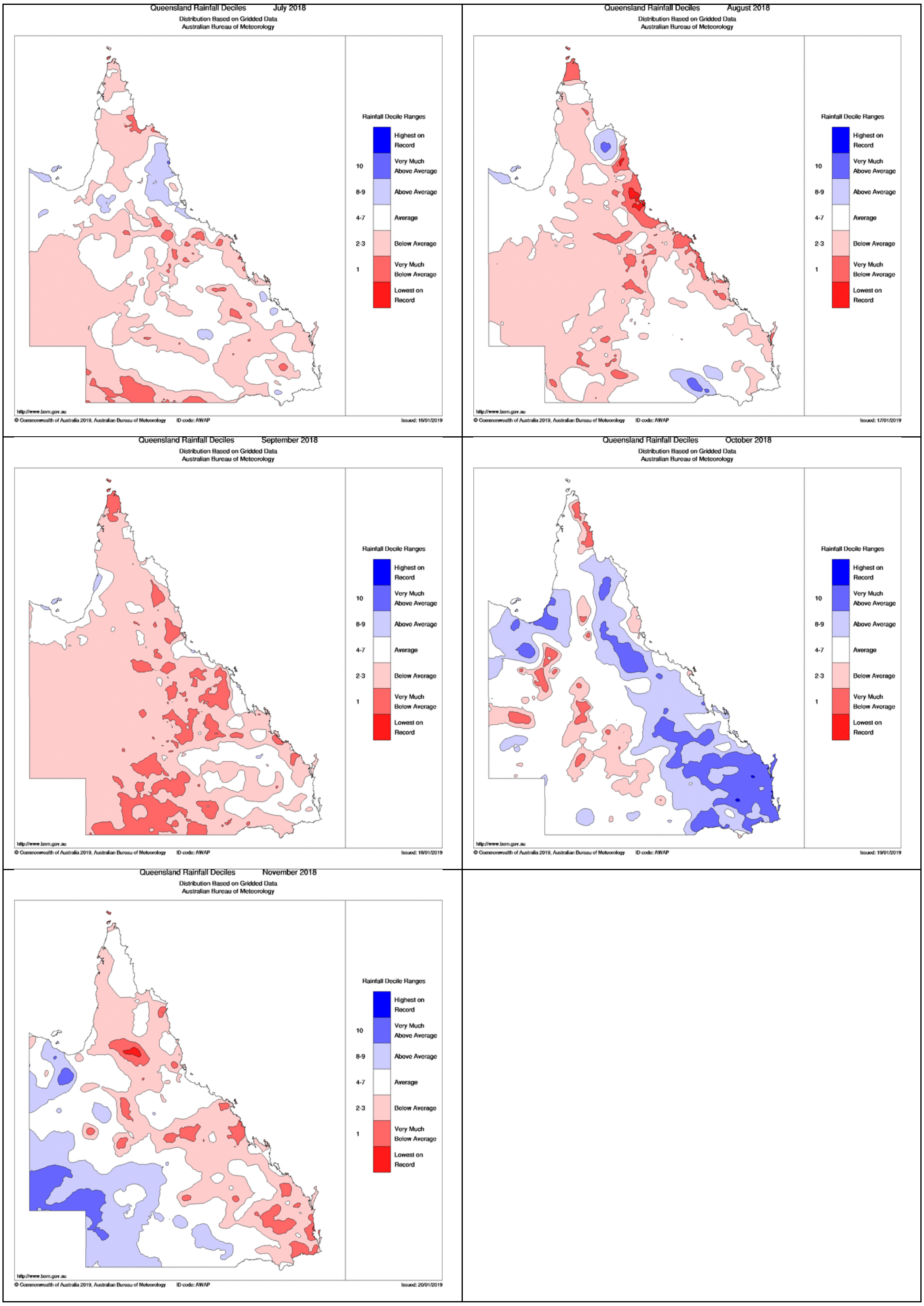

Figure 8. Monthly rainfall deciles for July, August, September, October and November 2018, from the BOM AWAP rainfall analyses.

3.2 Temperature Anomalies

Figure 9 shows the monthly maximum temperature anomalies for each month from June-November 2018. Most of Queensland had a had a positive anomaly in each of the six months. Of particular note are:

- the enormous pool of very hot air over southwest Queensland in October
- a positive anomaly that extended to the Queensland coast in November, with particularly the Central Coast and Capricornia having a positive anomaly between 2 and 3C

Putting these anomalies into a climatological context (Fig. 10), the monthly decile ranking of the average maximum temperature is shown for the 6-month, 3-month, and 1-month periods to the end of November 2018. For the 3-monthly and 6-monthly periods almost all of northern Queensland is very much above average, and with areas of highest on record between Rockhampton and Mackay and inland, and north of Townsville. The 1-month decile map again shows a large area with very much above average temperatures (decile 10) in an area east of a line joining Fraser Island to the Gulf of Carpentaria, and with an extensive near-coastal region of highest mean monthly maximum temperature on record extending from Gladstone to Cooktown.

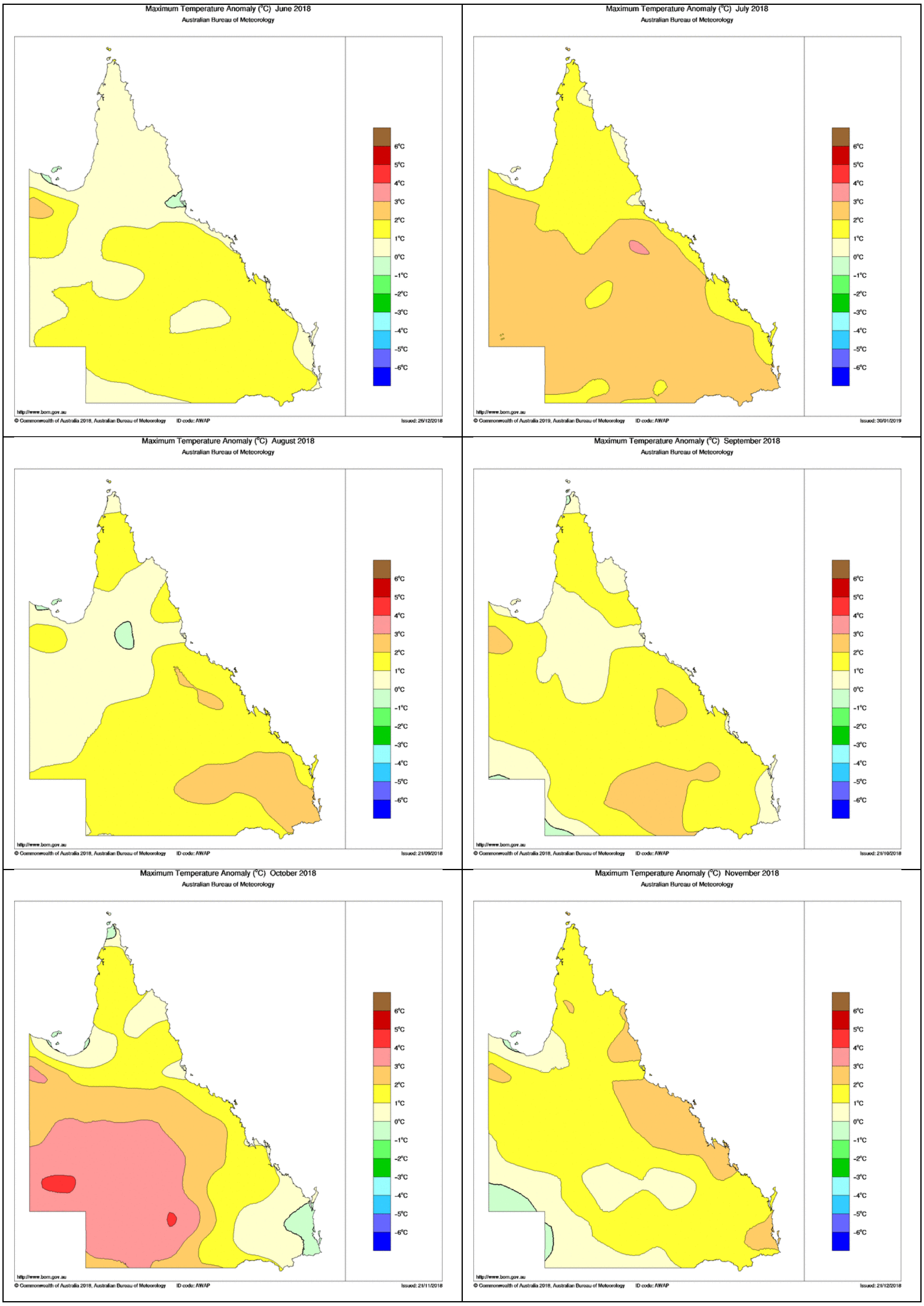

Figure 9. Monthly maximum temperature anomalies for July – November 2018 from the BOM AWAP analyses.

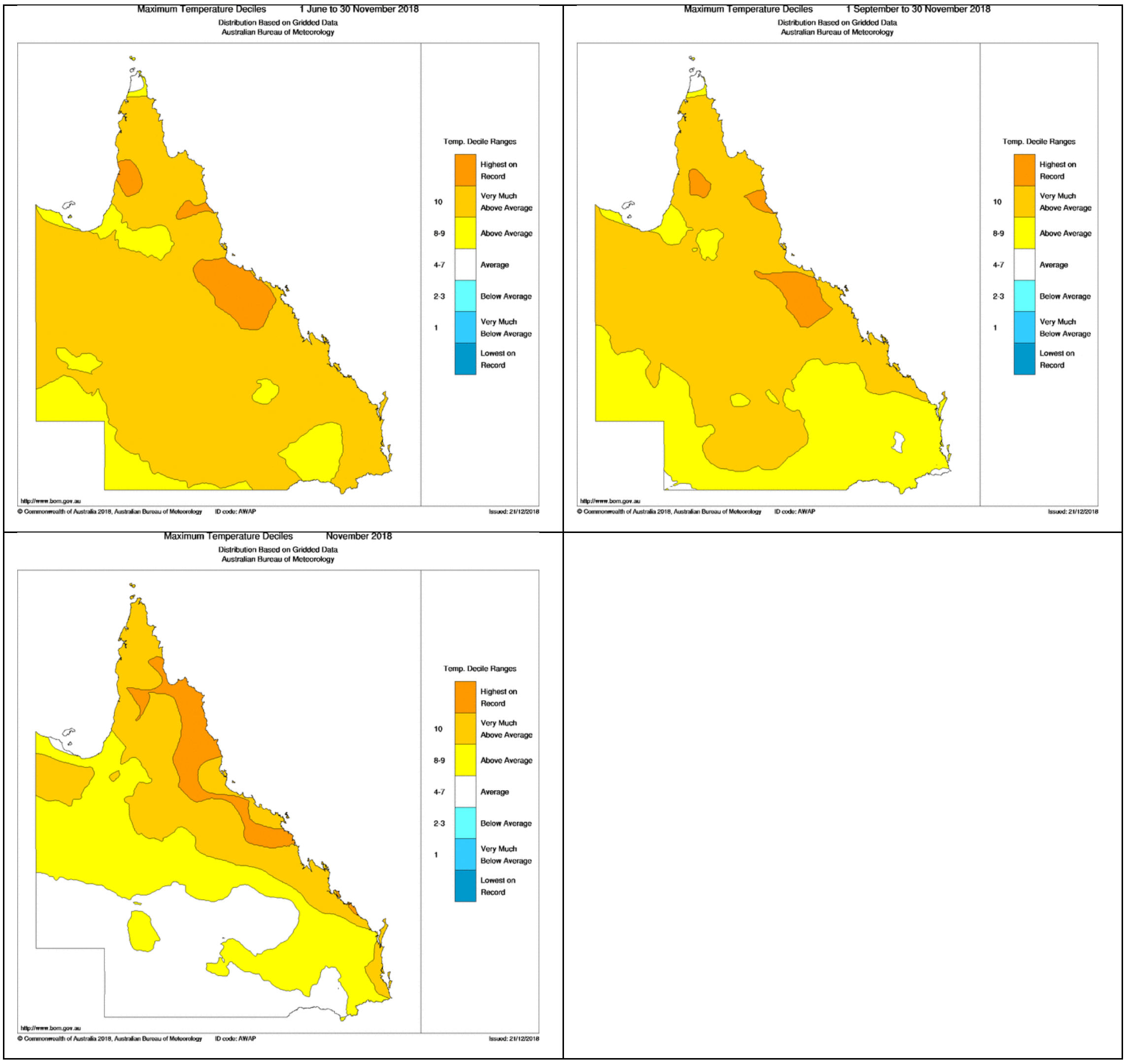

Figure 10. Maximum temperature decile ranking for the 6 months, 3-months, and 1-month to 30 November 2018 from the BOM AWAP analyses.

3.3 Vapour Pressure Anomalies

Both live and dry fine fuels respond to atmospheric humidity on a range of timescales. The BOM AWAP analyses present vapour pressure at 9am and 3pm as its humidity measure. While this is not a metric perhaps as familiar to users as is relative humidity or dewpoint, it is a conservative measure of humidity (a measure that is independent of temperature) and the spatial distribution of its absolute values and anomalies are readily available from the BOM AWAP site. In this section we present the vapour pressure anomaly at 0900 (Fig. 11) and 1500 (Fig. 12) for September, October and November 2018. A negative vapour pressure anomaly indicates a drier atmosphere.

In September most of Queensland was less humid than average, with the greatest negative anomalies in a band extending south from the Gulf of Carpentaria to the Channel Country, but it was less humid than normal eastwards to the coast apart from the region just north of the NSW border.

In October a large area of southeast Queensland was more humid than average, consistent with the rainfall distribution in October seen in Fig. 7. However, a small area near Mackay, and the region north of Townsville were less humid than average. In November all but far west Queensland was less humid than normal, and anomalies in Capricornia and inland over the Central Highlands and Coalfields were the most negative (driest) in the state.

Thus there was a sustained period of several months when near surface atmospheric humidity was below average, with the effect strongest in November, in the regions where the fires eventuated.

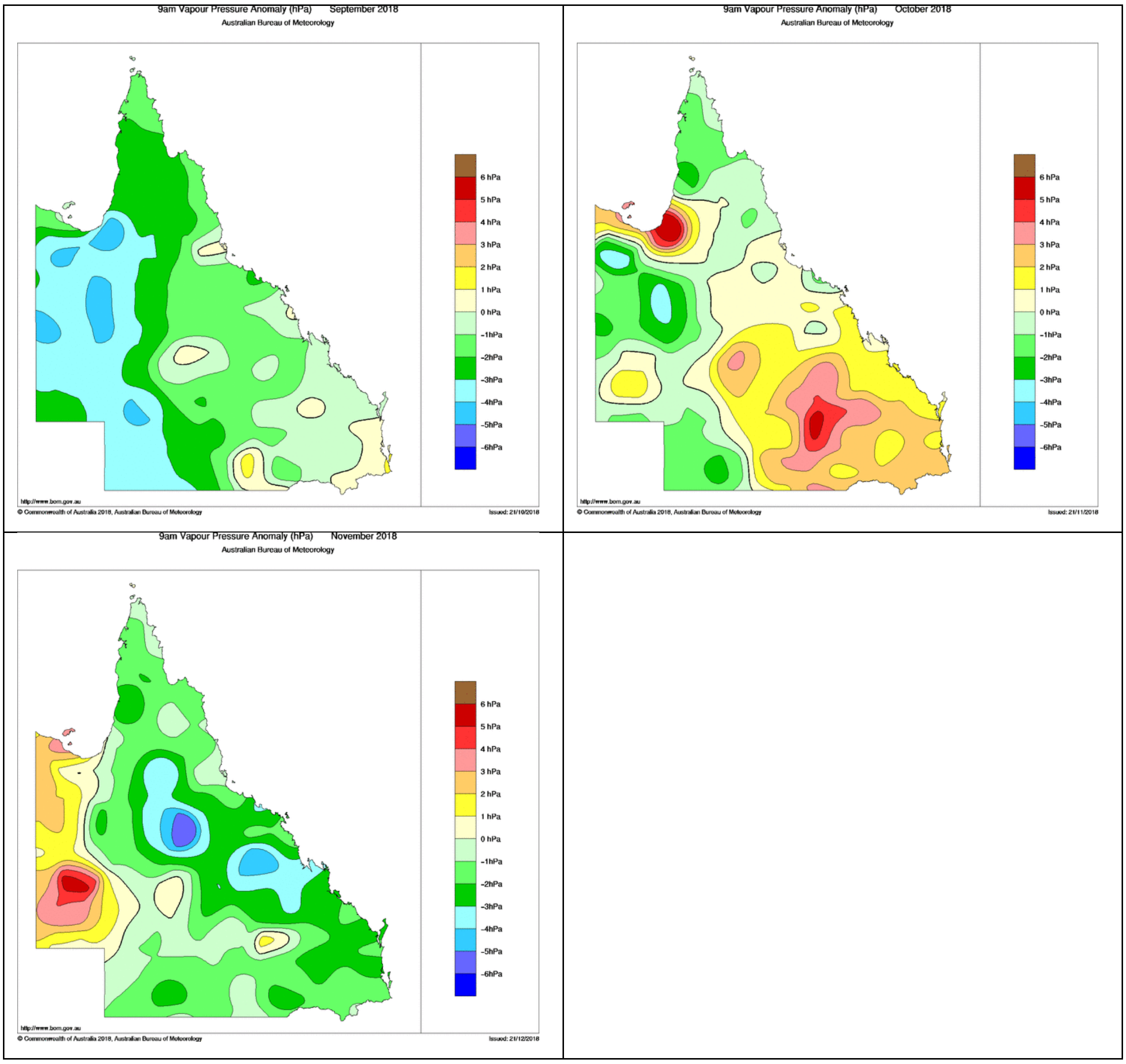

Figure 11. Vapour pressure anomalies at 0900 EST for the months of September, October and November 2018 from the BOM AWAP analyses.

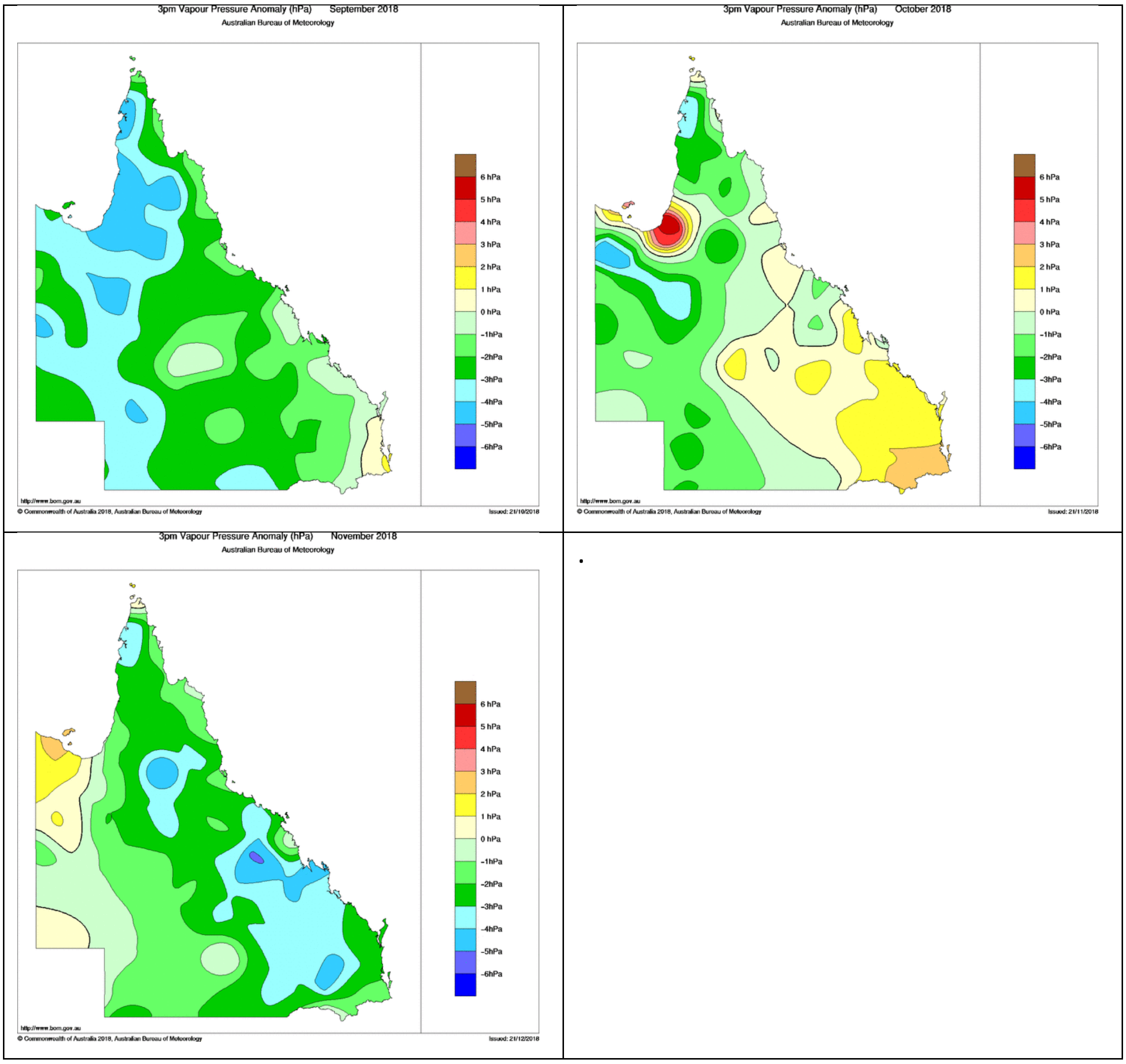

Figure 12. Vapour pressure anomalies at 1500 EST for the months of September, October and November 2018 from the BOM AWAP analyses

3.4 Soil Moisture Anomalies

Figure 13 shows the monthly progression of the root zone soil moisture anomaly from the AWRA data (cf Fig. 5). The first four months show vast areas of Queensland with very much below average root zone moisture. The October rainfall mitigates these areas, but perhaps importantly there is a narrow coastal strip from Bundaberg to Cairns that remains much drier than normal, with the driest areas north of Townsville, near and including Mackay, and inland from Rockhampton, that persist through October and November.

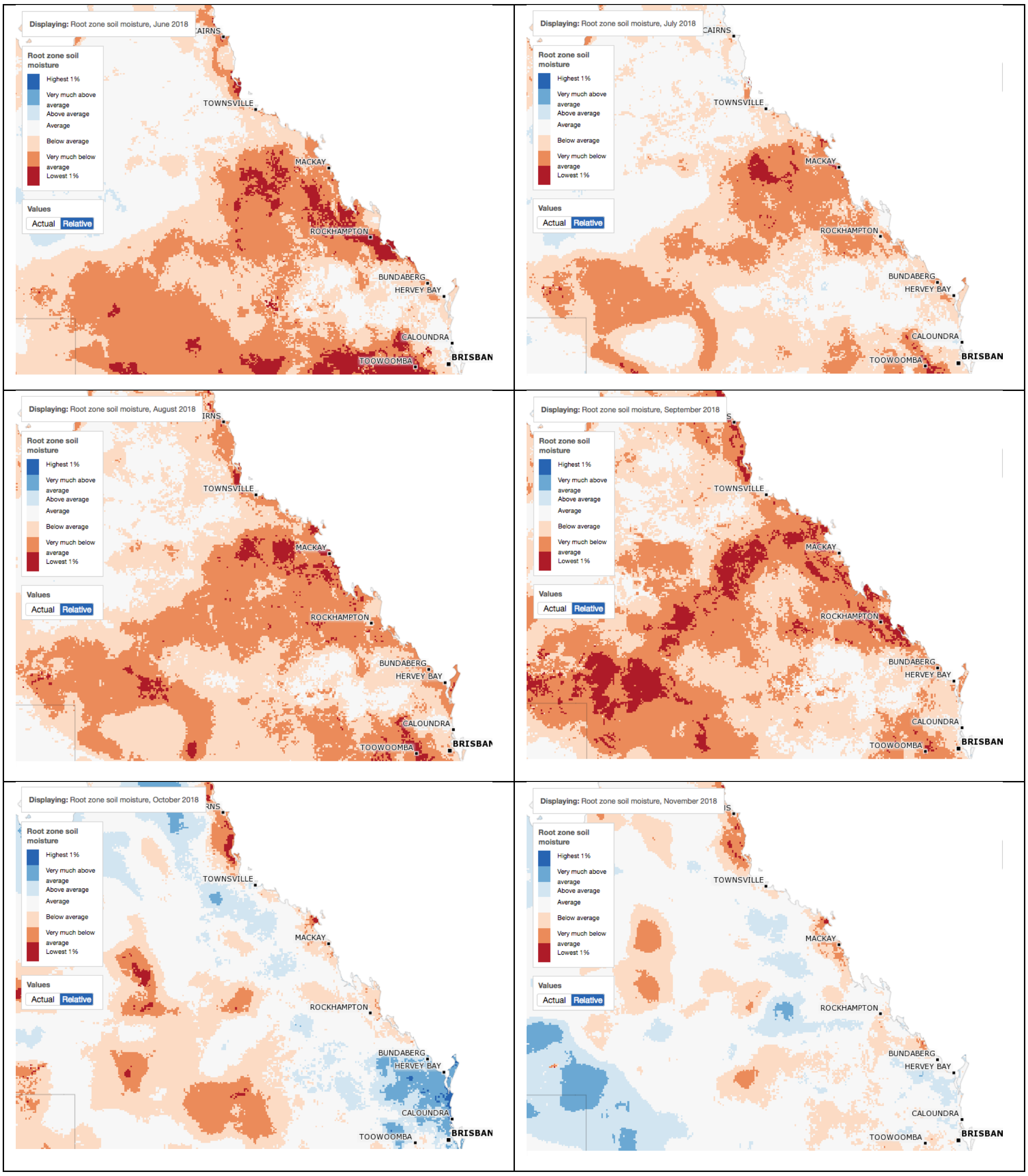

Figure 13. Root zone monthly soil moisture anomalies from June to November 2018 from the AWRA-L landscape water balance model.

A slightly different perspective is gained if the upper layer (0-10 cm) soil moisture anomaly is considered. The live fuel moisture is perhaps aligned with root zone soil moisture, while the moisture content of the litter layer is likely more aligned with upper layer soil moisture. The equivalent maps to those shown in Fig. 13, but for the upper soil layer, are shown in Fig. 14. The upper soil layer responds more rapidly than the root zone to both inputs (rainfall), and outputs (infiltration, evapotranspiration) and so while the broad patterns are similar between Figs. 13 and 14, there are some differences as well. The upper layer shows general below average soil moisture over much of the state in June through September, then a change to moister conditions following October's rainfall, although the coastal strip north of Bundaberg is less affected, as noted above in terms of lesser rainfall (Fig. 7) and root zone soil moisture (Fig. 13). November shows a rapid return to drier than normal upper zone soil moisture along the coast and ranges, and this transition is particularly evident in southeast Queensland where the positive anomalies in October rapidly changed to negative anomalies in November.

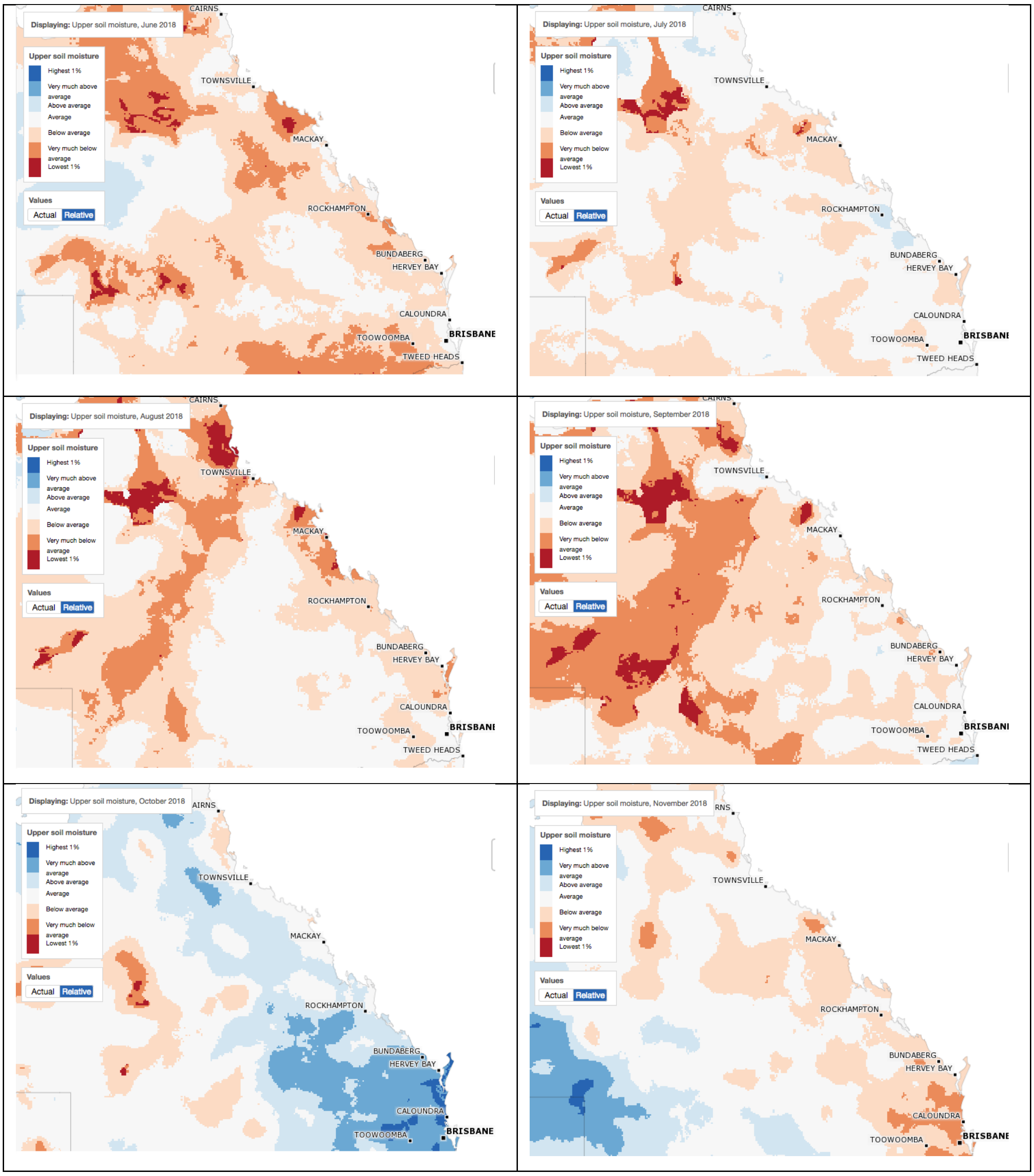

Figure 14. Upper soil layer monthly soil moisture anomalies from June to November 2018 from the AWRA-L landscape water balance model.

The dynamic nature of the upper layer soil moisture is emphasised by comparing the daily anomaly fields on 23 November 2018 and 30 November 2018 (Fig. 15) with the monthly anomaly field for November in Fig. 14. On 23 November there is widespread positive anomaly, reflecting scattered rainfall over the preceding few days (not shown), but only 1 week later on 30 November there are generally dry anomalies stretching from the NSW border to north of Mackay, and extending to the western side of the ranges.

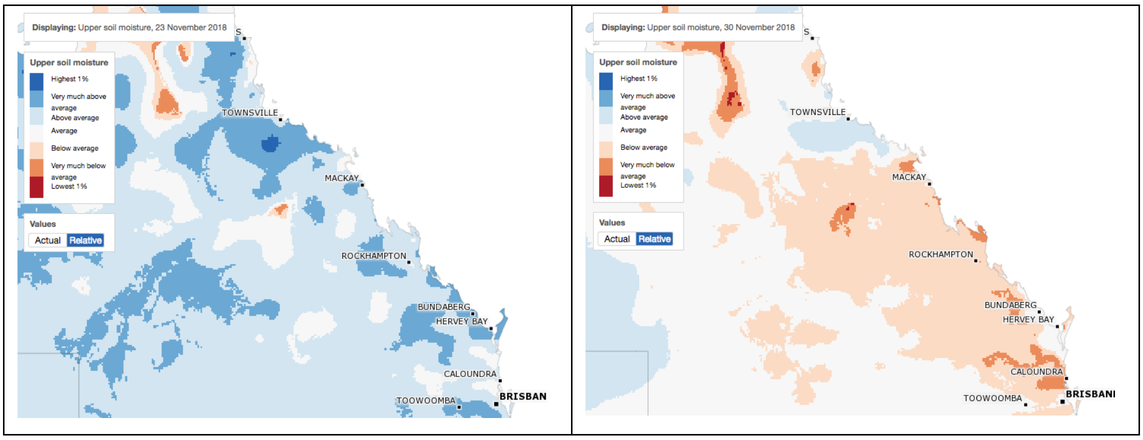

Figure 15. Upper layer soil moisture anomalies for 23 and 30 November 2018 from the AWRA-L landscape water balance model.

3.5 Keetch-Byram Drought Index

The Keetch-Byram Drought Index (KBDI) estimates soil moisture deficit based on daily rainfall and maximum temperature (Finkele et al 2006). While it is a far more simplistic formulation than is the AWRA model, it is the measure that is used in calculating the Drought Factor used in the calculation of Forest Fire Danger Index (FFDI), and fire agencies in Australia have wide experience in its use.

For the purposes of this report, the KBDI has been calculated at Cairns Airport, Townsville, Rockhampton MO, Mackay MO, and Amberley. Rockhampton was chosen for its proximity to Gracemere, , and Mackay following mention in early discussions re the burning into rainforest during the Critical Period. This was reinforced of by the ABC's presentation at https://www.abc.net.au/news/2018-12-08/from-space,-the-ferocity-of-queenslands-bushfires-is-revealed/10594662 , in which described fires burning into rainforest at Eungella, inland from Mackay. The daily time series at Cairns Airport, Townsville, and Amberley provide a wider geographic and climatological perspective. At each of these locations long-period and comprehensive records extend from the early 1940's.

The required data (daily maximum temperature and 24-hour rainfall to 9am) were downloaded from the BOM[2] and the KBDI calculated according to Finkele et al (2006a,b). The data time series were examined for large gaps in the record, and these stations selected for their consistency through the periods computed. The KBDI was calculated for the periods shown in Table 1.

Isolated missing data were filled by assuming, for rainfall, zero rain, and, for temperature, the last preceding maximum temperature. The annual average rainfall, required for the evapotranspiration estimation, was calculated for the full period for each station. The differing periods of averaging will have small consequences in the

[2] http://www.bom.gov.au/climate/data/

calculations, but will not materially affect the discussion to follow. Comparison with KBDI data acquired from the BOM for Work Package #3 of this project shows differences of less than 1 on any day over the 2018 year.

Table 1. Observation sites and periods of record for which daily KBDI was calculated.

Station	Period	Duration
Cairns Aero	1943 -2018	76 years
Townsville	1941 - 2018	76 years
Mackay	1960 – 2018	59 years
Rockhampton	1942 – 2018	77 years
Amberley	1942 – 2018	77 years

The average annual cycle of KBDI through these periods at each station was calculated by averaging the KBDI on each calendar date, and then applying a centred +/- 7 day moving average.

The daily time series for the full period at each location is shown in Fig. 16, together with the long-term smoothed average. The 2018 calendar year values are shown in Fig. 17 to better focus on the conditions leading in to the Critical Period.

The long period time-series in Fig. 16 show that there is a wide annual amplitude in KBDI at, in particular, the northern locations, with Cairns and Townsville each regularly reaching values of 200 in the dry season and 0 following the wet season. This amplitude decreases to the south, as seen in the lesser amplitude of the annual mean range for, in particular Rockhampton and Amberley. It should be remembered that the highest value of KBDI is limited to 200 in its formulation, and so is an artificial limit that does have a direct relationship with fuel state.

At Rockhampton and Amberley, and to a lesser extent at Mackay, there appears to be longer period (multi-annual) variations of wetter or drier conditions than at the two more northern stations. For example Rockhampton shows periods of several years when the soil moisture deficit remains well above zero, with the mid-1960's, the 1980's and the 2000's being readily apparent. There is some tendency for these periods to coincide with the occurrences of greatest soil moisture deficit.

A qualitative inspection of Fig. 16 suggests that the peak values of KBDI recorded in November at these stations, while unusual, are not unprecedented. A percentile analysis of the highest value at each station for November KBDI (Table 2) shows that the values recorded at Cairns, Rockhampton, Mackay and Amberley were above the 90th percentile of values calculated for November, and at Mackay was above the 96th percentile – equivalent to an average expectancy of around 1 day/month.

Table 2. Highest value of KBDI at each station during November 2018, and its percentile ranking for all November days in the record.

Station	No of days	Highest KBDI Nov 2018	Percentile Rank	Equivalent days/month
Cairns	2280	200.0	94.1	1.8
Townsville	2340	189.4	67.7	9.7
Mackay	1770	194.5	96.6	1.0
Rockhampton	2370	174.4	91.6	2.5
Amberley	2310	150.4	91.8	2.5

The daily time series of KBDI or 2018 (Fig. 17) show some common features between stations, and also some differences. All show an increase after the wet season ceases, but this occurs later at Mackay and Townsville. There is then a sustained period where the KBDI is above the long-term average before rainfall resumes in early December. Townsville is the only location where the KBDI falls below the long-term average through this period, although the southeast Queensland rains in October did substantially reduce the deficit at Amberley.

Rockhampton is distinctly different from the other locations and with KBDI being essentially drier than the long-term average from the beginning of the calendar year.

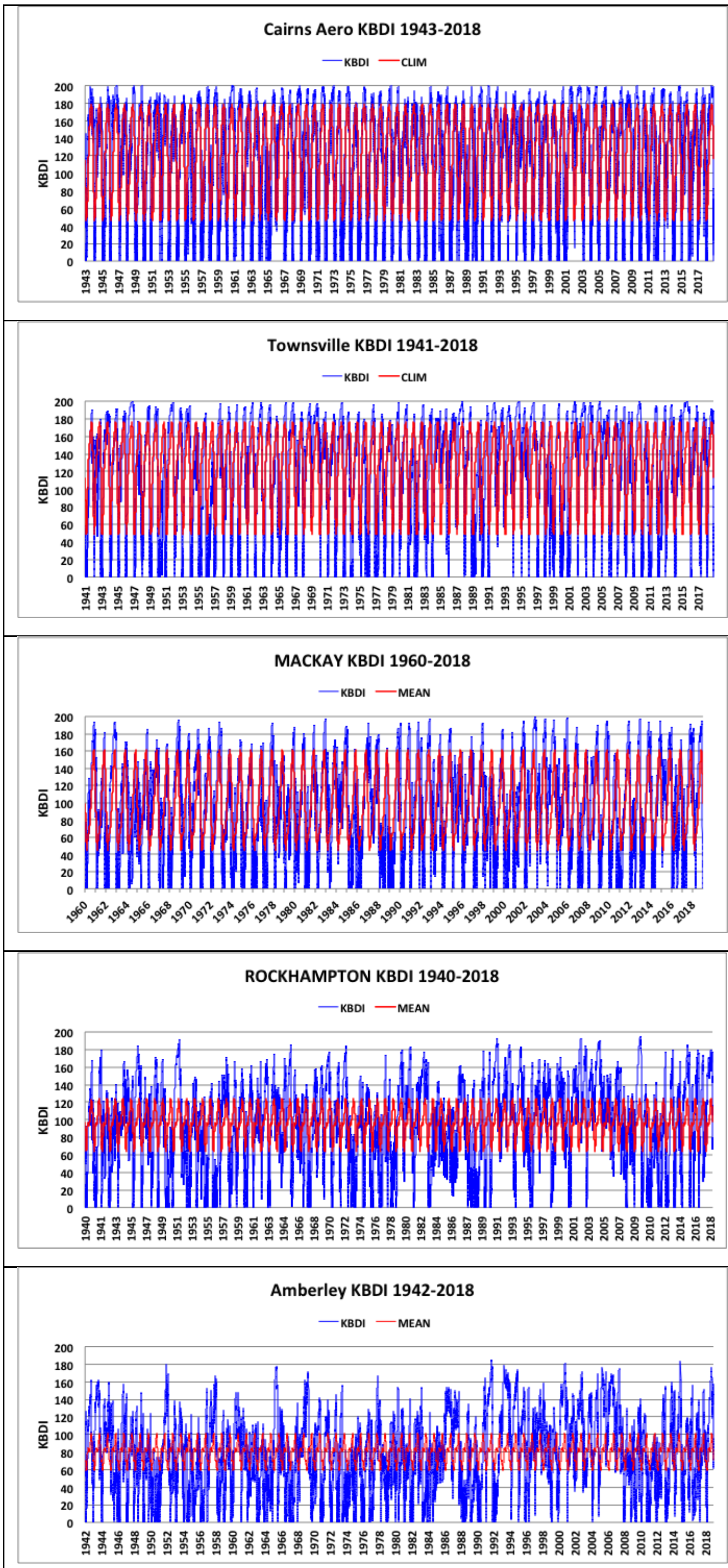

Figure 16. Daily time series of KBDI (blue) and daily mean KBDI (red) at Cairns Airport, Townsville, Mackay, Rockhampton, and Amberley for the full period of records at each location.

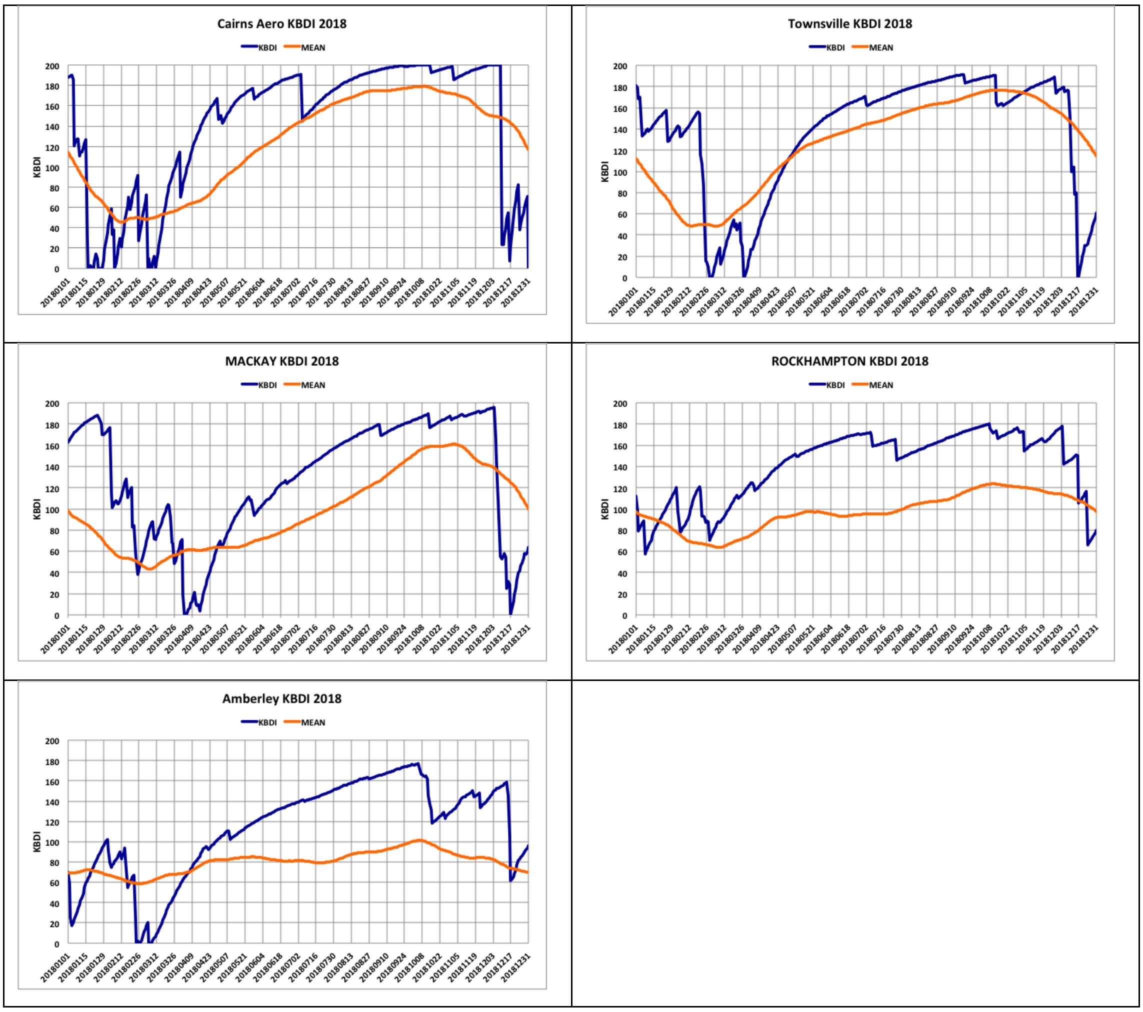

Figure 17. Daily time series of KBDI (blue) and daily mean (orange) at Cairns Airport, Townsville, Mackay, Rockhampton, and Amberley for the 2018 calendar year.

While many of the above statistics indicate unusually high KBDI, these are not unprecedented values. However, all stations show a sustained period of above average (drier than normal) KBDI. In order to explore the climatological ranking of these sustained deficits, Fig. 18 shows, for the above 5 stations, the accumulated difference between calculated daily and daily mean KBDI from 1 March (the approximate climatological minimum) to the end of November 2018.

At Cairns, Mackay, and Rockhampton the 2018 anomalies are each the 3rd highest in the record, while Amberley has the 9th highest in its record in spite of the effects of the October rainfall. It must be remembered that this accumulated anomaly is at this stage a curiosity-driven analysis, and has no body of knowledge relating it to fuel state. These statistics do, however, put the periods of above average KBDI seen in Fig. 17 into some climatological context, and show that at several of these stations the accumulated KBDI anomaly was highly unusual. Such a measure may be worth exploring in relation to fuel states, and similar analyses based on AWRA soil moisture analyses may also prove instructive.

Figure 18. Accumulated March-November difference between daily and daily climatological KBDI for all years of record at Cairns, Townsville, Mackay, Rockhampton and Amberley.

Thus, while the KBDI values at these locations were not unprecedented, in total the various statistics indicate highly unusual values of soil moisture deficit, both leading into and at the time of the heatwave period in late November 2018. These conclusions are qualitatively consistent with he soil moisture anomalies discussed in Section 3.4.

KEY POINTS : SECTION 3

- There were widespread below average rainfall, atmospheric humidity, and soil moistures measured over Queensland during the months following June 2018, and leading up to and including the Critical Period.
- There were widespread warmer than average temperatures over much of Queensland during the same months.
- While many of the measures of moisture deficit were not unprecedented, many were in their lowest 5-10% of occurrences.
- The duration of some of these deficits was extended, and studying the effects of extended moisture deficit on fuel moisture may prove instructive.
- The relationships between the rainfall deficit, AWRA and KBDI deficit, and atmospheric humidity deficit, and fuel state may prove instructive.

4. SEASONAL OUTLOOKS

The BOM issues 3-monthly seasonal outlooks twice per month. These are based on an ensemble of global Numerical Weather Prediction (NWP) model forecasts using (from August 2018) the BOM ACCESS-S[3] numerical model (Hudson et al 2017). This model has higher resolution than its predecessor, so the character of the maps has changed slightly after August 2018, and the accuracy of the forecasts is improved: however, these changes in accuracy and structure are unlikely to affect the conclusions to be drawn in this report.

The outlook issued on 12 July 2018 is that used in the NASBA (see Section 2). Rainfall and temperature outlooks are couched in terms of "probability of exceeding median rainfall/maximum temperature" over the following 3-months. These outlooks are issued twice per month.

Figures 19-22 show the probability for above median rainfall and for above median maximum temperature for the outlooks issued 12 July, 26 July, 16 August, 30 August, 13 September, 27 September, 11 October, and 25 October 2018, with verifying anomaly maps from the AWAP data set shown in the lower row of each panel set. The July, August, and September outlooks are for the 3-month periods August-October, September-November, and October-December respectively (Figs 19-21), while the October outlooks show only the outlook for November (Fig. 22).

For temperature, successive outlooks are very consistent, predicting greater than average probability of above median maximum temperatures over Queensland, with large areas having a greater than 80% chance of exceeding the median maximum temperature. The verifying analyses (as discussed in Section 3 of this report, and in the lower panels of Figs. 19-22) show consistently above to well above average temperatures over most of Queensland throughout these verifying periods.

The rainfall outlooks show rather more variability than do the temperature outlooks. However, for almost all the outlooks there is a very consistent below to very much below average probability of exceeding median rainfall over much of Queensland, and broadly the verification analyses are consistent with these. There is even an indication of lower probabilities of above median rainfall before and after October, with some areas of near average probability over southeast Queensland indicated in the August outlooks (Fig. 20), with a return to much lower probabilities of above median rainfall for the later outlooks, and the late spring periods (Figs. 21 and 22).

The verifying analysis fields indicate an encouraging level of qualitative accuracy. The BOM website[4] includes objective verification of their seasonal outlooks.

Overall the seasonal outlooks showed considerable consistency from issue to issue, with (broadly) predictions of above average probability of higher than normal temperatures and lower than normal rainfall. The consistency of these outlooks, and particularly the outlooks issued on and after 16 August 2009 that included the Critical Period, supported the NASBA that highlighted the Capricornia and Central Coast as having above normal bushfire potential.

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[3] http://poama.bom.gov.au/general/access-s.html

[4] http://www.bom.gov.au/climate/ahead/about/#tabs=Past-accuracy

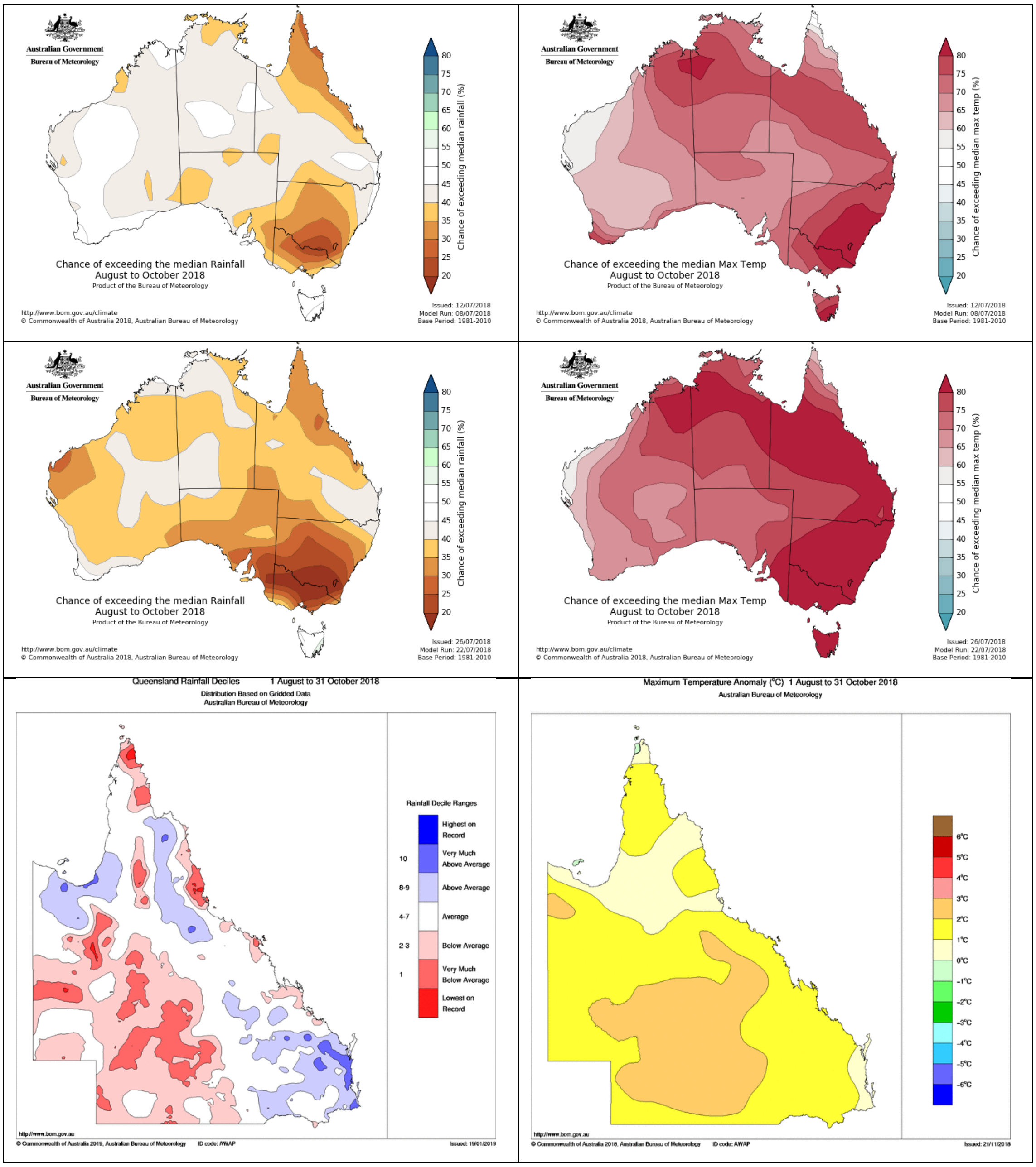

Figure 19. Seasonal outlook for rainfall and temperature issued 12 July 2018 (top) and 26 July 2018 (middle) for the August-October period. Lower panels show the verifying rainfall deciles and maximum temperature anomalies for the outlook period from the AWAP analyses.

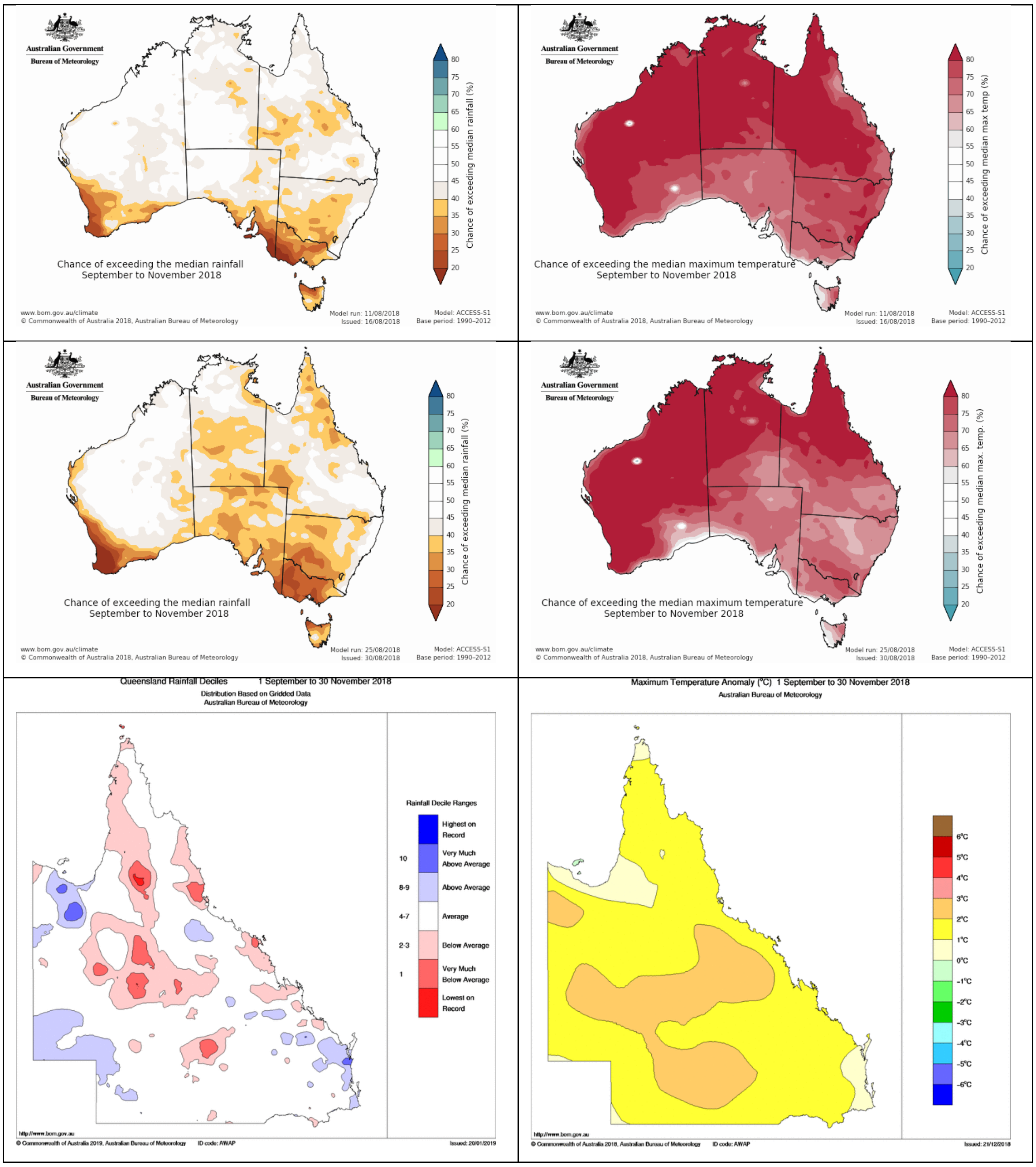

Figure 20. Seasonal climate outlooks for rainfall and temperature issued 16 August 2018 (top) and 30 August 2018 (middle) for the September-November period. Lower panels show the verifying rainfall deciles and maximum temperature anomalies for the outlook period from the AWAP analyses.

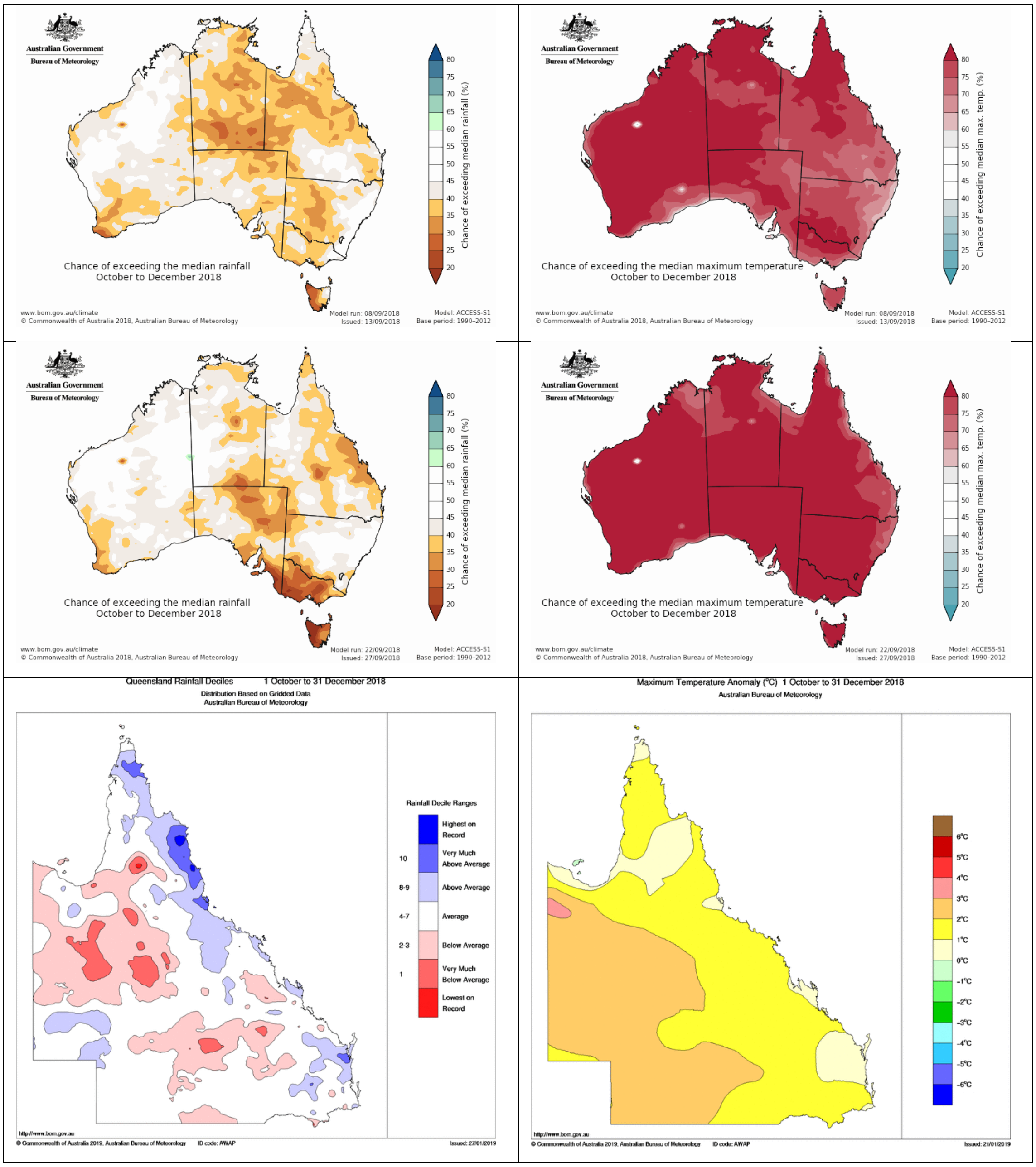

Figure 21. Seasonal climate outlooks for rainfall and temperature issued 13 September 2018 (top) and 27 September 2018 (middle) for the October-December period. Lower panels show the verifying rainfall deciles and maximum temperature anomalies for the outlook period from the AWAP analyses.

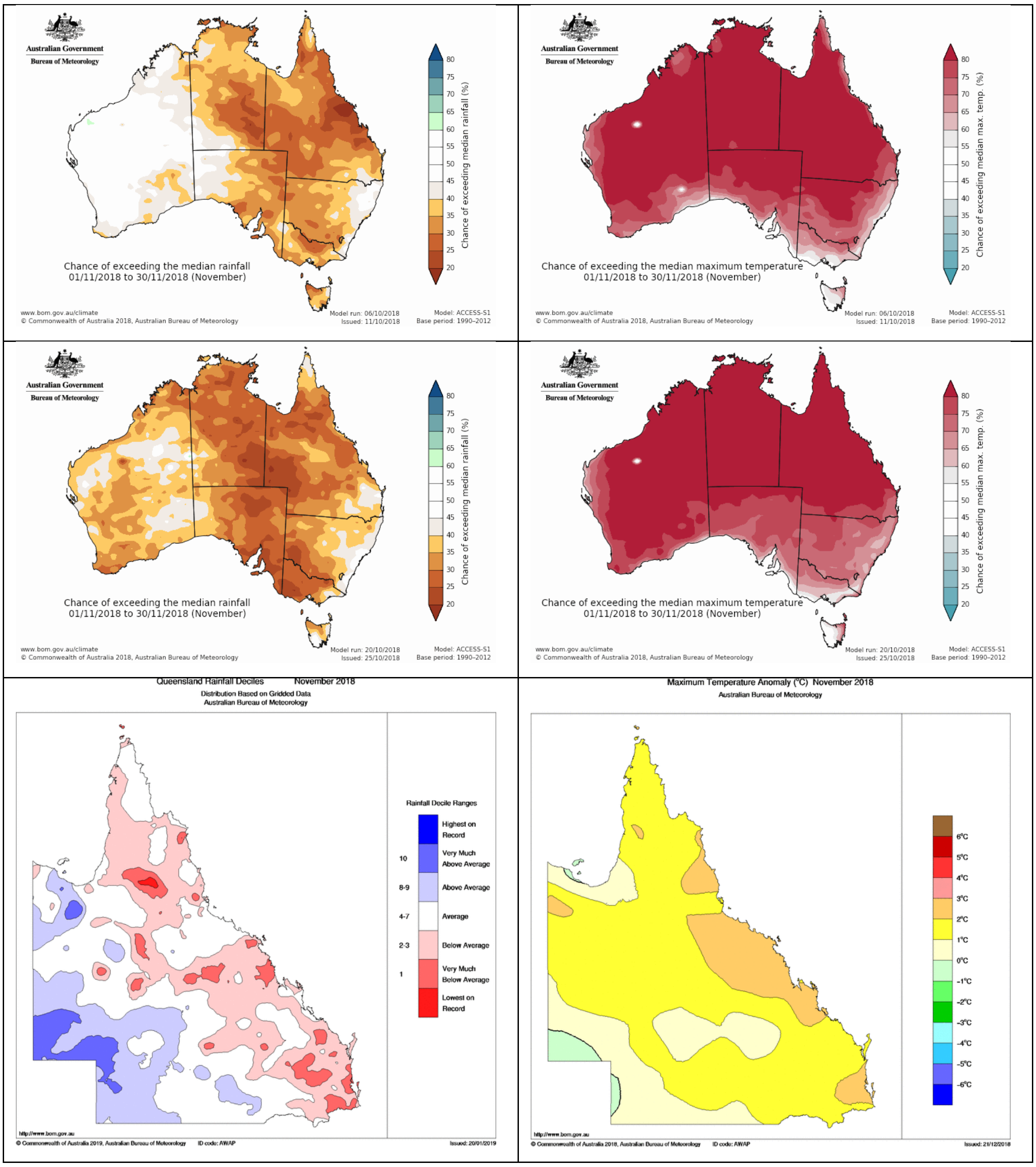

Figure 22. Seasonal outlooks for rainfall and temperature issued 11 October 2018 (top) and 25 October 2018 (middle). Note these panels are for 1-month rather than 3-month periods due to shorter lead-time to the Critical Period. Lower panels show the verifying rainfall deciles and maximum temperature anomalies for the outlook period from the AWAP analyses

KEY POINTS : SECTION 4

- Successive BOM seasonal outlooks issued between June and October 2018 were consistent in their anticipation of above average probability of lower than median rainfall and higher than median temperatures over Queensland.
- These conditions were broadly experienced
- The consistency of these outlooks supported the NASBA outlook prepared in late June.

5. HEATWAVES AND THE CRITICAL PERIOD

5.1 Overview

The Bureau of Meteorology Special Climate Statement 67 (Bureau of Meteorology 2018b), hereafter SCS67, describes the heatwave over the northern Queensland coastal areas that occurred between 24 November 2018 and 29 November 2018. In that report the areas where long-standing temperature records were broken, and the margins by which previous November maximum temperature records were broken, are shown (Fig. 23).

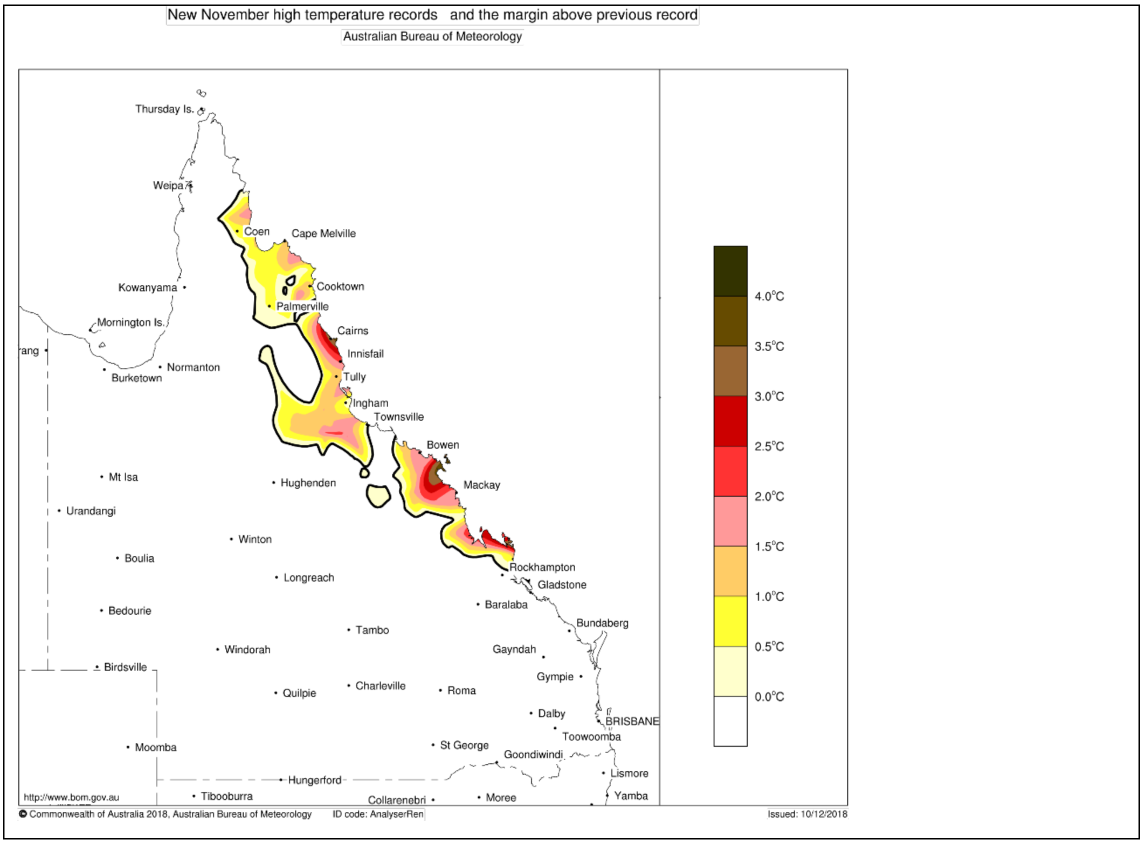

Figure 23: Areas in the BOM gridded analysis data that set a new record-high November temperature between 25 and 29 November 2018, and the margin by which the previous record was exceeded (from Bureau of Meteorology 2018, their Figure 9).

One notable feature of the event was the margin by which some temperature records were broken – the highest margin at a single station with a long period of records was at Cairns Airport where the old record of 37.2C was exceeded by 5.4C on 26 November 2018. This was the highest November temperature since 1971. Further, the previous highest temperature (on 15 November 1971) only exceeded the next highest temperature by 0.3C.

Given the average maximum temperature at Cairns Airport in November is 30.7 (1942-2018), and that the standard deviation of the November maximum temperature there is 1.45C, the temperature on 26 November exceeded the mean by 8.5 standard deviations!

The fact that the now 5 highest November maximum temperatures at Cairns Airport occurred on 26, 27, 28, 29, and 30 November 2018 highlights the unprecedented nature of the temperatures experienced during the Critical Period.

Similar, if less spectacular, records were set at other stations as well. At Mackay 5 of the highest 7 November maximum temperatures experienced to date were set between 24 and 28 November 2018, and at Rockhampton 3 of the highest 6 ever November maximum temperatures were recorded on 25, 26, and 28 November.

A number of other aspects of the event are featured or mentioned in the report, including maps of the heat wave severity (Excess Heat Factor, EHF), Nairn and Fawcett 2013, 2015, 2017), which indicates the extent of the heat wave and documented other notable Queensland heatwaves, the role of low-pressure systems over NSW in advecting hot air from the interior of Queensland to the coast, and which were climatologically anomalous, and the Forest Fire Danger Index (FFDI) which exceeded the Catastrophic rating at locations including Rockhampton on 28 November 2018.

In the remainder of this section the background of these features of the Critical Period is explored by reviewing the theory of heatwave development and of measurement, and presenting aspects of the weather and the climatology of the region during the Critical Period that have relevance to the extraordinarily high FFDI values observed. As FFDI is a function of Drought Factor, temperature, wind speed and relative humidity, some discussion of the wind and relative humidity climatology at selected locations will be presented to contextualize the spatial anomaly maps in Section 3 of this report, and the vertical stability environments observed during the heat wave will be described.

5.2 Circulation Patterns Leading to Heatwave Events

The literature regarding heat waves has tended to focus on the mid latitudes as reviewed by Perkins (2015), and by Parker and Reeder (2014) in their analysis of the January 2009 heatwave over southeast Australia. These papers identify the main ingredients leading to a heat wave:

- the presence of a mid- to upper-tropospheric[5] anticyclone that leads to prolonged subsidence and thus warming at mid-tropospheric levels,
- a slow-moving near-surface synoptic pattern that allows re-circulation in the lower troposphere in the region of the upper anticyclone.
- Parker (2015) also indicates a role for lower than normal soil moistures which allow a greater proportion of incoming energy to be partitioned into surface sensible heat flux rather than latent heat flux, thus heating the boundary layer of the atmosphere to a greater extent.

It is broadly the combination of these ingredients that leads to the development of a pool of hot air over a continental land mass.

The final ingredient is some synoptic-scale weather system that advects this hot air from its source area to a more climatologically benign environment where the impact and deviation from climatology is relatively greater than at the source of the hot air. Such an example is that of late January 2009 over Victoria in the period leading to Black Saturday when extremely hot air was advected southwards over southern

[5] The *troposphere* is the lowest layer of Earth's atmosphere. Most of the mass (about 75-80%) of the atmosphere is in the *troposphere*. Almost all weather occurs within this layer. It extends typically to 10-12km above the earth's surface over Queensland.

Victoria by, generally, weak cold frontal systems. SCS67 points to the role of the low-pressure system over NSW in causing this advection during the Critical Period.

Leading into November 2018 the temperature anomalies in Fig. 9 show that, particularly in October, a huge pool of extremely hot air developed over central and southwest Queensland, and was seen further east, albeit with lesser amplitude but perhaps greater impact (see next section), through November. The soil moisture deficits (Figs. 13, 14) are consistent with Perkin's comments re association of below normal soil moisture and heatwave development.

In order to assess the mid-troposphere ingredients, the mean circulation in the over eastern Australia during November in the period leading to the heatwave is now discussed. Figure 24 shows the 400 hPa (approximately 6 km) geopotential height composite (the average of all 6-hourly analyses) for 1-23 November 2018, together with the composite vector wind and vertical motion, from the NCEP reanalysis data[6] on the left panels. The same fields for the last week of November, the period of the coastal heatwave, are shown on the right.

During the first three weeks of November (Fig.24, top left) a broad upper ridge extends from the Gulf of Carpentaria southwards through Queensland. The wind field shows anticyclonic curvature through this ridge. A large area of subsidence covers most of northern Australia, with the highest values over the central Queensland coast.

The anomalies (deviation from long-term climatology) of the geopotential height and vector wind fields are shown in Fig. 25. The geopotential height anomaly field for 1-23 November shows an elongated positive anomaly from northwest Western Australia to northern NSW, while the vector wind anomaly, showing the anomaly in circulation over the area, shows an elongated anticyclonic centre, coincident with the geopotential anomaly. The easterly wind anomaly to the north indicates weaker than normal westerly winds.

The last week of November (Fig. 24, right column) shows a considerable change from the pattern of the previous three weeks, with location of the upper ridge moving westwards to near 130E and low pressure centre in the Tasman Sea. This leads to a stronger pressure gradient over northern NSW and southern Queensland with a vigorous a west-southwesterly jet stream developing there. This evolution of the circulation is an integral part of the development of the low pressure systems over NSW that generated the westerly advection of hot air from the interior of Queensland to the coast during this period (SCS67). During this week the composite mean subsidence is focused over south-Central Queensland. The maximum average rate of subsidence is some 1 Pa s^{-1}, or ~36 hPa hr^{-1}. While air parcels would not sustain this rate of subsidence for extended periods, as they would pass through these zones of subsidence, this would equate to an adiabatic warming of some 0.7C per hour (~16 C/day), and thus contribute significantly to any accumulated heating.

The most positive geopotential height anomalies in the last week of November (Fig.25) extend from the Northern Territory eastwards crossing the Queensland coast around the Herbert and Lower Burdekin district and into the Coral Sea, while the circulation

[6] https://www.esrl.noaa.gov/psd/data/composites/hour/

anomaly shows an anticyclonic centre over the Barkly Tableland. Importantly, the jet stream over southern Queensland is much stronger than the climatological strength.

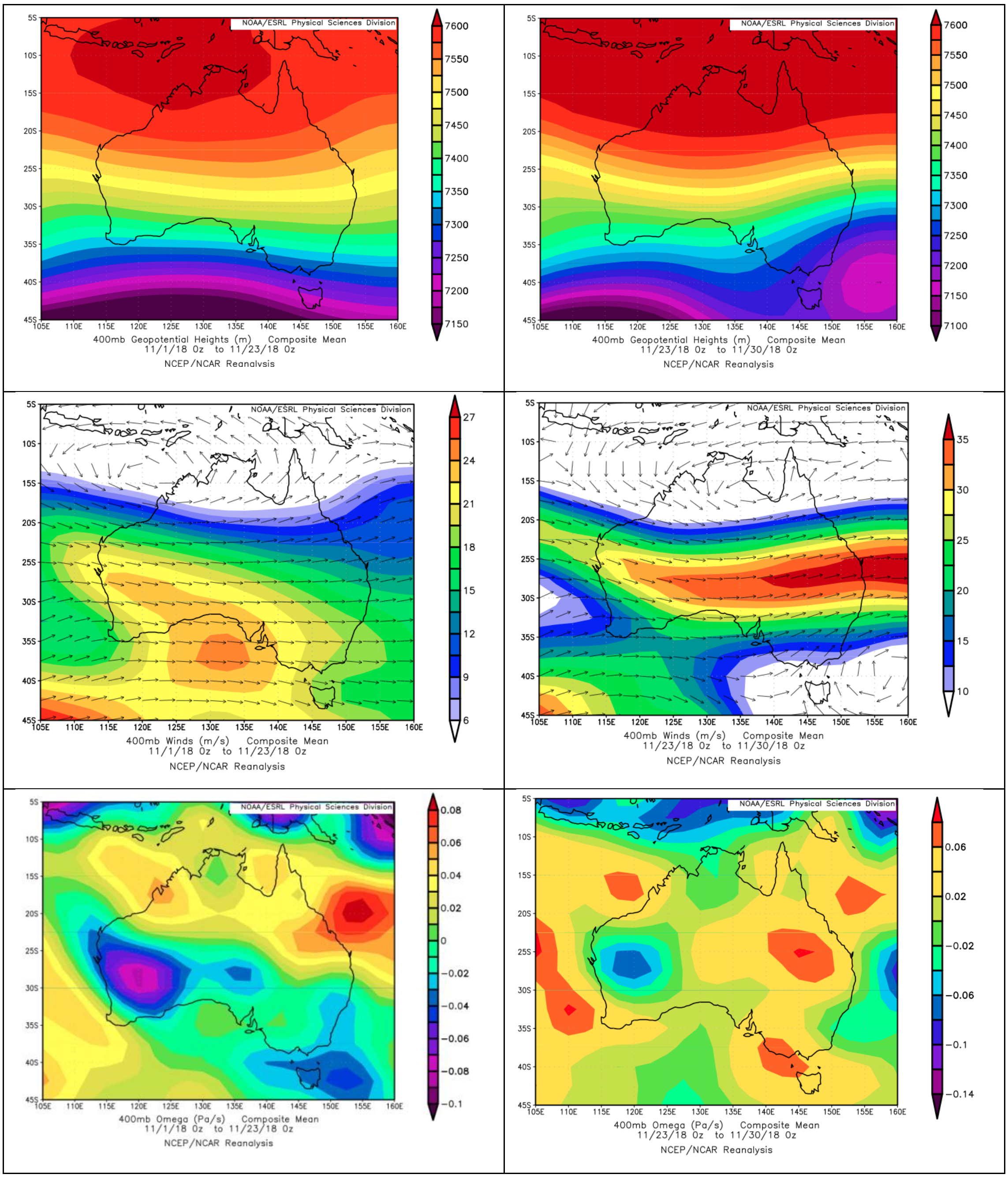

Figure 24. Top row shows composite 400 hPa geopotential height fields, middle row composite 400 hPa vector wind patterns with shaded wind speeds, and the lower panels show composite 400 hPa vertical motion (positive values show descending motion) from 6-hourly NCEP reanalyses. Left column show a composite of for 1-23 November 2018, right column for 23-30 November 2018. The date convention is month/day/year.

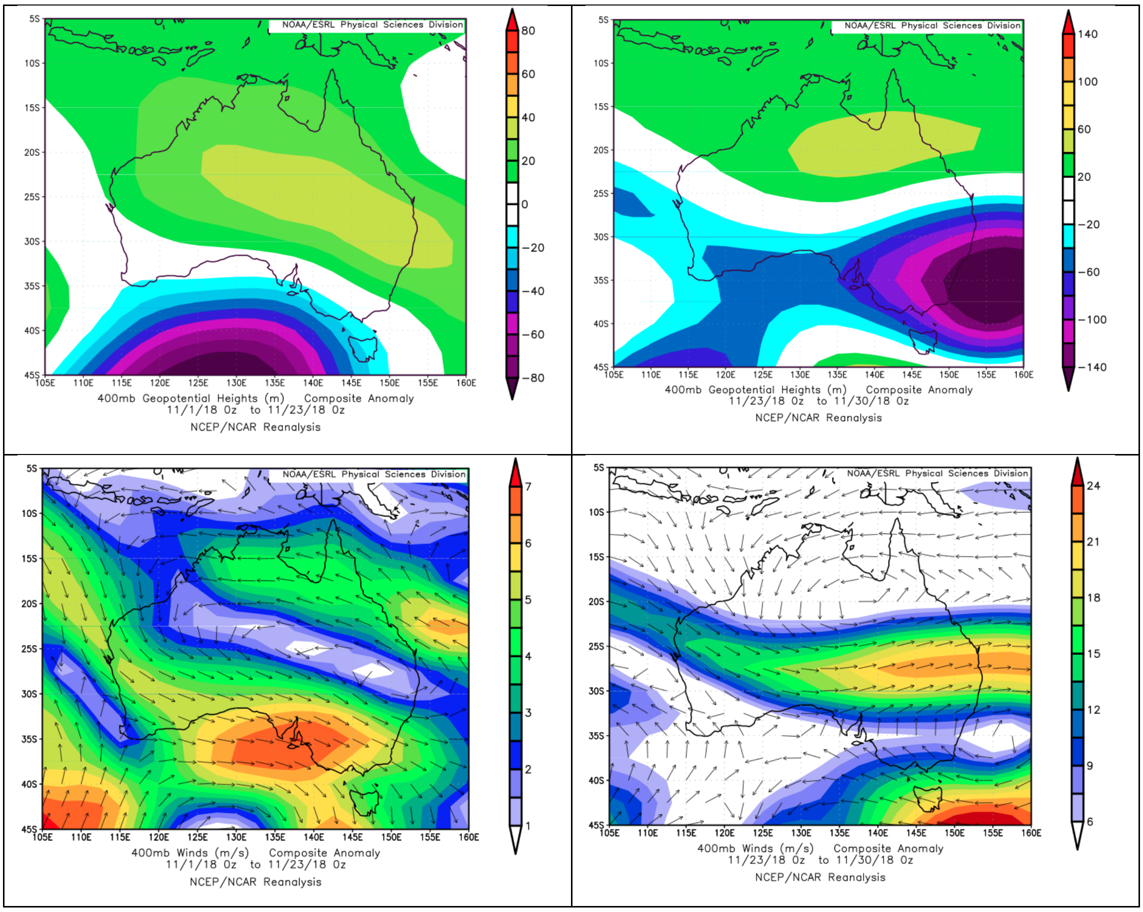

Figure 25. Top row shows composite 400 hPa geopotential height anomaly fields and lower panels show composite 400 hPa vector wind anomaly patterns with shaded wind speeds from 6-hourly NCEP reanalyses. Left column show a composite of for 1-30 November 2018, right column for 23-30 November 2018. The date conventions are month/day/year.

The change in low-level circulation between the first three weeks of November and the Critical period is seen in Fig.26, where the mean 1000 hPa (near surface) circulation patterns for those two periods are shown. Prior to the critical period the circulation over Queensland was generally weak easterly. However, there is an abrupt transition in the last week of November when stronger southwesterly flow covers all but western parts of Queensland. Notably the strongest band of southwesterly winds crosses the coast near Capricornia.

This transition from weak flow during the development of the pool of hot air over central Queensland to a system that advects this hot air to the coast is very consistent with the quoted studies of heatwave events.

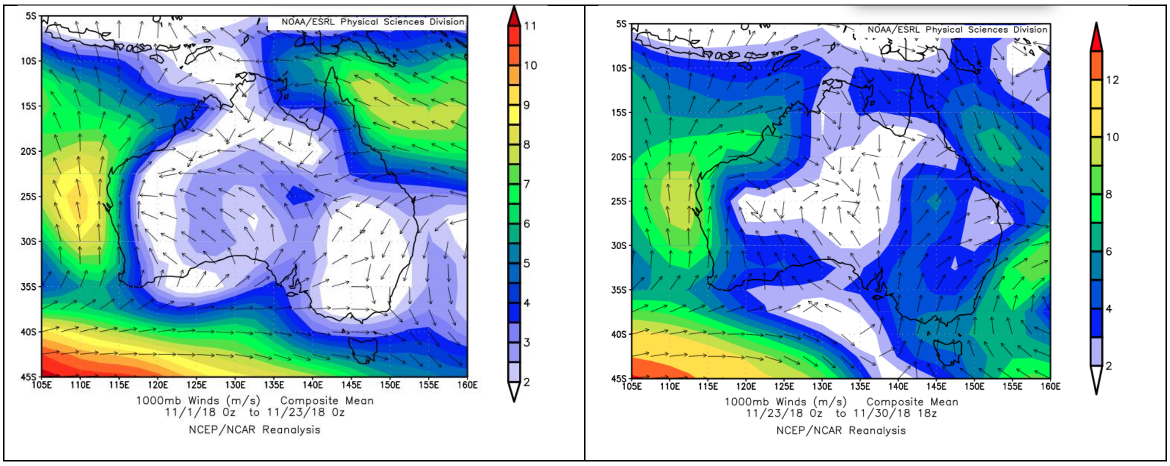

Figure 26. Composite 1000 hPa (near surface) wind fields from 6-hourly NCEP analyses. Left, 1-23 November 2018, right 23-30 November 2018. The date conventions are month/day/year.

Thus, while the broad ingredients (upper anticyclone, slow movement) noted in studies of heatwaves in other regions, as reviewed by Perkins (2015), were broadly present in this case, these patterns in the mid-troposphere were more apparent in the anomaly fields than they were in the fields themselves. Whether this is common to other Queensland heatwave events, or peculiar to this event, is not determined, and an exhaustive diagnostic analysis would be required to fully understand the detailed dynamic and kinematic evolution of the atmosphere over Queensland prior to and leading up to the heat wave. However, a more comprehensive study of Queensland heatwave events may provide a better understanding of the circulation patterns and anomalies that lead to such lower latitude heatwaves.

5.3 Measures of Heatwave Intensity

Perkins (2015) reviews several definitions of heatwave that have been used in the published literature. Most use a local percentile of temperature as a threshold, often with a duration criterion as well. The BOM issues heat wave advisories based on the Excess Heat Factor (EHF) developed by Nairn and Fawcett (2013, 2015,2017) which is a variant of this type of definition. The EHF consists of two components, the first designed to measure the significance (EHI_{sig}) of the event relative to the local climatology, and the second (EHI_{acclim}) a measure of acclimatization:

- EHI_{sig} = (3-day average temperature) – (95th percentile of average temperature)
- EHI_{acclim} = (3-day average temperature) – (previous 30-day average temperature)
- Multiplied, these comprise the EHF

Heatwave conditions are then defined as follows:

- A heatwave occurs when EHF>0
- A severe heatwave occurs when the EHF exceeds the 85th percentile of EHF at that location (EHF_{85})

- An extreme heatwave is defined to be when $EHF > 3*EHF_{85}$

It is these definitions that are used in the maps of heatwave severity that were published in SCS67.

During the Critical Period the most extreme heatwave severity was experienced along the Queensland coast from Lockhart River south to near Bundaberg (Fig. 27), and became less severe inland.

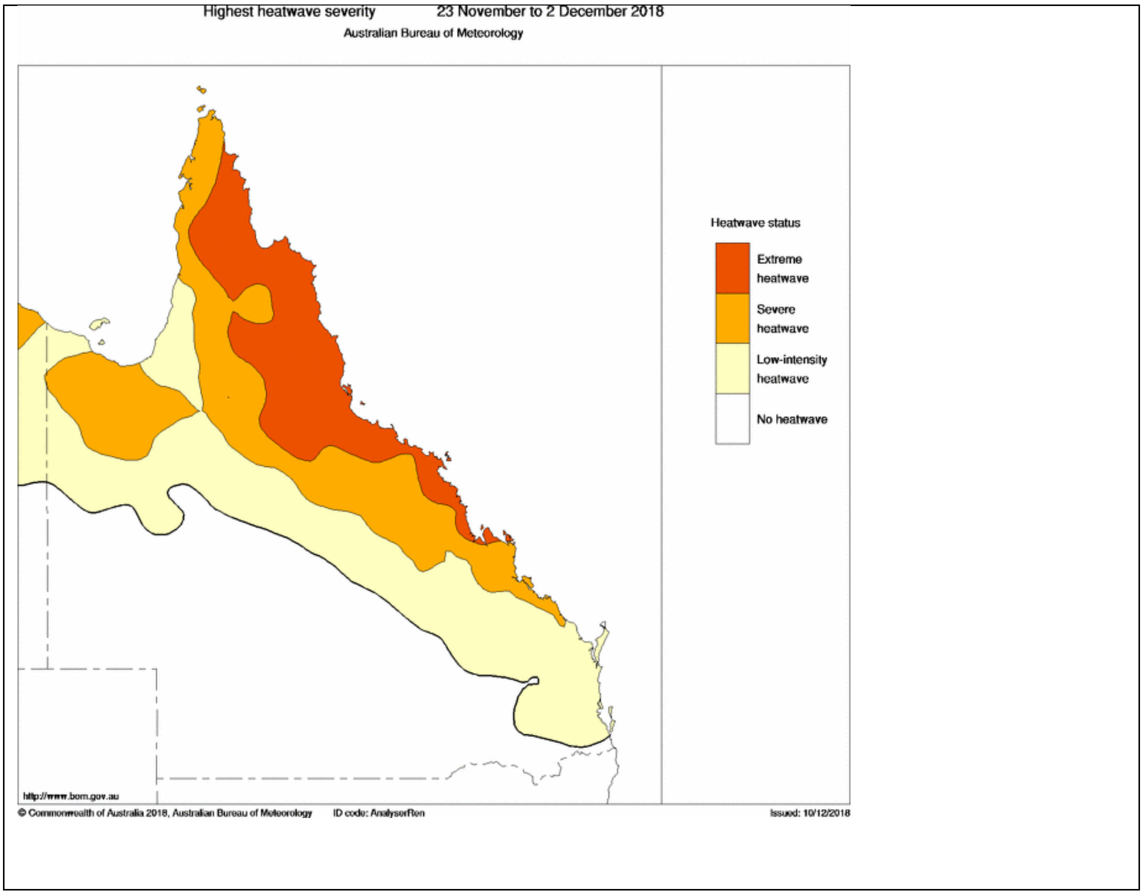

Figure 27. Maximum heatwave severity category during the event. (from SCS67, Bureau of Meteorology 2018)

In SCS67 several other notable Queensland heatwaves are documented, most of which have strong signals along parts of the coast.

Nairn and Fawcett (2017) present a climatology of Queensland heatwaves and show that there is some tendency for both Severe and Extreme heatwaves to occur along the north Queensland coast (Figs. 28 and 29) at similar frequencies to those farther inland. While the climate along the coastal side of the ranges is generally moderated by the influence of the sea, the fact that there are climatologically higher temperatures generally experienced inland from the divide means that if these warmer air masses do move over the coastal strip both components of the EHF tend to be large, leading to heatwave conditions in coastal regions.

Nairn and Fawcett (2017) also show that there has been a trend for more such events in latter years (1986-2015) than in their base 1951-2011 period (although the period for later events overlaps that used in the baseline analysis).

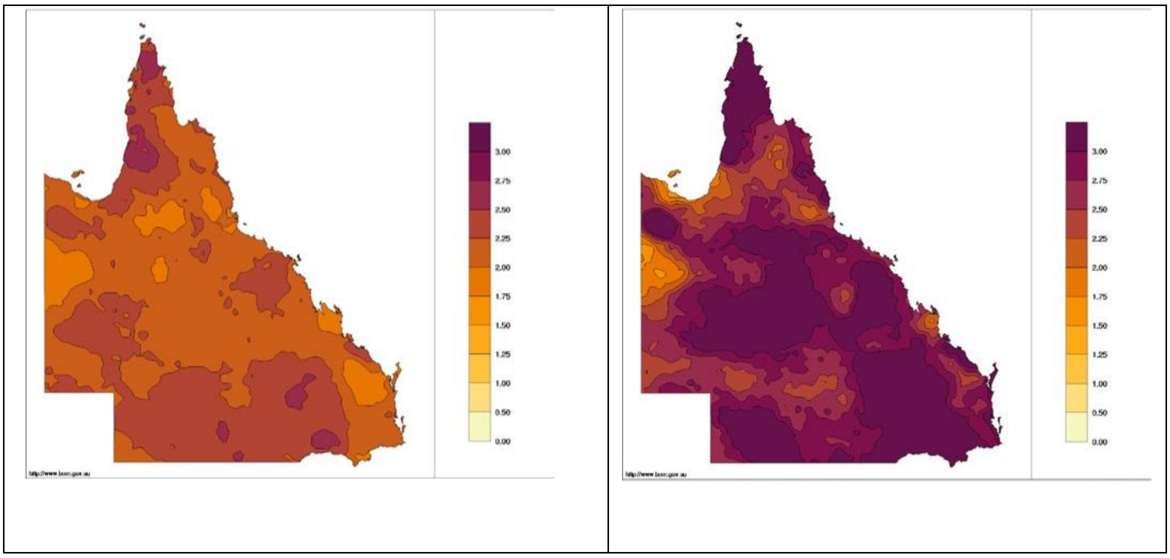

Figure 28. Average annual number of three-day periods with EHF greater than "severe heat wave EHF_{85}"(left 1958-2011, right 1986-2015), from Nairn and Fawcett 2017.

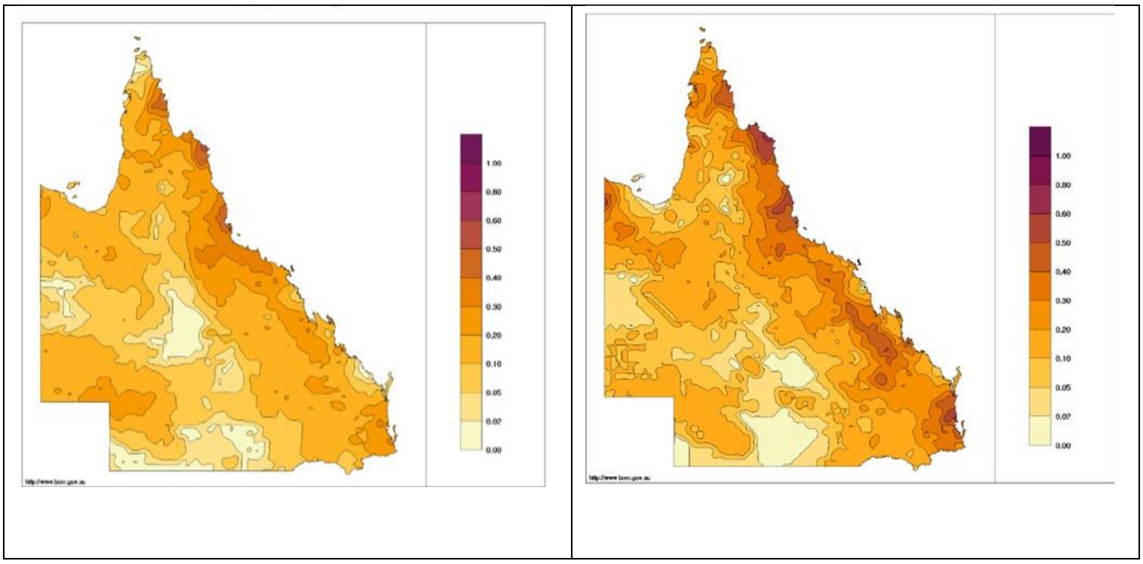

Figure 29. Average annual number of three-day periods with EHF greater than 3 times EHF_{85} criterion for an Extreme heatwave (left 1958-2011, right 1986-2015) from Nairn and Fawcett 2017.

Perkins and Alexander (2013) also show, using slightly different metrics and independent data, a positive trend in heatwave days over the 1951-2013 period, with a similar distribution to Figs. 28 and 29.

These analyses indicate that severe or extreme heatwaves along the Queensland coast are not unprecedented, and there is some indication that this frequency has been increasing in recent decades. It should be noted though that while not unprecedented in occurrence, this heatwave was perhaps unprecedented in terms of record temperatures and duration of temperature.

5.4 Wind Climate and the Heatwave

As argued in the previous section it is likely that heatwave index events, and extreme maximum temperatures, on the Queensland coastal strip are associated with westerly wind events, with the generally maritime warm humid air being replaced by hot, dry air from the interior. Such a scenario potentially brings together three factors that all contribute to enhanced FFDI, particularly in periods of drought. While it is not a necessary condition for westerly winds to be strong in order to advect hot dry air masses eastwards, the FFDI formulation is highly sensitive to wind speed, and this sensitivity increases as the FFDI increases (Dowdy et al 2009, 2010), and so if these westerly winds are strong, then high levels of FFDI are likely to ensue.

This issue is first explored by presenting a series of back trajectory plots – the path of the air that reaches a certain spot at a certain time. The HYSPLIT model (Stein et al 2015, available at the NOAA/ARL web site[7]) was used to generate these trajectories, and three examples are presented here: paths ending at 1500 AEST (0500 UTC) on 25 November at Gracemere, at 1500 AEST (0500 UTC) on 28 November at Deepwater, and at 1500 AEST (0500 UTC) 26 November at Eungella. The “ensemble” option was chosen to allow some assessment of the sensitivity of the results to small perturbations in the input meteorology. These three plots are shown in Fig. 30.

Each of the three panels show lengthy west to southwest paths of the air reaching the end-point locations, with the air having been over central Queensland only 24-hours prior. The first and third examples do, though, show that there was likely a near-coastal gradient with air parcels just to the east of the specified end points having some likelihood of an origin farther north.

[7] https://ready.arl.noaa.gov/HYSPLIT.php

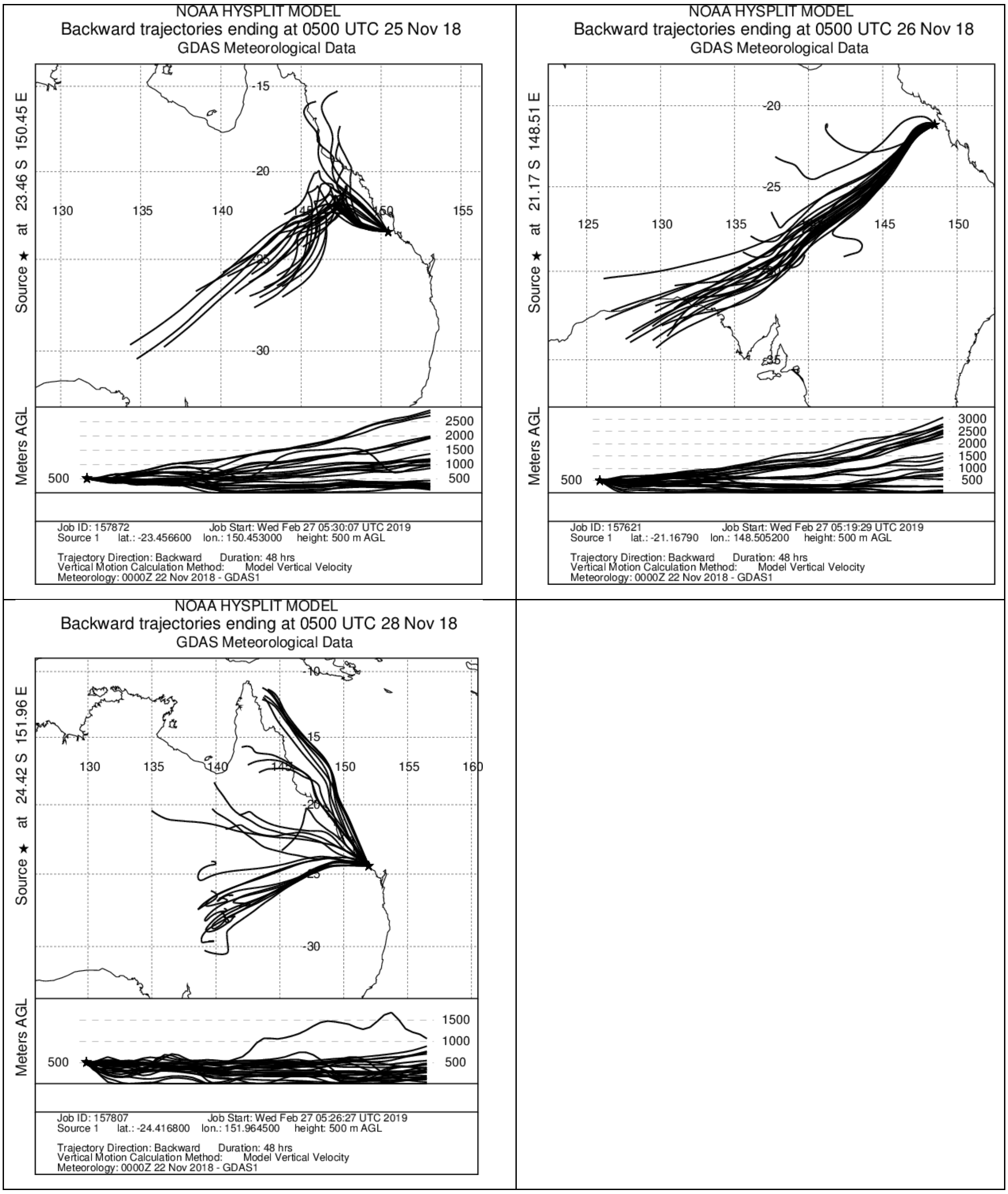

Figure 30. Forty-eight hour back trajectories for air parcels reaching a location near Gracemere at 1500 AEST (0500 UTC) on 25 November 2018 (top left), a location near Eungella at 1500 AEST (0500 UTC) on 26 November 2018 (top right), and a location near Deepwater at 1500 AEST (0500 UTC) on 28 November 2018 (bottom left).

The wind climate of the area is limited, as it is in most parts of the country – see Jakob (2010) for discussion and description of this issue. The BOM[8] publishes wind roses for 9am and 3pm for a number of stations at which long-term records are available, and in the region of interest to this report Rockhampton and Mackay are available. These wind roses for November are shown in Fig. 31, and text versions of these data are

[8] http://www.bom.gov.au/climate/averages/wind/selection_map.shtml

included in Appendix A2. It is from those data that the percentages in the next paragraph are calculated.

At Rockhampton the majority of winds come from the north through southeast octants in November. Winds from the western octants (northwest, west, and southwest, 202.5^o – 337.5^o) are less frequent, with some 13.8 % of days having winds from these directions at 9am, but with only 0.9% of days are winds from these octants >20km/hr. At 3pm 11.6% of days having winds from these three octants. Winds above 20km/hr occur on only 3.1% of days from these octants at 3pm – approximately 1 day per year. These statistics indicate strong winds (>20km hr^{-1}) from the western sector, while unusual, are not unprecedented in November at this location.

For Mackay the frequency of winds from the three western octants is very low at both 9am and 3pm, although slightly more frequent at 9am. At 9am winds are from the three western octants 8.3% of the time, with winds >20km/hr on only 0.9% of occasions, while at 3pm these percentages fall to 1.1% and 0.7%, this latter equating to some 1 November day every 5 years.

In interpreting the conditions in November 2018 in the context of these climatologies, there are a number of points that need to be considered. First, there were instrument changes at Rockhampton in 1993 and at Mackay in 1995 (see BOM Station Metadata documents, accessed 2 March 2018), when Synchrotach anemometers were installed, and at these times a substantial change in the statistical character of the wind observations can be seen (see 3pm wind speed time series for full period of records at these locations in Appendix A3). During the earlier period too, up till 1994, wind directions were reported in 16 direction groups (N, NNE, NE, ENE, E, ESE, SE, SE, S, SSW, SW, WSW, W, WNW, NW, and NNW) making the data in the wind roses somewhat ambiguous when a large number of winds are reported at, say, 337.5^o in this period (NNW) yet the wind roses use that direction as a divider between N and NW. Further, a large proportion of the stronger winds at both Rockhampton and Mackay occurred in the pre-Synchrotach period. Finally, only 9am and 3pm wind rose data are available on the Bureau's web site.

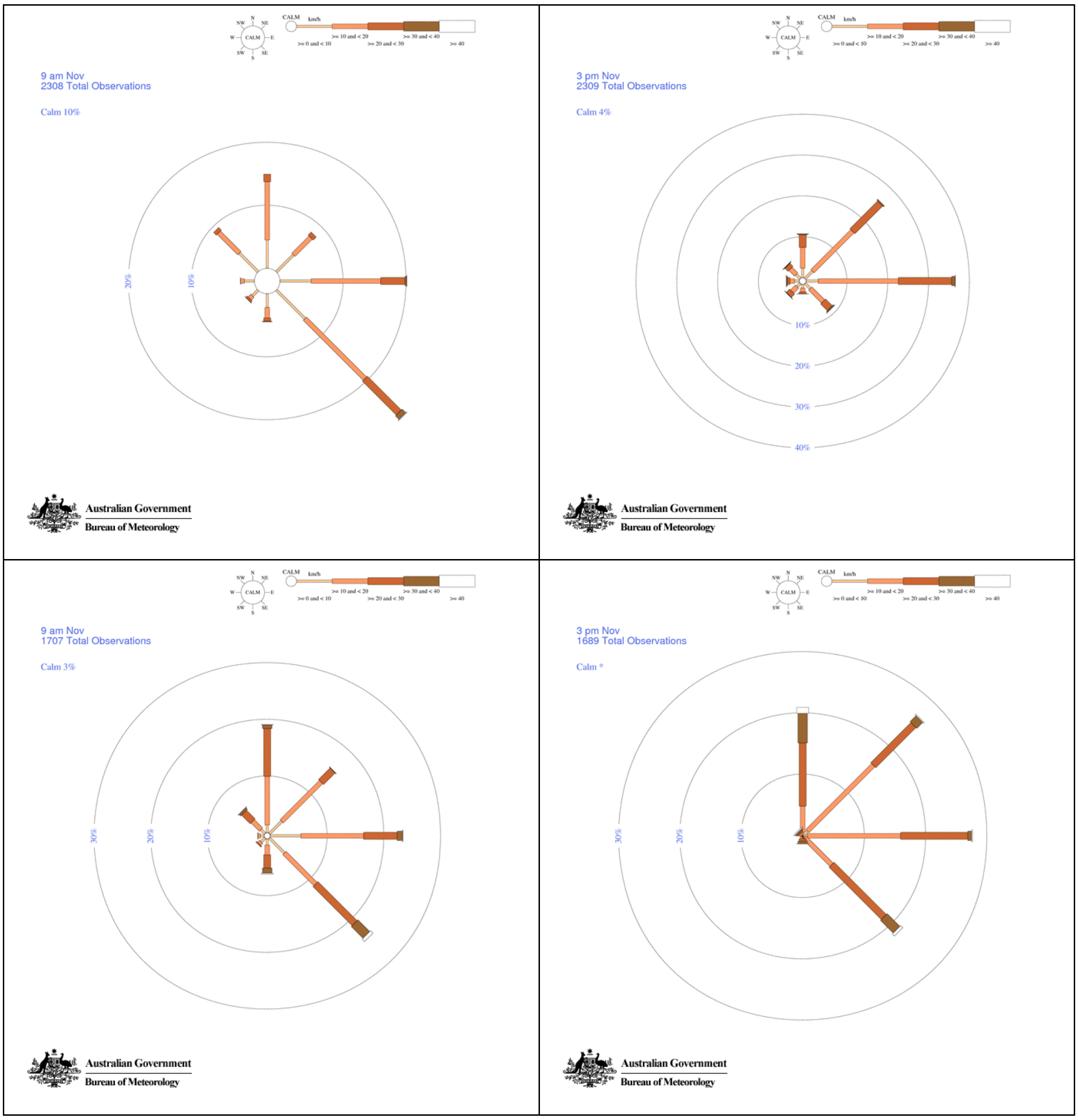

Figure 31. Rockhampton (top) and Mackay (bottom) wind roses at 9am (left column) and 3pm (right column). Note different speed (radius) scales for the two times at Rockhampton from those at Mackay

These aspects of the wind record suggest exploring the wind climatology at Rockhampton and Mackay in greater depth. Using the BOM 3-hourly observation data archive for November for these two locations, and at each 3-hourly interval and for the period since Synchrotach anemometers were installed, the number of observations, the number of observations with winds from the western sector, and the number of those western sector observations with a speed >20km/hr were extracted, and these data are summarized in Tables 3 and 4.

At Rockhampton (Table 3) the percentage of western sector winds are just a little lower than the long-term averages at 9am and 3pm (Appendix A2), but the diurnal variation shows that the daytime hours are the most likely for western sector winds, and that the peak frequency is at 1200 hours. These western sector winds are above

20km/hr essentially only in the daytime hours, with peak frequencies above 3% at 1200 and 1500 hours – a little more than 1 day per month of November.

Of the 20 strongest November wind speeds at Rockhampton in the synoptic (3-hourly) record, 7 were from the western sector, and 3 of these occurred on 28 November 2018, and one on 23 November 2018. Thus 4 of the strongest November western sector wind speeds at Rockhampton in the 26-year period of anemometer records occurred during the Critical Period (cf the mean low level wind flow over Queensland during the Critical Period shown in Fig. 26).

Further, the highest speed in this record, of 51.8 km/hr (there have been unit conversions from knot to m/s to km/hr) on 28 November 2018 at 1500 hours substantially exceeds the next highest speed November speed of 46.4 km/hr. With the 1200 and 1500 hour observations also falling in the highest 20 wind speeds (from any sector) it is highly likely that this is the highest sustained wind speed over three synoptic observations recorded at Rockhampton in November over that 26 year period. The only 3pm wind speed in any month in the post-1993 era that exceeded the 51.8 km/hr recorded on 28 November was the 76km/hr recorded on 20 February 2015 during the passage of TC Marcia, and this was likely associated with a thunderstorm outdraft as 56.4mm of rainfall were recorded in the 3 hours leading to that observation.

At Mackay (Table 4) the climatology of western sector winds is quite different, with the highest frequencies between midnight and 6am, and extremely low frequencies during the day and evening hours. Strong (>20km/hr) western sector winds occur at low frequencies at all hours, with only weak diurnal variation. Thus, if there is a western sector wind during the daytime, there is a high probability that it will be >20km/hr. The frequency of such events equates to around 0.6% of November days: ie around once in every 5-6 years, and are thus rare. On no day in 2018 was there a daytime wind speed at Mackay > 20km/hr, but at two successive hours, at 2100 EST 25 November and 0000 EST 26 November, northwesterly winds exceeded 20km/hr. Of the daytime 3-hourly observations (0900, 1200, 1500, and 1800 EST) in November 2018, the only western sector winds were at 0900 EST on 23, 24, and 16 November, with a highest speed of 9.4km/hr.

The somewhat different climatologies of (strong) westerly winds at Rockhampton and Mackay may well be influenced by the different topographical gradients inland from these locations, with additional contributions from their differing distances from the coast.

Table 3: November wind frequencies from western sector by synoptic hour: Rockhampton 1993-2018 (26 years)

Hour	Total No of Observations	Western sector No (337.5°>DIR>202.5°)	Western sector and SPD>20km/hr
0000	779	41 (5.3%)	1 (0.0%)
0300	780	56 (7.2%)	0 (0.0%)
0600	780	54 (6.9%)	0 (0.0%)
0900	780	95 (12.2%)	8 (1.0%)
1200	780	108 (13.8%)	24 (3.1%)
1500	779	75 (9.6%)	28 (3.6%)
1800	780	35 (4.5%)	7 (0.9%)
2100	780	50 (6.4%)	1 (0.0%)

Table 4: November wind frequencies from western sector by synoptic hour: Mackay 1995-2018 (24 years)

Hour	Total No of Observations	Western sector No (337.5°>DIR>202.5°)	Western sector and SPD>20km/hr
0000	719	120 (16.7%)	7 (1.0%)
0300	719	221 (30.7%)	6 (0.8%)
0600	720	293 (40.7%)	5 (0.7%)
0900	720	45 (6.3%)	9 (1.2%)
1200	720	4 (0.6%)	4 (0.6%)
1500	720	3 (0.4%)	2 (0.3%)
1800	719	9 (1.2%)	5 (0.7%)
2100	720	39 (5.4%)	8 (1.1%)

5.5 Station Relative Humidity

Based on the 3-hourly SYNOP observations at Rockhampton (1940-2018) and Mackay (1960-2018) the mean November relative humidity at each 3-hour observation time was computed, together with the mean relative humidity at those times for November 2018. These are plotted against observation time for the two locations in Fig. 32. At Mackay November 2018 was consistently below the long term mean, with the largest deficits, around 5-7%, between 0900 and 1500 hours. The deficits at Rockhampton were substantially larger, around 10% and had less diurnal variation.

The differences between the two locations are at least partly affected by the relative distances from the ocean of the two locations, with strong coastal humidity gradients seen in the vapour pressure analyses on many days during the heatwave[9]. The relative differences are also consistent with the lower November-average vapour pressure deficits at Mackay compared with Rockhampton shown in Figs. 11 and 12.

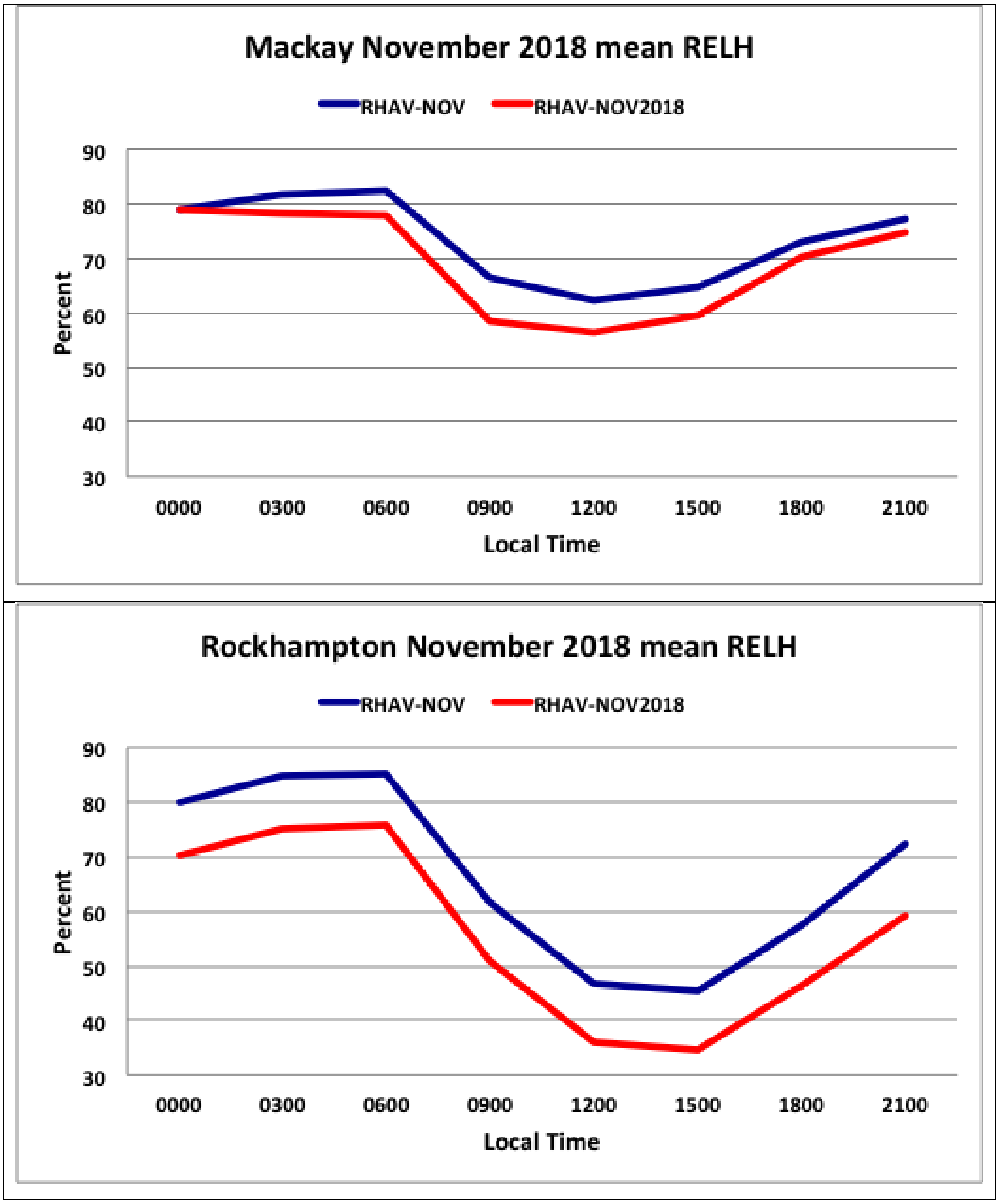

Figure 32. Average relative humidity (percent) at Mackay (top) and Rockhampton (bottom) for November 2018 (red) and the long-term November average (blue).

The time-series of relative humidity at each of the 3-hourly times for each day of November is shown for each of Mackay and Rockhampton in Figs. 33 and 34, with the

[9] http://www.bom.gov.au/jsp/awap/vprp/index.jsp

long-term averages included. At Mackay there is a general trend for slightly below average relative humidity on most days and at most times through the first 3 weeks of November. In the last week, though, overnight relative humidities tend to show some positive excursions, while daytime values become more negative relative to climatology. A significant exception is the large negative relative humidity anomaly in the early hours of 29 November.

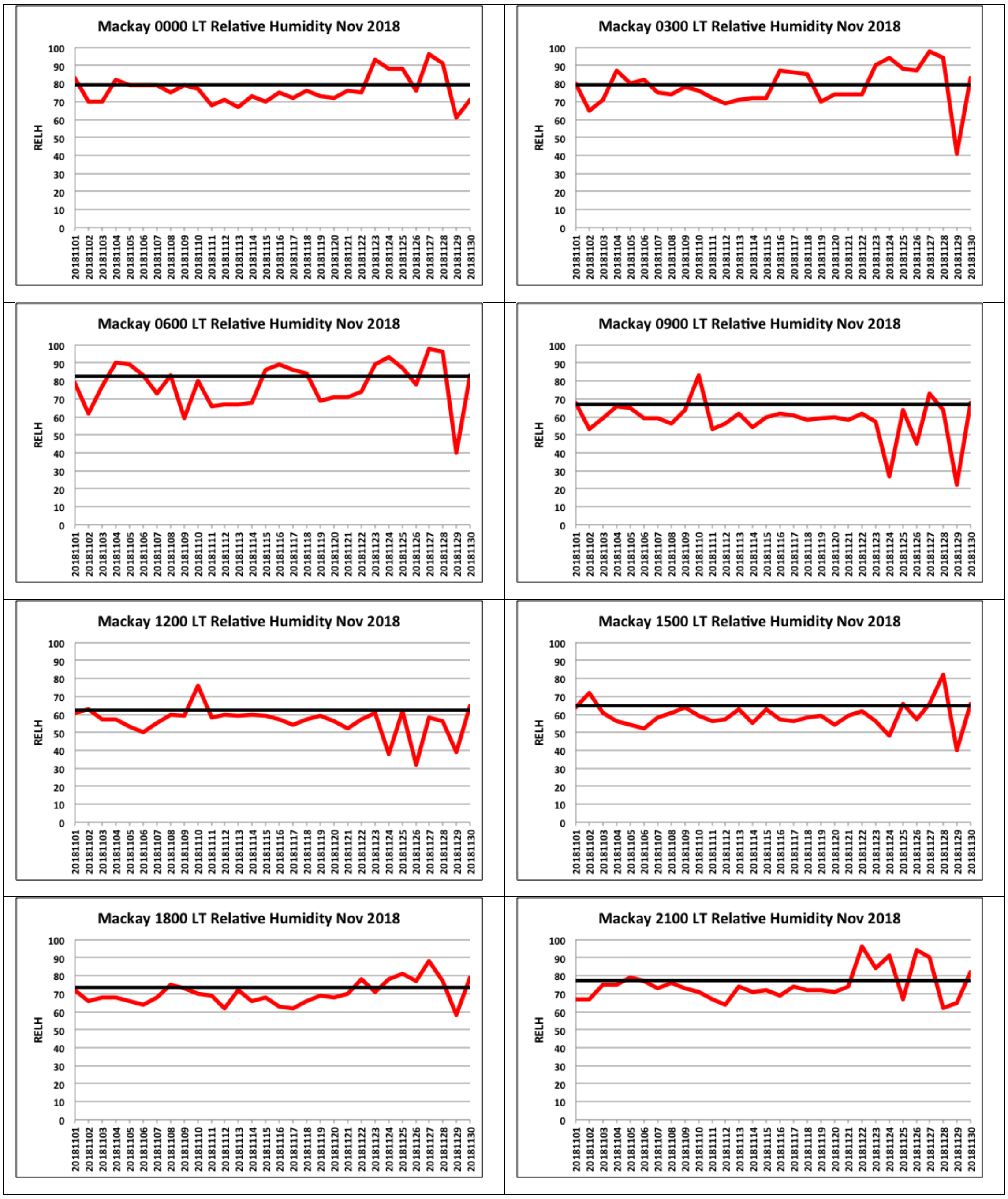

Figure 33. Time series of relative humidity (percent) at Mackay for each 3-hourly observation time for each day of November 2018. The black lines show the long-term November averages for that hour.

The equivalent time-series for Rockhampton (Fig. 34) show rather more variance, but a consistent negative bias from climatology, and during the heatwave period extremely low humidity, both overnight and particularly during the afternoon.

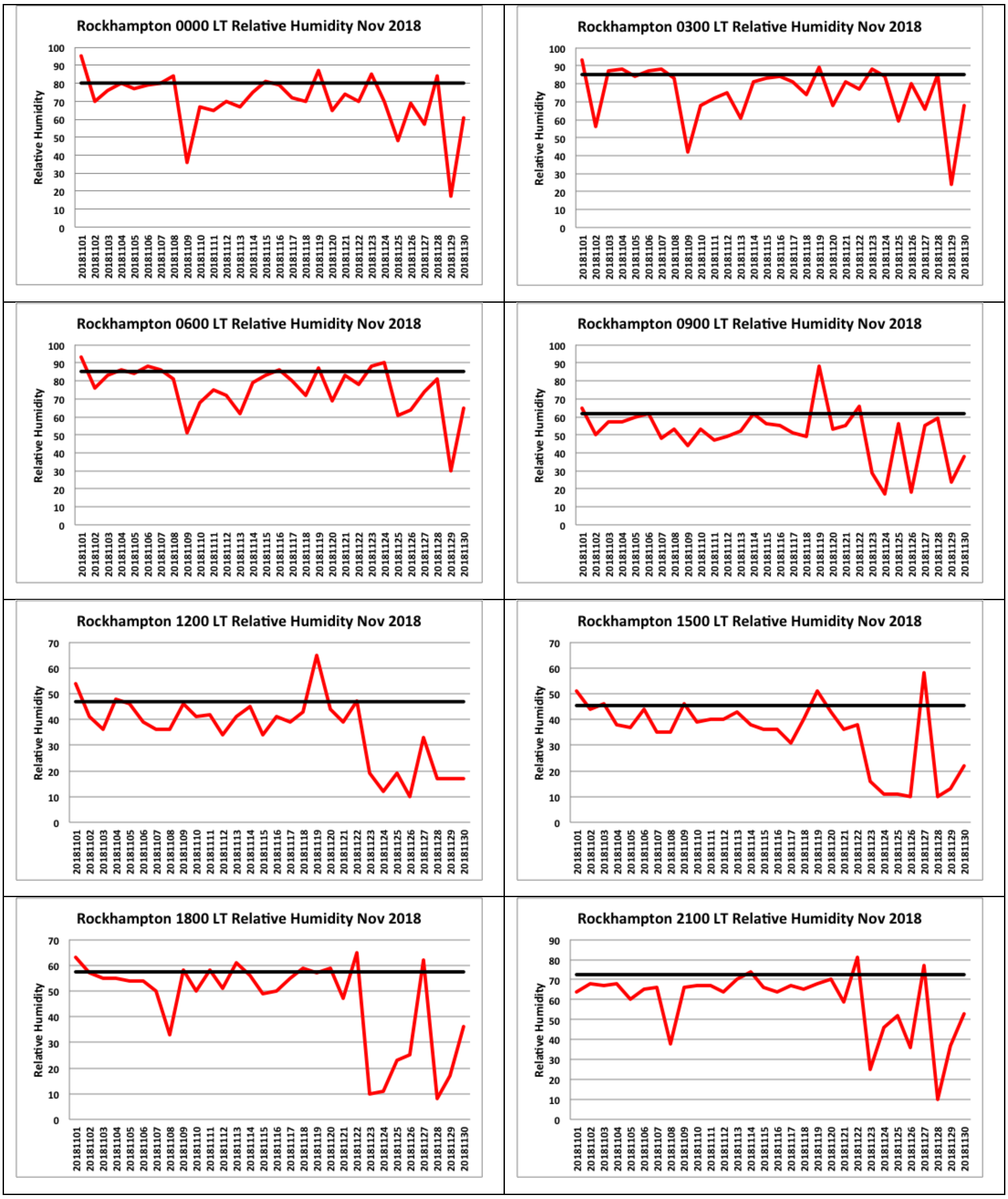

Figure 34. Time series of relative humidity (percent) at Mackay for each 3-hourly observation time for each day of November 2018. The black lines show the long-term November average for that time.

These plots provide some context to the spatial vapour pressure anomalies presented in Figs. 11 and 12 and show several days on which overnight relative humidity recovery was low, as well as demonstrating an overwhelmingly negative relative humidity anomaly through most of the month.

Difficult to estimate quantitatively without exhaustive numerical modeling, but hinted at in the back trajectory analyses (Fig. 30), the composite low level flow (Fig.26) and inferred by the lesser humidity deficits at Mackay than Rockhampton, as well as the daily vapour pressure spatial plots through the heatwave period, are the representivity of the absolute values seen at Mackay compared with what might have been experienced on the slopes of the ranges inland from there due to coastal gradients in temperature and relative humidity,

5.6 Vertical Stability

It is considered that a less stable atmosphere is conducive to more active fire behavior through the easier development of a deeper convective fire circulation in a less stable vertical atmospheric profile, and through the entrainment of drier and/or higher momentum air from aloft.

An index of atmospheric stability that has some use in Australia is the Continuous Haines Index (CH) proposed by Mills and McCaw (2010). This is an extension of the original Haines Index, developed in the United States (see Mills and McCaw 2010 for details), and has two components:

- A value based on the dewpoint depression at 850 hPa (approx. 1500 m) – the humidity component.
- A value based on the 700 – 850 hPa (approx. 3000 -1500m) temperature difference – the lapse rate component.

The direct association between a particular value of CH and fire behavior is not quantitatively, or perhaps not even qualitatively, established. However, using unusually high values of the index as an alert to assess more carefully the vertical structure of the atmosphere, and the evolution of this structure, may have some utility. Mills and McCaw (2010) suggested that the deviation from the local climatology was a useful indicator of extremes in a region, and at their most northern location on the east coast, Bribie Island, found a 95th percentile value of 6.7, based on numerical weather prediction model data. Dowdy and Pepler (2018) (their Figure 1) suggests a 95th percentile of CH between 7-8 along the Queensland coast from the NSW border to near Cairns, based on reanalysis data and over a longer period than that of Mills and McCaw (2010).

The CH parameter has been computed for each radiosonde ascent at Rockhampton and Brisbane Airport from 20 November 2018 through 4 December 2018, with data accessed from the University of Wyoming archive[10]. The time series of CH at each location are shown in Figs. 35 and 36.

At Rockhampton (Fig. 35) there were 4 occasions when the CH was over 8: at 1000 AEST (0000 UTC) 25 November, 1000 AEST (0000 UTC) 27 November, and 2200 AEST (1200 UTC) 28 November. On the first two occasions there was a moist mid-level layer above 700 hPa, but dry from 900-700 hPa. The instability component would have been enhanced later in the day on each of 25 and 27 November all other things being equal as, based on the maximum temperature on these days the mixed layer during the afternoon would have extended above 700 hPa.

At 1000 AEST (0000 UTC) 28 November there was strong instability through the Haines layer, but a relatively moist atmosphere below 600 hPa. However, the maximum

[10] http://weather.uwyo.edu/upperair/sounding.html

temperature on this day was 44.4, and the 2200 AEST (1200 UTC) radiosonde trace showed massive drying below 700 hPa relative to 12 hours earlier, and at that time the CH was 12.2.

Another interesting example is at 1000 AEST (0000 UTC) 26 November, when CH was around 4. Examining the radiosonde trace, though, shows a marked drying just above 800 hPa. If values representative of this air were used as input to the CH calculation, the index would have increased to above 9.

These examples point to both the relatively rapid time-evolution of CH, as discussed in several case studies by Mills and McCaw (2010), and also the need to also examine the input data to assess the sensitivity of the calculations to large vertical gradients in humidity or lapse rate in the atmosphere.

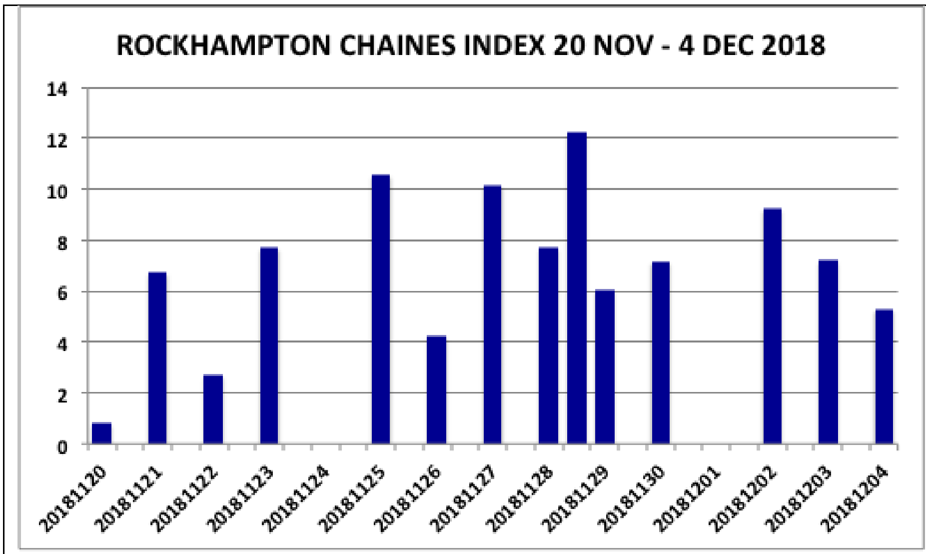

Figure 35. Time series of C-Haines Index computed from Rockhampton radiosonde data for each profile available between 20 November and 4 December 2018. The dates mark the 1000 AEST (0000 UTC) time.

At Brisbane Airport (Fig. 36) there were 4 occasions when the CH exceeded 8 – at 1000 AEST (0000 UTC) on 23 November, 25 November, 28 November and 2 December. These show various combinations of moisture and lapse rate contributions to the CH value, and again show marked day-to-day variability, as well as some sensitivity to the particular vertical location of strong vertical moisture gradients: eg 1000 AEST (0000 UTC) 24 November 2018 when a much higher CH would have resulted if the moisture observed at 800 hPa was used.

The vertical profiles on at 1000 AEST (0000 UTC) 23, 24, and 26 November 2018 at Brisbane Airport are particularly notable for their very deep layers of low humidity, with the CH values on these days modulated strongly by the greatly varying temperature lapse rate component of the CH.

Mills and McCaw (2010) hypothesised that in different cases the separate humidity and lapse components of the CH may well associate in different ways with fire behavior, and that there may be merit in assessing these components independently as well as via the C-Haines Index. In several cases presented in their report they also show, using NWP model fields of CH, that there are substantial variations in spatial and temporal variability of the CH, with large variations over periods of hours or over small regions. Accordingly, in the forecast mode, NWP spatial patterns with hourly temporal resolution may well be more useful than once-daily radiosonde data.

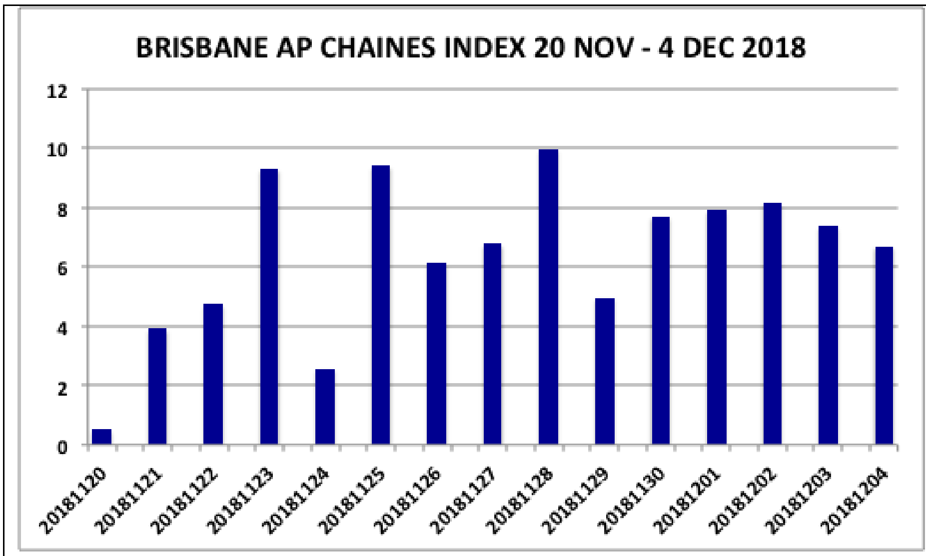

Figure 36. Time series of C-Haines Index computed from Brisbane Airport radiosonde data for each profile available between 20 November and 4 December 2018. The dates mark the 1000 AEST (0000 UTC) time.

KEY POINTS : SECTION 5

- Unprecedented maximum temperatures were recorded at many locations along the northern Queensland coastal regions, from Lockhart River to Bundaberg.
- At a number of stations the previous highest maximum temperature was exceeded by several degrees, and the previous maximum temperature record was broken on a number of days during the Critical Period.
- The synoptic scale ingredients commonly found to lead to mid-latitude heatwaves were present over Queensland, but their morphology was somewhat different to that described in published reviews.
- The unprecedented FFDI values recorded at Rockhampton on 28 November were critically dependent on climatologically rare westerly winds of hitherto unrecorded strength.
- The relationship between heatwave occurrence and the occurrence of exceptionally high values of FFDI during those periods should be further examined.
- Atmospheric stability during the Critical Period, as measured by the Continuous Haines Index, showed several times when values exceeded their 95th percentile. The highest observed value was at Rockhampton at 2200 AEST (1200 UTC) 28 November, when a value approaching the theoretical maximum was reached.

6. SUMMARY

6.1 Introduction

This report has:

- described aspects of the climate and soil moisture anomalies over Queensland in the period leading to the Critical Period,
- summarised the NASBA prepared in July 2018,
- presented and discussed the seasonal outlooks that were issued by the BOM in months subsequent to the NASBA, together with verifying temperature and rainfall anomaly fields,
- described the large-scale factors that lead to heatwaves, the BOM Heatwave Index, and described the broad atmospheric circulation over eastern Australia in the period leading to the heatwave.
- discussed the consequent wind, temperature, and humidity anomalies experienced during the Critical Period, and
- documented the upper atmospheric profiles at Rockhampton and Brisbane Airport during the Critical Period.

The following sections synthesise some of the key factors that these analyses reveal, and point to areas of knowledge that could be enhanced with further investigation. They are grouped to summarise the weather and climate extremes that were observed through the Critical Period, and then discuss these factors in the context of:

- extremes,
- predictability,
- drought,
- climate trends,
- heatwaves.

6.2 Weather and Climate Extremes During the Critical Period

As described in SCS67, a large number of temperature records were set in northern Queensland during late November 2018. Highest ever November maximum temperatures were recorded at a number of observing sites, including Cairns Airport where the previous highest maximum temperature was exceeded by 5.4 degrees. The extremity of the heat event is highlighted by the fact that now the 5 highest November maximum temperatures at Cairns all occurred during the heatwave period. At Rockhampton 3 of 6, and at Mackay 5 of the 7 highest November maximum temperatures were also recorded during November 2018. Thus not only the magnitude by which some of the records were broken is remarkable, but also the sustained period of record or near record temperatures is unprecedented.

Also unprecedented is the catastrophic fire weather that was observed at Rockhampton, particularly on 28 November when wind speeds of over 50km/hr were observed, and sustained mean winds above 40 km/hr for over 3 hours, together with temperatures around 43C and relative humidity less than 10%. SCS67 states that this led to the highest FFDI values ever recorded at Rockhampton.

In addition, a number of antecedent and concurrent soil moisture deficit, rainfall deficit, and atmospheric humidity measures were apparent, together with antecedent atmospheric temperature and vapour pressure anomalies. Many of these were "very much above/below average", while others were subjectively sufficiently different from the norm to be noted in this report. A further aspect of these anomalies was their sustained nature – they were persistent over many months. While the magnitudes of some of these were not unprecedented they were highly unusual, being in the most extreme 5-10% of their climatological range.

How these factors all combined to affect fire activity and behavior, or what is the probability of occurrence of some of these combinations is beyond the scope of this document, and it must be acknowledged that some of these factors are inter-related. However, the probability of occurrence of a the combination of two or more "highly anomalous" factors would tend to indicate a greater degree of risk than that due to any individual factor, although cross-correlations must be allowed for in such assessments.

Further investigation into the combined role of multiple anomalies, and the effect of a long duration of sustained anomaly, in risk assessment would be worthwhile.

6.3 Predictability of Fire Weather

Fire weather in the context of uncontrollable bushfires is an extreme event: that is, the occurrence of FFDI events in the Severe (FFDI>50) range and above occur in the tails of the FFDI distributions, and usually also in the tails of the individual distributions of temperature, humidity and wind speed. Accordingly the issue of predictability of the worst fire weather conditions is one of predicting the highly unusual – a task generally considered more difficult than predicting conditions closer to the median. Such events also typically occur over periods of some hours at particular locations, and may not necessarily be widespread over even a forecast district at any particular time, although may occur at different locations at different times. On the longer time scale outlooks become more general until on the seasonal timescale they are couched in terms of "probability of above median" conditions, and then only for temperature and rainfall, with fire weather outlooks being purely qualitative.

Predictability is thus highly dependent on context: what is being predicted, the degree of accuracy required in a forecast, and duration of an outlook etc. The BOM verifies all its forecasts, and in their submission to the IGEM Review[11] described the accuracy of their fire weather forecasts during the Critical Period.

As outlook periods increase, or as the degree of accuracy becomes more important in decision-making, then there is benefit in not just using a single deterministic forecast, but using ensemble forecast techniques, where a range of outcomes is available, not just the most likely outcome. This technique has been widely used in medium range (0-10 day) global numerical weather prediction models in recent decades, and is also used in generating the seasonal outlooks (Hudson et al 2017). The BOM is developing an ensemble version of its highest resolution numerical weather prediction system that will have application to the more extreme fire weather situations at weather forecast timescales, with scope for probability forecasts of FFDI by hour across the landscape, worst-case scenario assessment etc, and this emerging forecast system should provide additional short-term forecast awareness.

[11] BOM Submission. Review of 2018 Queensland Bushfire & Heat Wave Event

While rigorous objective verification of forecasts leading up to and including the Critical Period are outside the scope of this report, the following subjective comments, based on the investigations detailed in Sections 2-5 above, are worth making:

- Given the conditions experienced on the Capricornia and Whitsunday coast and near coastal areas during the Critical Period, the NASBA was remarkably informative.
- The successive seasonal outlooks were consistent through July-October in predicting higher probabilities of above average temperature and below average rainfall. While persistence of forecasts does not necessarily mean accuracy, it does engender greater confidence than if forecasts change too much from issue to issue. The verifying analyses also suggest that these outlooks were qualitatively accurate and would not have caused the NASBA outlook to be questioned.
- It is noted that the two-day fire weather forecast[12] for the Capricornia coast for 28 November were for Severe conditions on the Capricornia coast, and increased to Extreme in the 1-day forecast. Given the sensitivity of FFDI to small changes in input parameters at the high end, this is highly useful guidance, as is the indication of escalating fire danger. The Heat Wave forecasts (same submission) also showed consistent extreme EHF along the Queensland coast from south of the Capricornia coast to eastern Cape York. These forecasts again provided excellent guidance.

6.4 Drought and Fire Weather

A number of studies (see review in Work Package 2 of this sequence of reports to IGEM) point to antecedent drought as a factor contributing to major fire events. Section 2 demonstrated that there had been lengthy periods of rainfall, soil moisture, and atmospheric humidity deficit over Queensland and extending to the central Queensland coast in the months (and even years – see Bureau of Meteorology 2018a) leading up to the Critical Period. As drought is a factor in this event, and in many other events (see Work Package 2) it is worth considering the ways in which drought can be defined.

According to the Bureau of Meteorology[13]

"Drought is a prolonged, abnormally dry period when the amount of available water is insufficient to meet our normal use. Drought is not simply low rainfall; if it was, much of inland Australia would be in almost perpetual drought. Because people use water in so many different ways, there is no universal definition of drought. Meteorologists monitor the extent and severity of drought in terms of rainfall deficiencies. Agriculturalists rate the impact on primary industries, hydrologists compare ground water levels, and sociologists define it by social expectations and perceptions.

It is generally difficult to compare one drought to another, since each drought differs in the seasonality, location, spatial extent and duration of the associated rainfall deficiencies. Additionally, each drought is accompanied by varying temperatures and soil moisture deficits. "

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[12] BOM Submission. Review of 2018 Queensland Bushfire & Heat Wave Event_attachments

[13] (http://www.bom.gov.au/climate/drought/)

Thus there are definitions of meteorological drought, hydrological drought, agricultural drought, or socio-economic drought. While there will be considerable overlap between the various definitions, some applications may find that one particular drought metric is more useful than the others.

The BOM definition of meteorological drought is based on rainfall deficit, while the drought index used in the calculation of FFDI, the KBDI, is essentially an index of hydrological drought.

In this report it was shown that many moisture anomaly measures – rainfall, atmospheric humidity, KBDI, root-zone and upper-layer soil moisture from the AWRA - showed large anomalies from climatology, ranging from below average to very much below average values in November 2018. Intriguing was the period of sustained low values over many months up to and including November 2018, and at several locations the accumulated KBDI deficit from the end of the previous wet season was likely to occur only once in ~ 25 years.

It may be worthwhile establishing some monitoring of the time evolution of some or all of these drought indices, preferably based on the BOM gridded products, or even testing alternatives (eg the Evaporative Demand Drought Index, EDDI, Hobbins et al 2016) that has been proposed to have utility in fire weather applications in the United States. It is important to link any metric used, though, to the fuel moisture state for particular vegetation types. Use of fuel moisture modeling (eg Matthews et al 2010) to provide a more direct link between atmospheric and soil moisture states and fuel moisture would provide some calibration of any new metrics.

6.5 Heat Waves and Fire Weather

The synoptic scale drivers of mid-latitude heat waves described in Section 5.2 were identified during November 2018 over Queensland. The ingredients – a mid-upper tropospheric anticyclone leading to subsidence warming above the mixed layer, a slow moving surface pattern that allows recirculation and accumulation of heat in the mixed layer, and a soil moisture deficit that allows the majority of incoming radiation energy to be partitioned into heating rather than evaporation, and finally some (sub-) synoptic-scale weather system that advects the hot air from (typically) inland source regions to more benign environments near the coast, were all identified in the weeks leading up to the Critical Period. However, there were some differences in these patterns from those in previously published case studies of mid-latitude heat waves

While the net result of these circulation patterns becomes evident in large-scale surface temperature anomalies, which are readily monitored, it may be beneficial to study the atmospheric environment of previous Queensland heat waves (several were documented in SCS67) in order to have greater understanding of, and awareness of, developing Queensland heat waves.

The relationships between heatwaves and fire weather in different regions of Queensland also needs to be better defined. High temperatures and drought are key ingredients of both, and those factors during a heatwave provide two of the four components that lead to high values of FFDI. The third, relative humidity, has been hypothesized in this report to be likely low during Queensland coastal heatwaves, thereby providing a third fire danger ingredient in this region, but this has yet to be quantitatively established. The fourth ingredient, high wind speed, is a necessary ingredient for high FFDI, and while it was present on some but not all days, and in some regions, during the Critical Period, how often this occurs during or in association with heatwaves on the Queensland coast should be established.

6.6 Climate Trends

As shown in Fig. 2 there has been an extended period of above average temperature over Queensland in the most recent 20 years, and the Queensland Government agencies are well aware of these trends (Queensland Climate Adaption Strategy: Emergency Management Sector Adaption Plan for Climate Change 2018).

Much of the literature regarding future trends in fire danger has focused on the southeastern states (eg Lucas et al 2007), but there are recent reanalysis-based studies that cover the Australian continent (eg Dowdy 2018) that show some trends for increasing fire weather over southeastern and coastal Queensland. Clarke et al (2013) also show some positive trends in FFDI over southeastern Queensland extending northwards to Rockhampton and Mackay based on long period station observation data, although not all these trends are statistically significant in all seasons. More focussed analysis over Queensland may be beneficial.

The shifting of the mean temperature suggests that if the distribution about the median remains the same, then the most extreme values will be higher, and there is some suggestion that there is an increasing trend for heatwaves along the Queensland coast (Perkins 2015, Nairn and Fawcett 2017). This broadly coincides with the extended period of above average Queensland temperatures (Fig 2). How this trend relates to fire weather is more complex, since fire weather includes antecedent and current moisture deficit, temperature and in particular wind speed, and the distribution about the median may also be changing. As noted in Section 6.6 the relationship between heatwave events and fire weather events should be a focus of future research, and this should also address trends into the future.

6.7 Future Research

A number of avenues of research that may lead to improved knowledge, awareness, and prediction of dangerous fire weather conditions over Queensland, and in particular the Queensland coastal regions have been suggested in this report. These include:

- The relationship between current and antecedent rainfall, soil moisture, atmospheric humidity, and drought index anomalies could be examined in order to determine their internal relationships and which, or which combination, of these provide the best indication live and dead fuel moisture state. The study should address the roles of current anomaliies, or accumulated periods of anomaly.
- The relationships between heatwaves and fire weather over Queensland should be established, with particular emphasis on wind variability during heatwave periods.
- The late November 2018 heatwave over Queensland developed under circulation anomalies and in conjunction with soil moisture anomalies that were consistent with those described in published studies of mid-latitude

heatwaves. However, the morphology of some of these features differed, and studies of the circulations leading to previous Queensland heatwaves may provide greater understanding of any region-specific features that could be monitored.

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APPENDIX

A1. Queensland Forecast Districts and locations

Figure A1. Bureau of Meteorology Forecast Districts for Queensland. (www.bom/gov.au).

A2 Wind rose data used in Figure 30

Table A1. Wind rose data for Rockhampton at 3pm

STN NO	Time	No OBS	Speed Range km/hr	% from N	% from NE	% from E	% from SE	% from S	% from SW	% from W	% from NW	% calm	Row Total
39083	3pm Nov	2309	≥ 0 & < 10	2.3	2.5	2.9	1.8	0.9	1.1	1.1	1.4	4.0	18.0
39083	3pm Nov	2309	≥ 10 & < 20	5.1	13.8	19.6	4.4	0.9	1.7	1.1	1.9		48.5
39083	3pm Nov	2309	≥ 20 & < 30	3.1	9.6	13.1	2.3	0.4	1.1	0.6	1.0		31.2
39083	3pm Nov	2309	≥ 30 & < 40	0.2	0.3	0.8	0.3	0.0	0.0	0.2	0.1		1.9
39083	3pm Nov	2309	≥ 40	0.1	0.0	0.0	0	0.0	0.0	0.1	0.0		0.3
39083	3pm Nov	2309	Column Totals	10.7	26.2	36.5	8.8	2.3	4.0	3.1	4.5	4.0	

Table A2. Wind rose data for Mackay at 3pm

STN NO	Time	No OBS	Speed Range km/hr	% from N	% from NE	% from E	% from SE	% from S	% from SW	% from W	% from NW	% calm	Row Total
33119	3pm Nov	1689	≥ 0 & < 10	0.3	1.0	0.7	0.3	0.1	0.0	0.0	0.1	0.2	2.7
33119	3pm Nov	1689	≥ 10 & < 20	4.4	15.2	15.2	6.3	0.3	0.1	0.0	0.3		41.7
33119	3pm Nov	1689	≥ 20 & < 30	10.3	9.3	11.0	12.0	0.4	0.1	0.0	0.2		43.2
33119	3pm Nov	1698	≥ 30 & < 40	4.8	1.4	0.6	2.9	0.4	0.0	0.0	0.2		10.4
33119	3pm Nov	1689	≥ 40	1.0	0.1	0.1	0.5	0.1	0.0	0.0	0.2		2.0
33119	3pm Nov	1689	Column Totals	20.8	27.0	27.6	22.0	1.3	0.2	0.0	1.0	0.2	100.0

Table A3. Wind rose data for Rockhampton at 9am

STN NO	Time	No OBS	Speed Range km/hr	% from N	% from NE	% from E	% from SE	% from S	% from SW	% from W	% from NW	% calm	Row Total
39083	9am Nov	2308	≥ 0 & < 10	4.5	3.8	4.9	6.4	2.1	1.3	1.6	4.2	10.1	38.9
39083	9am Nov	2308	≥ 10 & < 20	9.3	3.9	11.0	13.5	1.6	0.6	0.6	4.6		45.0
39083	9am Nov	2308	≥ 20 & < 30	1.2	0.7	3.9	7.6	0.5	0.3	0.0	0.6		14.8
39083	9am Nov	2308	≥ 30 & < 40	0.0	0.0	0.3	0.8	0.1	0.0	0.0	0.0		1.2
39083	9am Nov	2308	≥ 40	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0		0.1
39083	9am Nov	2308	Column Totals	14.9	8.4	20.1	28.4	4.4	2.2	2.2	9.4	10.1	

Table A4. Wind rose data for Mackay at 9am

STN NO	Time	No OBS	Speed Range km/hr	% from N	% from NE	% from E	% from SE	% from S	% from SW	% from W	% from NW	% calm	Row Total
33119	9am Nov	1707	≥ 0 & < 10	1.3	3.0	5.4	3.7	1.1	0.9	0.6	1.0	2.6	19.7
33119	9am Nov	1707	≥ 10 & < 20	8.6	9.8	11.0	7.7	1.7	0.5	0.4	2.1		41.8
33119	9am Nov	1707	≥ 20 & < 30	8.4	2.9	5.9	9.7	2.3	0.2	0.0	2.1		31.6
33119	9am Nov	1707	≥ 30 & < 40	0.6	0.1	0.9	2.9	0.9	0.0	0.0	0.4		5.9
33119	9am Nov	1707	≥ 40	0.1	0.0	0.1	0.6	0.2	0.0	0.0	0.1		1.1
33119	9am Nov	1707	Column Totals	19.0	15.8	23.3	24.7	6.2	1.6	1.1	5.6	2.6	

A3. Long period wind speed observations.

Mackay 1500 AEST wind speed plotted from 1959-2018 incl (Fig. A2) shows discontinuity in character at the installation of the Synchrotach anemometer on 18 October 1995 (BOM station metadata file).

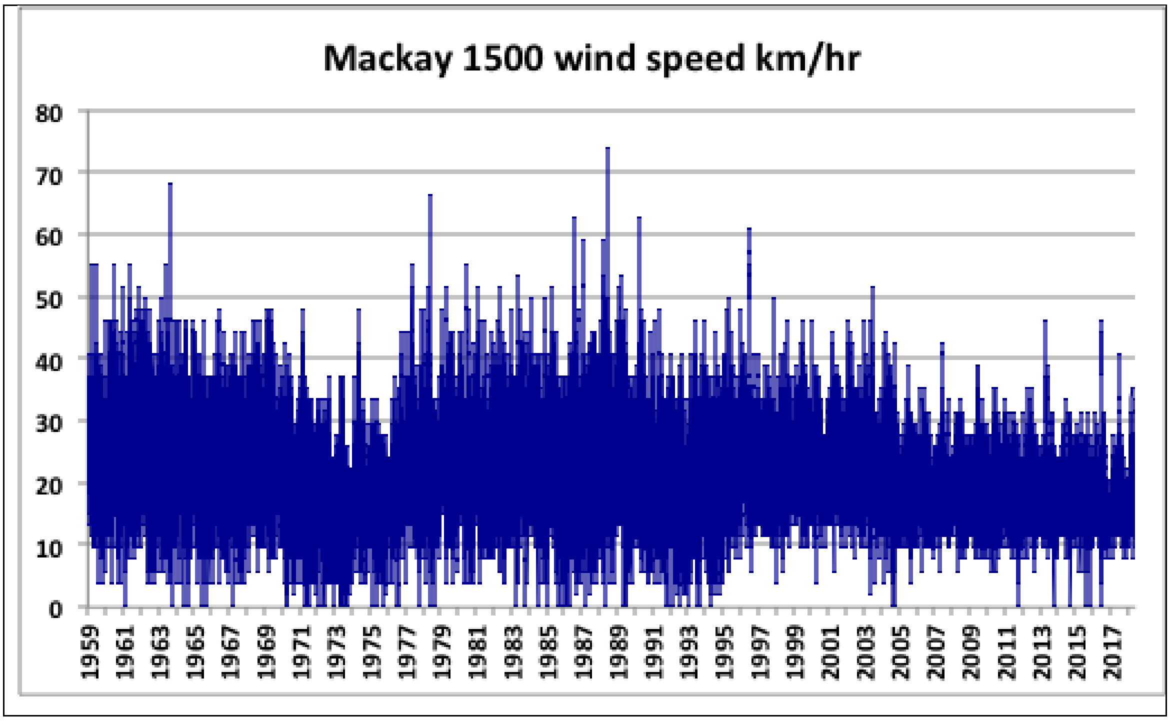

Figure A2. Time series of 1500 AEST wind speed observations (km/hr) at Mackay from 26 September 1959 to 31 December 2018.

The Rockhampton metadata file states "Synchrotach anemomenter installed 1 April 1993". The time-series plot of 1500 AEST wind speed observations (Fig A3) shows a discontinuity consistent with this installation time.

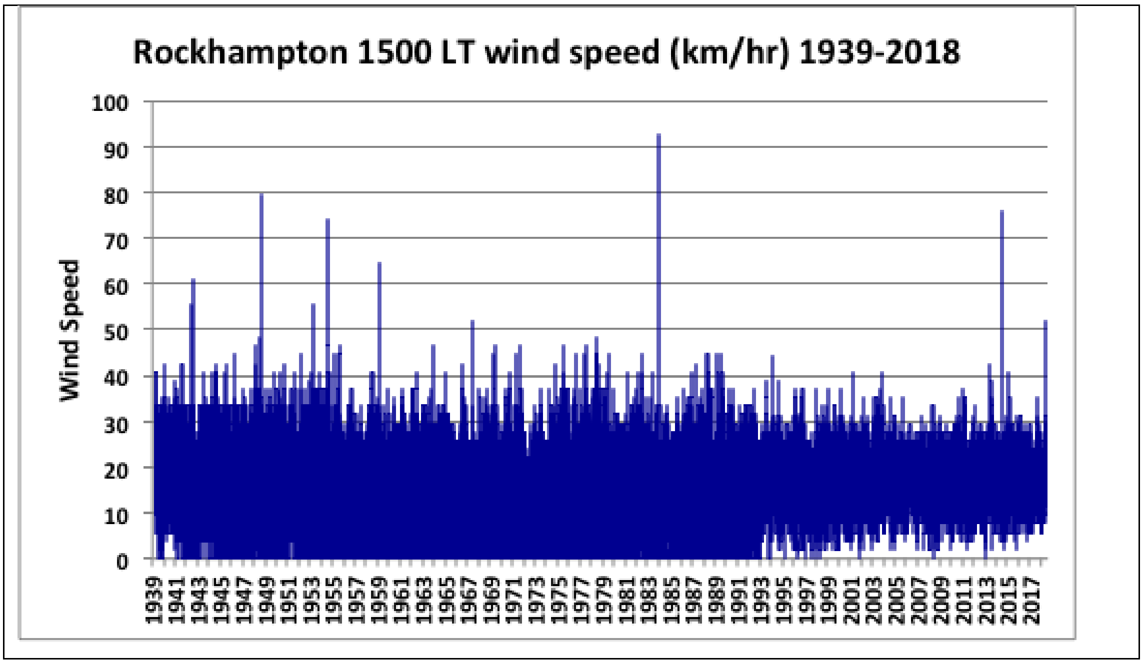

Figure A3. Time series of 1500 AEST wind speed observations (km/hr) at Mackay from 5 August 1939 to 31 December 2018.

A4. Radiosonde temperature and moisture profiles

Radiosonde profiles from Rockhampton and Brisbane Airport for the period 20 November – 4 December 2018 are shown below in Figs. A4-A8. Blank panels indicate missing data. While most data is for 1000 AEST (0000 UTC), there is an additional profile at Rockhampton at 2200 AEST (1200 UTC) 28 November 2018. The times of each radiosonde profile are shown at bottom left of each individual panel in Figs. A4-A8.

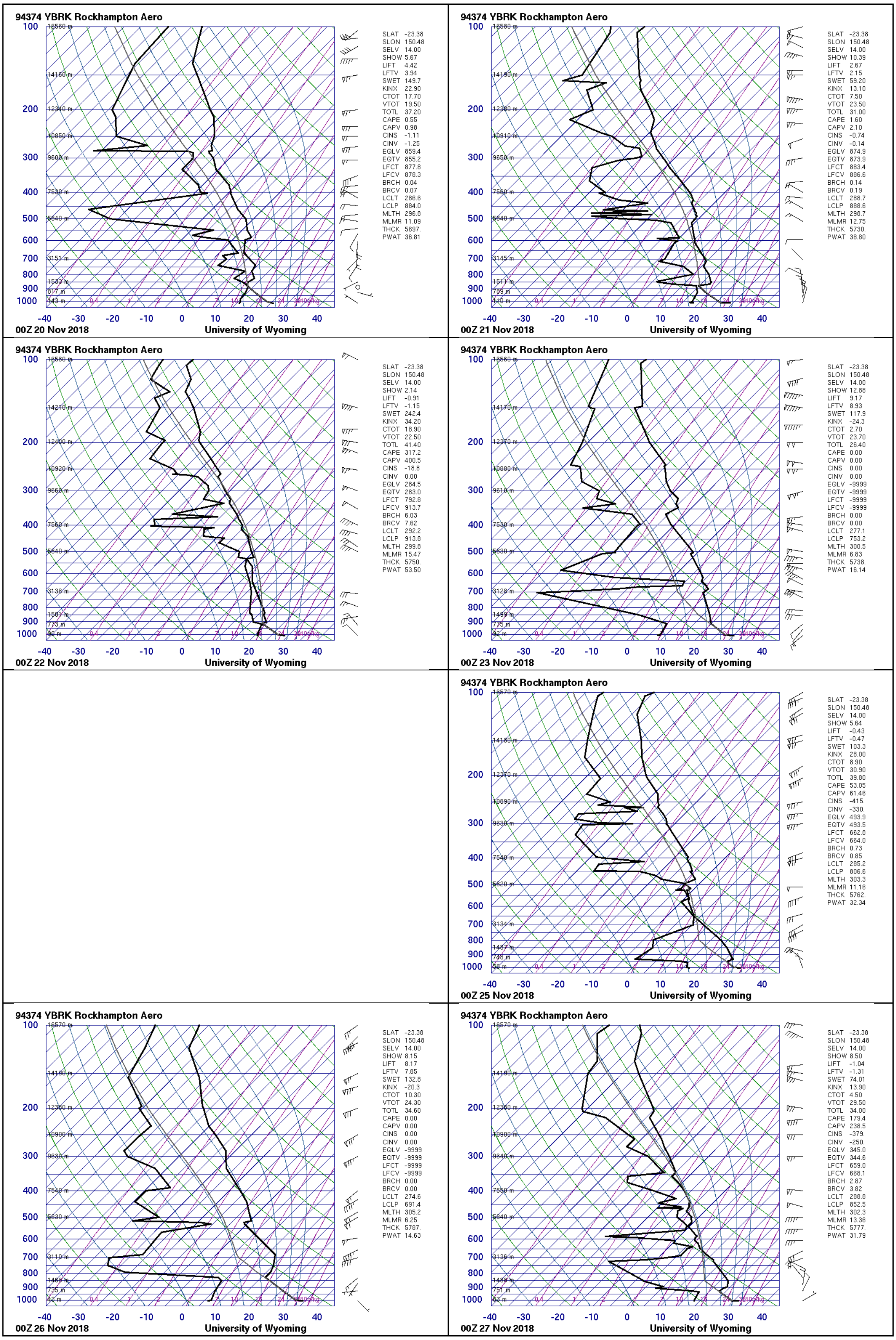

Figure A4. Rockhampton vertical temperature and moisture profiles from 20 – 27 November 2018.

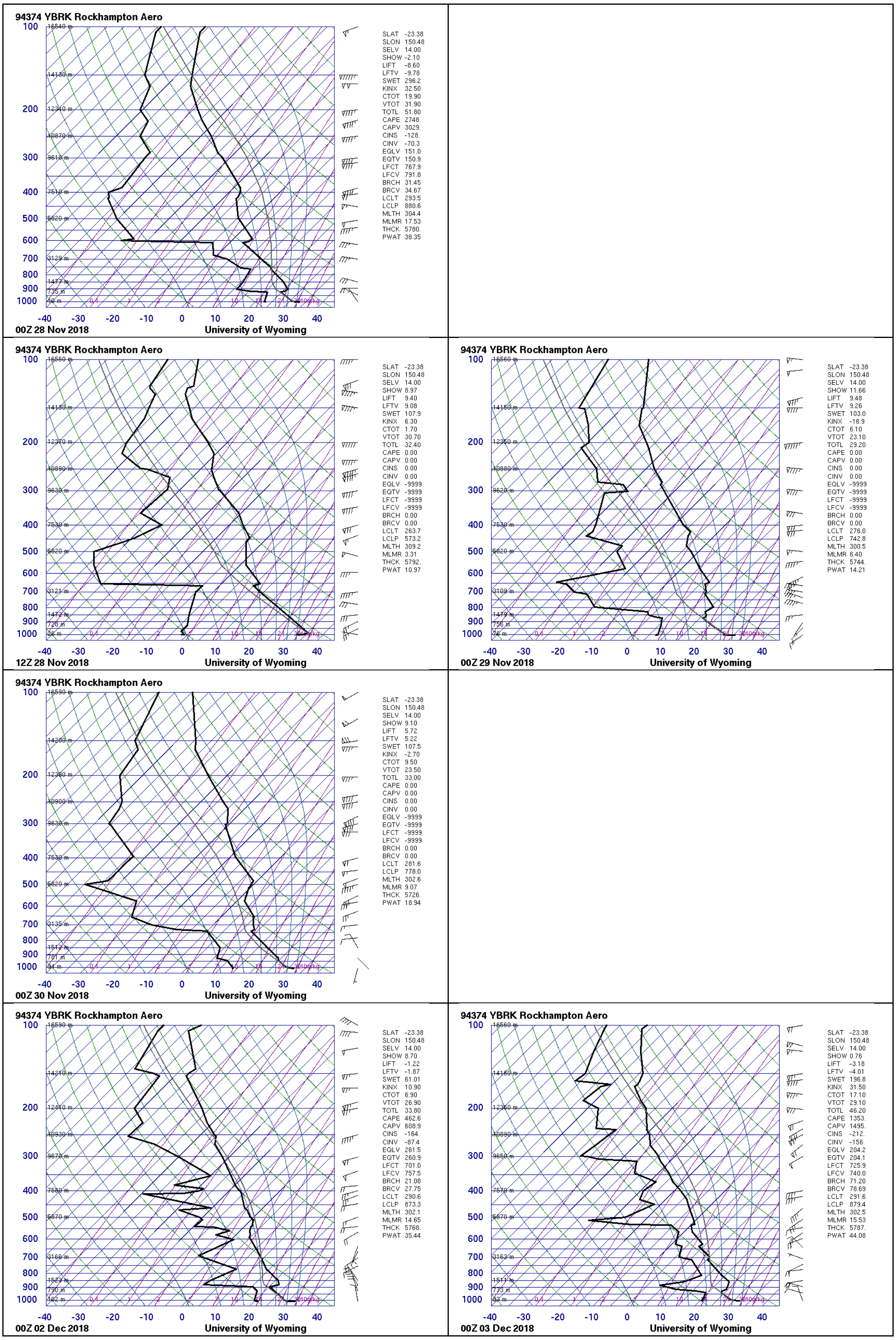

Figure A5. Rockhampton vertical temperature and moisture profiles from 28 November to 3 December 2018.

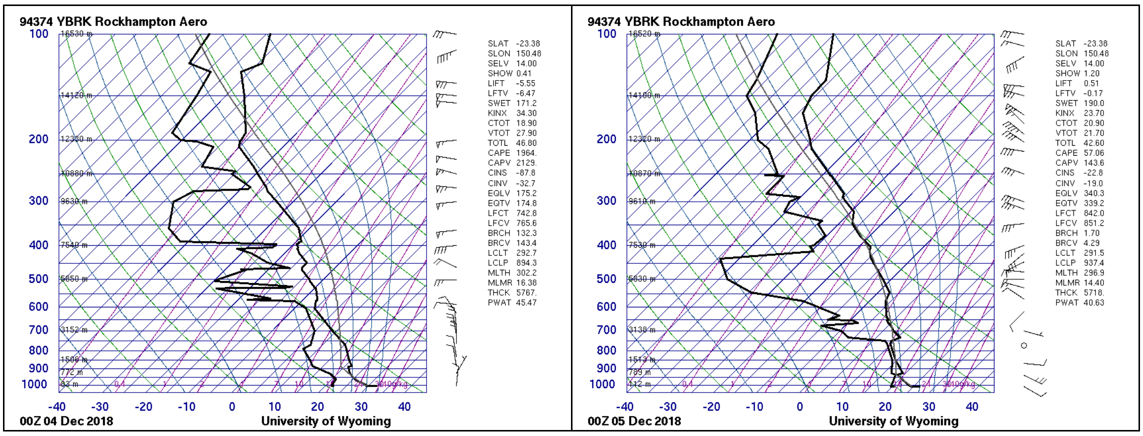

Figure A6. Rockhampton vertical temperature and moisture profiles from 4 December and 5 December 2018.

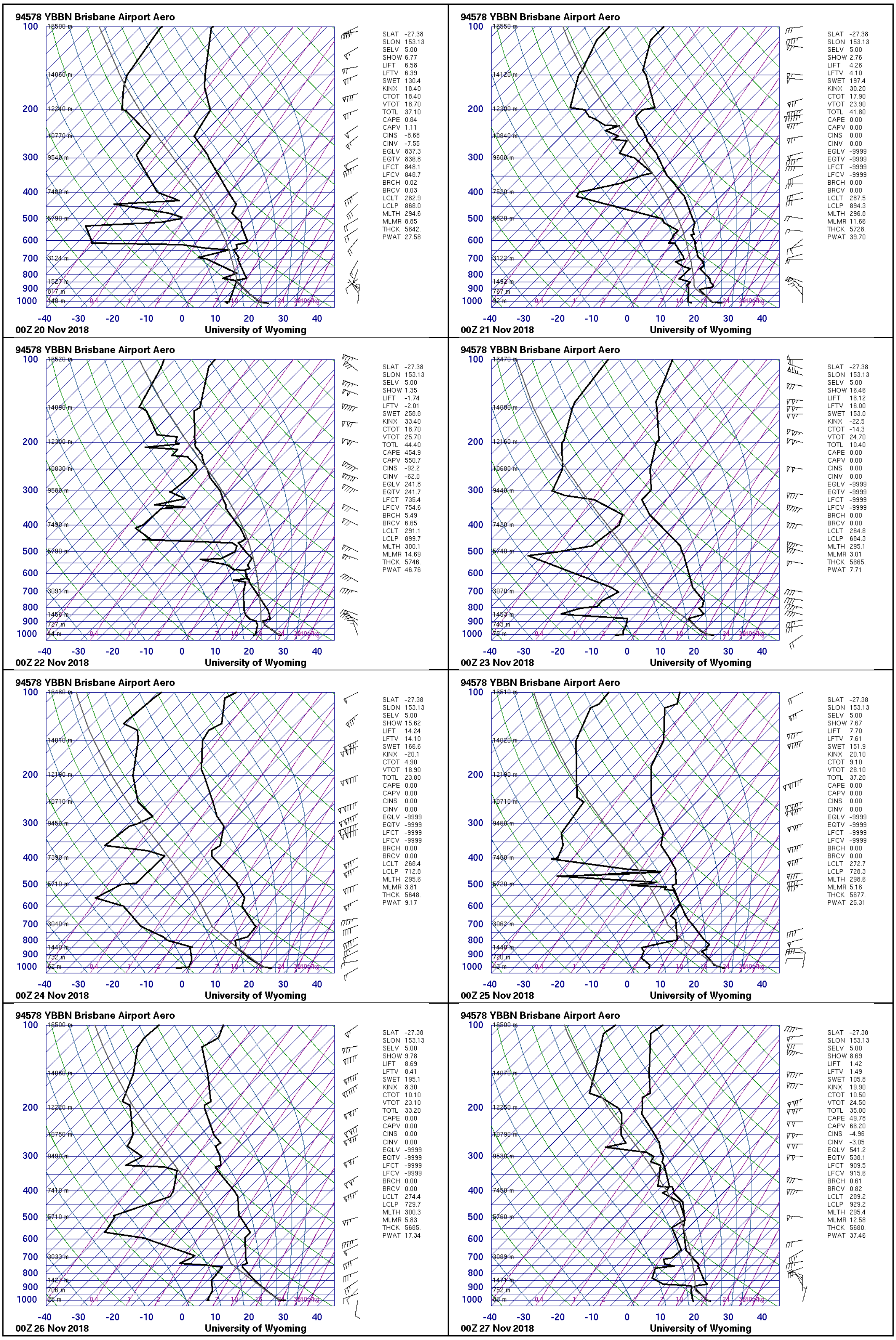

Figure A7. Brisbane Airport vertical temperature and moisture profiles from 20 to 27 November 2018.

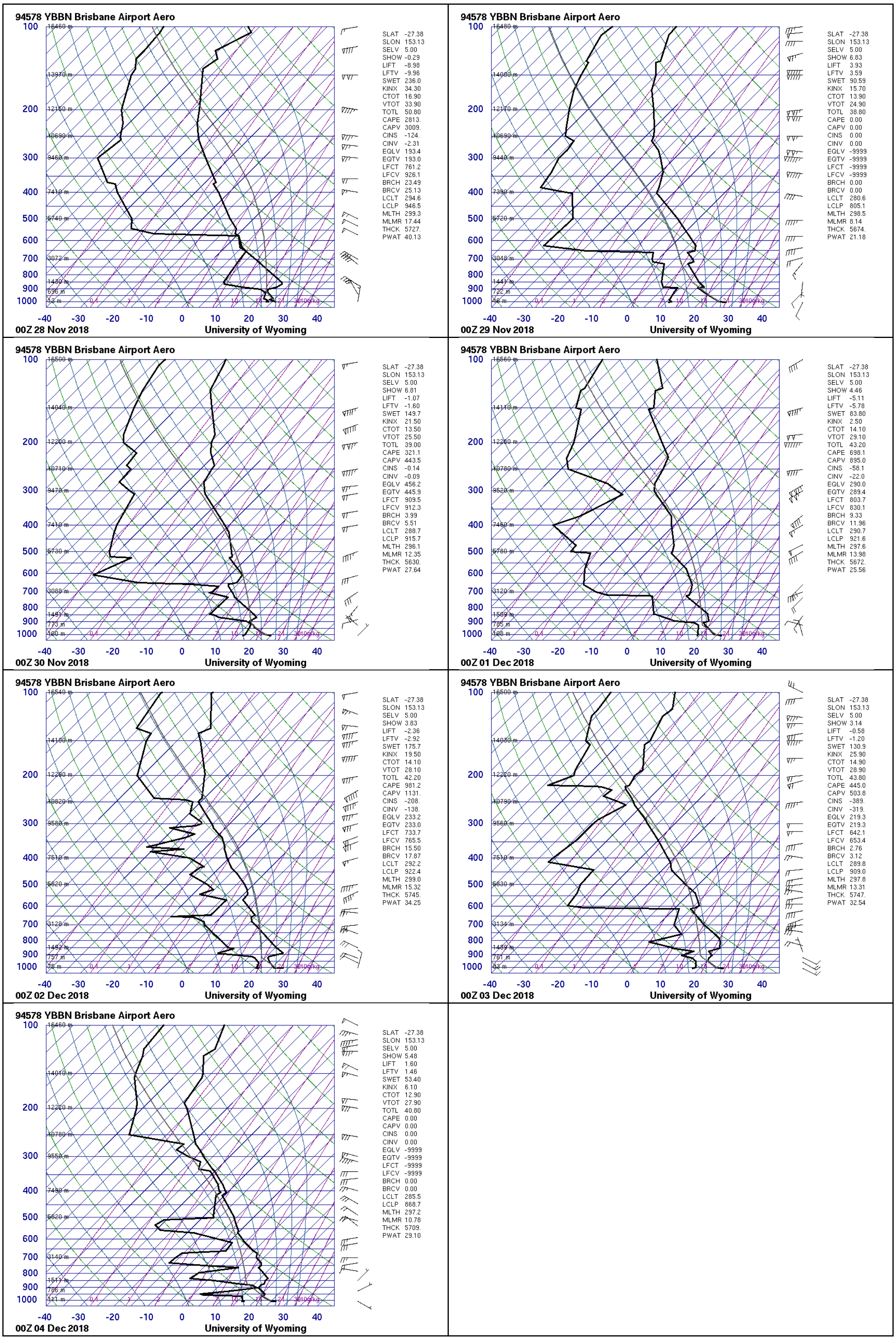

Figure A8. Brisbane Airport vertical temperature and moisture profiles from 28 November to 4 December 2018.