Annual climate summary Australia (2016): strong El Niño gives way to strong negative IOD.

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(Manuscript received July 2017; accepted August 2017)

Australian climate patterns and associated anomalies during 2016 are reviewed, with reference to relevant climate drivers for the Australian region. 2016 was the fourth-warmest year on record for Australia (annual anomaly of +0.87 °C), and the warmest year on record for the globe (the third year running that a new record has been set). Annual rainfall was above average for most of Australia, but below average for areas of the northern coasts between the Gascoyne in Western Australia and Townsville in Queensland, and pockets of coastal south-east Queensland and northeastern New South Wales.

The very strong 2015–16 El Niño contributed to a very warm and dry first quarter. Autumn was the warmest on record nationally, with a significant nation-wide heatwave occurring in late February to mid-March and bushfires at the start of the year in Victoria, Tasmania and Western Australia. In May the El Niño broke down and rainfall increased as a very strong negative Indian Ocean Dipole developed, lasting until November. While the central tropical Pacific approached La Niña thresholds during spring, a La Niña did not develop. The Southern Annual Mode commenced the year in a generally positive phase, was strongly positive in June and September, and was following by a strongly negative phase from late October until the end of the year.

The period from May to September was record wet, relieving areas of drought in Queensland and southeastern Australia, but also causing flooding in multiple states. The last three months of the year saw a return to near-average rainfall and, while October and November were cooler than average for large areas, December was very warm for the eastern states.

Ocean temperatures were also record warm for the Australian region during 2016, with an annual anomaly of +0.73 °C. Temperatures were particularly high during the first half of the year and resulted in widespread severe coral bleaching.

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1 Introduction

This summary reviews climate patterns for Australia during 2016, with particular attention given to climate drivers for the Australian region. The main sources of information for this report are analyses prepared by the Australian Bureau of Meteorology, using a variety of datasets sourced from a range of centres.

2 Discussion of Australian climate drivers in 2016

2.1 Introduction

The Australian climate in 2016 was influenced by a combination of natural drivers and anthropogenic climate change. The pattern of above average temperatures over land and in the oceans reflects the background warming trend.

El Niño, which had commenced in 2015, transitioned to neutral conditions during autumn 2016 (Chandler 2016, Martin 2016, Pepler 2016). However, ocean warmth continued to be a key feature of 2016, with above average sea surface temperatures persisting in the Pacific following the breakdown of El Niño during May, and remaining at record or near-record highs throughout the year around northern Australia.

The combination of El Niño and ongoing climate change led to record warm temperatures globally during 2016, as they did in 2015. Below average rainfall over much of eastern Australia during the first four months of 2016 is consistent with historical El Niño-driven rainfall patterns.

The year also started with record-warm waters across much of the Indian Ocean, and a strong negative Indian Ocean Dipole (IOD) developed in late May. The negative IOD event peaked in July with the largest negative value of the IOD index since reliable records started in 1960 (based on ERSST v4 data[1]), and the eastern node of the IOD (around and south of Sumatra) was the second-warmest on record for September.

Weak La Niña-like patterns emerged in the Pacific during winter, with a number of climate indicators approaching La Niña levels during spring. Ultimately, however, La Niña did not eventuate, and the tropical Pacific Ocean remained in a neutral phase of the El Niño–Southern Oscillation (ENSO).

This combination of a negative IOD, very warm waters north of Australia, and a La Niña-like Pacific Ocean was associated with the wettest May to September period on record for Australia. Australia often experiences above average rainfall during the months following the breakdown of a moderate-to-strong El Niño[2], and in 2016 this tendency was reinforced by a strong negative IOD.

The negative IOD began to weaken in October and had dissipated by late November, with a return of more average rainfall patterns in Australia.

A generally negative phase of the Southern Annular Mode (SAM) from late October may have contributed to below average rainfall on the eastern seaboard.

2.2 Temperatures in the tropical Pacific Ocean

The sequence of sub-surface temperature anomalies for the equatorial Pacific Ocean in 2016 (Figure 1, Figure 2) shows the strong warm anomalies were present at the surface and in the sub-surface of the eastern Pacific at the start of 2016, but rapidly declined as the 2015–16 El Niño concluded in autumn. A large pool of cooler than average water developed in the western Pacific during autumn, but development all but stalled then decayed as the year progressed and La Niña failed to fully develop.

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[1] Sea surface temperature timeseries are calculated from the NOAA Extended Reconstructed Sea Surface Temperature Version 4 (ERSST v4) data provided by the NOAA/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/. A full description of the ERSST v4 data can be found in Huang et al., (2015) and Liu et al., (2015).

[2] ttp://www.bom.gov.au/climate/updates/articles/a021.shtml

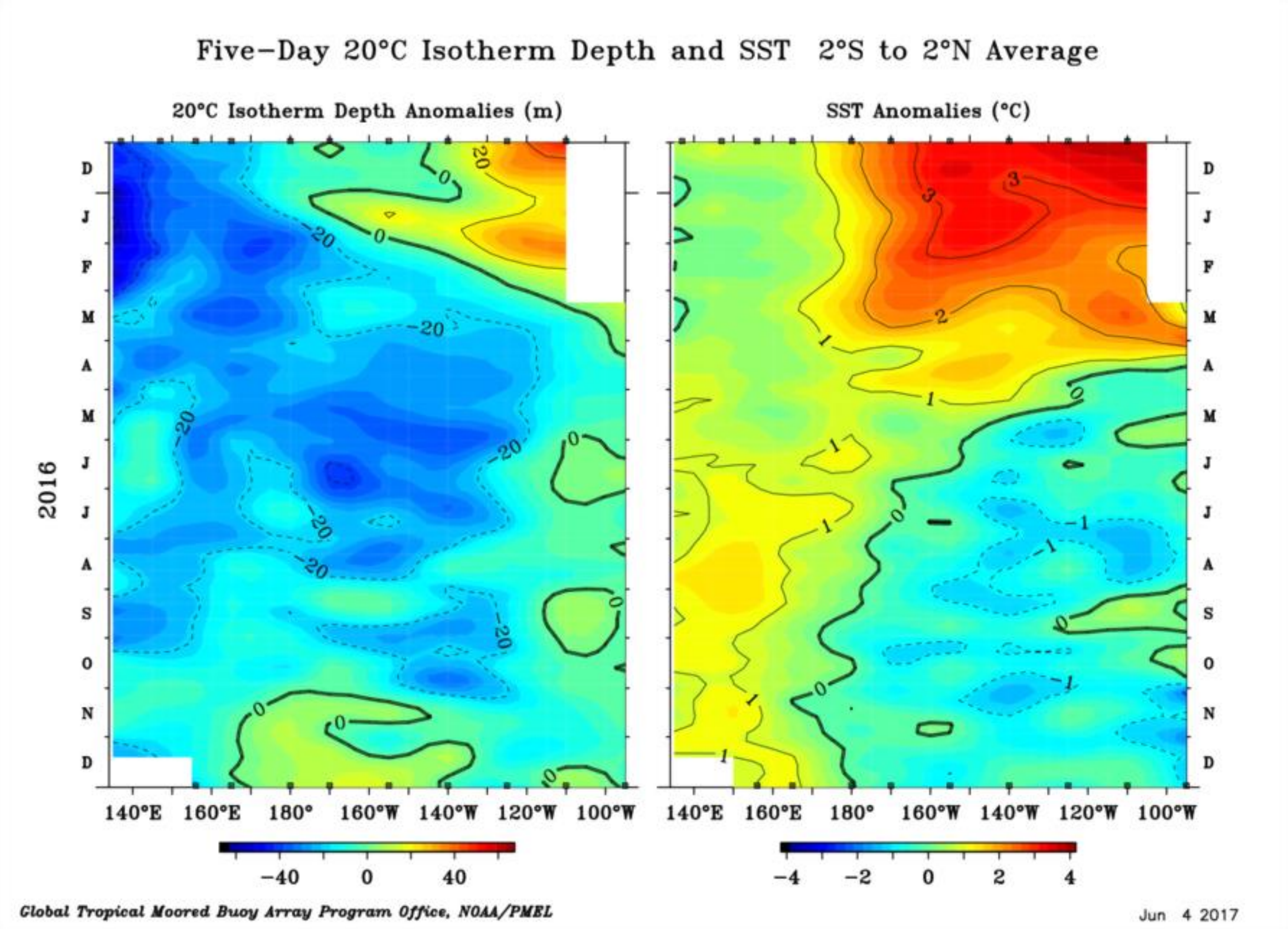

Fig. 1 Time-longitude section of the monthly anomalous depth of the 20 °C isotherm and the sea-surface temperature at the equator (2ºS to 2ºN) for 2016. (Plot obtained from the TAO Project Office, http://www.pmel.noaa.gov/tao/drupal/disdel/)

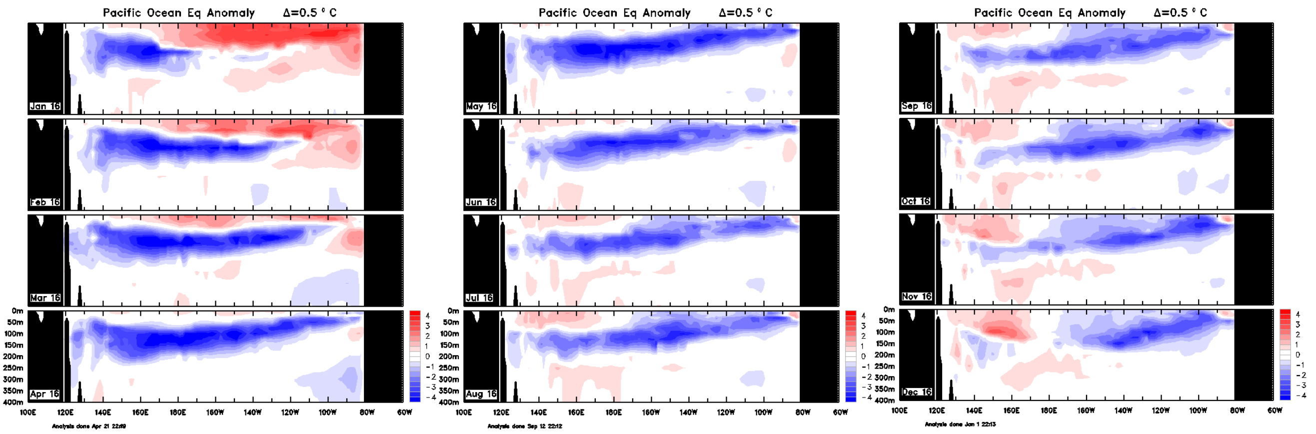

Fig. 2 Monthly sub-surface temperature anomalies for January to December 2016 in the equatorial Pacific Ocean (2ºS to 2ºN).

2.3 Southern Oscillation Index

The Troup Southern Oscillation Index (SOI)[3] for the period January 2012 to December 2016 is shown in Fig. 3, together with a five-month weighted moving average. 2016 commenced with strongly negative SOI values, with the SOI remaining negative until April, although the March value (–4.7) was markedly weaker than the other months. The April value of –22.0 was the sixth most negative value on record for the month of April (records commence in 1876). The weakly positive values seen during autumn to winter marked the swing towards a potential La Niña, though after peaking at +13.5 in September the SOI dropped back to neutral values and a La Niña did not eventuate.

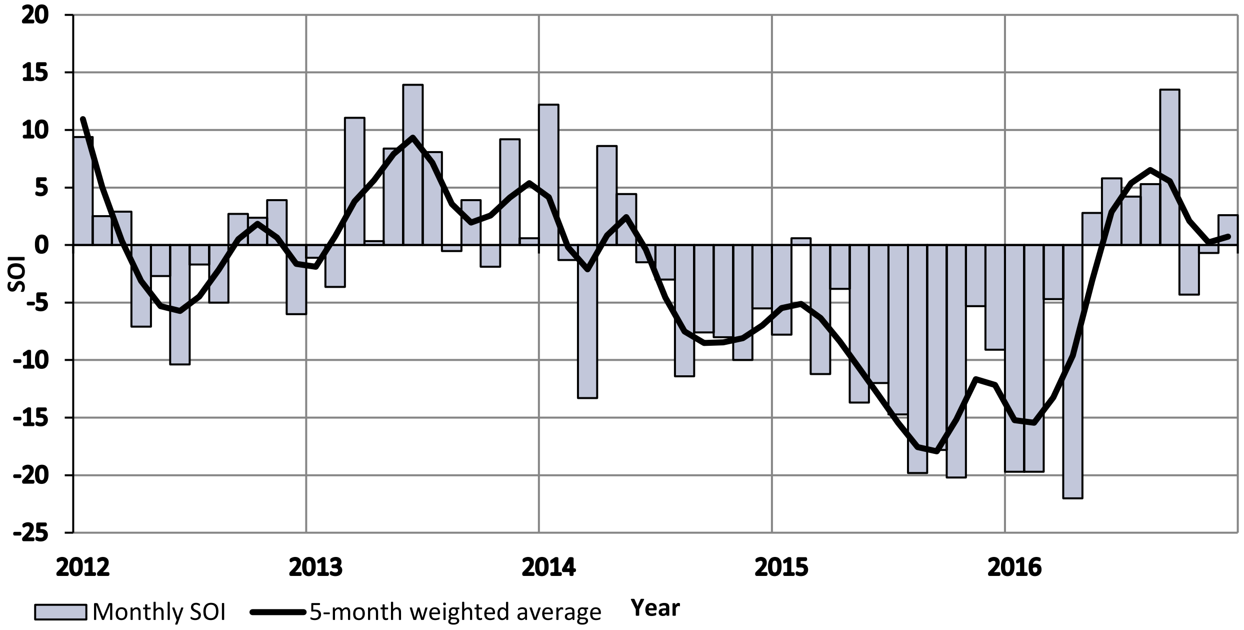

Fig. 3 Southern Oscillation Index, from January 2012 to December 2016, together with a five-month binomially weighted moving average. Means and standard deviations used in the computation of the SOI are based on the period 1933–1992. Sustained positive values in excess of +7 typically indicate La Niña while sustained negative values below −7 typically indicate El Niño. Values between about +7 and −7 generally indicate neutral conditions.

2.4 Composite monthly ENSO index (5VAR)

5VAR(Kuleshov et al. 2009) is a composite monthly ENSO index, calculated as the standardised amplitude of the first principal component of monthly Darwin and Tahiti mean sea level pressure (MSLP)[4] and monthly NINO3, NINO3.4 and NINO4 sea-surface temperatures[5] (SSTs), over the period 1950–1999. Persistent positive or negative 5VAR values of in excess of one standard deviation are typically associated with El Niño or La Niña events, respectively.

Monthly 5VAR values for the period January 2012 to December 2016 are shown in Fig. 4. The very strong El Niño of 2015–16 saw values of the index remain well above +2 standard deviations during June 2015 to February 2016, with monthly values dropping sharply thereafter. Values had declined to +0.6 standard deviations for May and reached –0.5 for September before remaining between –0.1 and –0.2 for the rest of the year; well short of La Niña levels.

The peak value of this event was reached during August 2016 (+2.6 standard deviations). This falls short of the peak value during February 1983 (+2.7 standard deviations), and surpassed the peak value during August 1997 (+2.5 standard deviations). Looking at the events more broadly, 5VAR exceeded +2 standard deviations for six consecutive months during 1982–83, ten consecutive months during 1997–98, and eleven consecutive months during 2015–16.

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[3] The Troup Southern Oscillation Index (Troup 1965) used in this article is ten times the standardised monthly anomaly of the difference in mean-sea-level pressure (MSLP) between Tahiti and Darwin. The calculation is based on a sixty-year climatology (1933–1992). The Darwin MSLP is provided by the Bureau of Meteorology, and the Tahiti MSLP is provided by Météo France inter-regional direction for French Polynesia.
[4] MSLP data obtained from http://www.bom.gov.au/climate/current/soihtm1.shtml. Tahiti MSLP is provided by Météo France inter-regional direction for French Polynesia.
[5] SST indices obtained from ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/sstoi.indices.

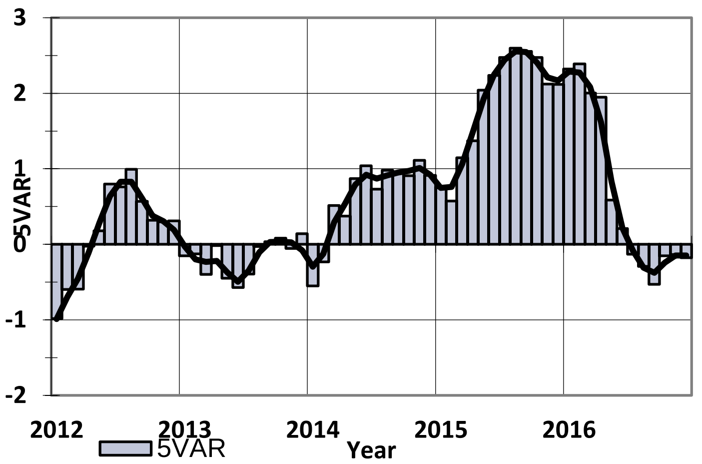

Fig. 4 5VAR composite standardised monthly ENSO index from January 2012 to December 2016, together with a three-month binomially weighted moving average.

2.5 Indian Ocean Dipole Mode Index

The Indian Ocean Dipole (IOD) can shift moisture towards or away from Australia. It is represented by the Dipole Mode Index (DMI) (Saji et. al. 1999). The DMI is the difference in SST anomalies between a western node centred on the equator off the coast of Somalia (50°E to 70°E and 10°S to 10°N) and an eastern node near Sumatra (90°E to 110°E and 10°S to 0°S). Sustained values of the DMI below −0.4 °C indicate a negative IOD event, while sustained values above +0.4 °C indicate a positive IOD event.

Following the strong positive IOD which developed during winter 2015, DMI values dropped below threshold levels in November (Fig. 5). Broad positive SST anomalies had persisted across the Indian Ocean from late 2015, with a strong negative IOD developing by the end of May 2016. The July DMI value was the most negative value observed since reliable records started in 1960 (based on ERSST v4 data), and the eastern node of the IOD (around and south of Indonesia) was the second-warmest on record for September. DMI values dropped over spring, having returned to neutral by late November. Sea surface temperature anomalies near the peak of the event in July are shown in Fig. 6.

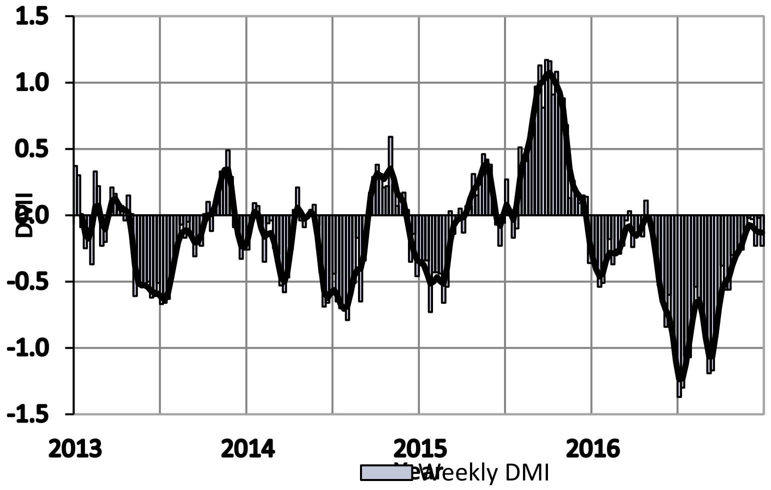

Fig. 5 Weekly Dipole Mode Index (DMI) values from January 2012 to November 2015, together with a five-week binomially weighted moving average. Baseline period is 1961–1990.

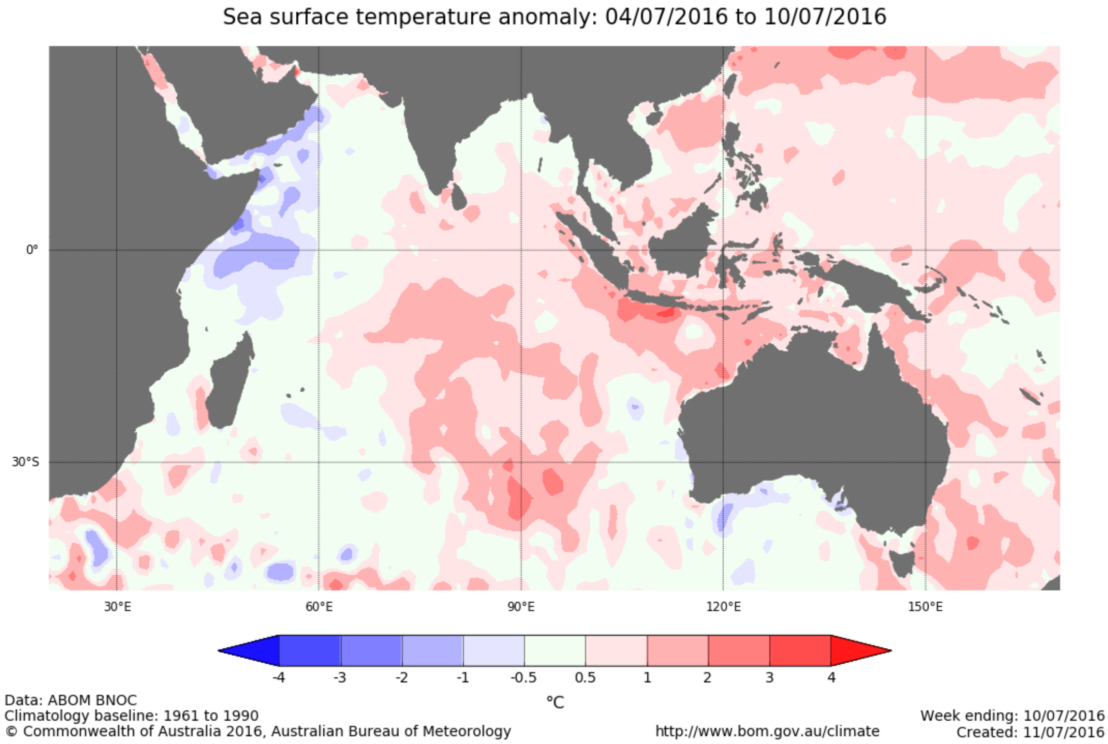

Fig. 6 Sea surface temperature anomalies in the Indian Ocean for the week ending 10 July 2016.

2.6 Southern Annular Mode

The Southern Annular Mode (SAM, also known as the Antarctic Oscillation or AAO) describes the strength and position of the belt of surface westerly winds that encircle Antarctica (e.g. Marshall 2003). The north/south movement of the westerlies is also associated with the track of storm systems and cold fronts in those westerlies, and thus affects rainfall in southern Australia

Positive phases of the SAM are characterised by anomalously high pressure over the mid-latitudes and anomalously low pressure over Antarctica, and an associated poleward contraction, and often strengthening, in the belt of westerlies. Conversely, negative phases of the SAM characterised by an equatorward expansion of the belt of westerly winds. This also shifts the sub-tropical ridge northward. The effect of positive and negative phases of SAM varies by season and region (Hendon et al. 2007).

Daily and monthly values for the SAM index are shown in Fig. 7. During the first three months of 2016 the SAM was in generally in a positive phase (monthly values for January, February, and March were +1.39, +1.09, and +2.04 respectively). The SAM index was strongly positive in June (+2.57) and September (+2.33). In winter and spring, a positive phase of SAM tends to be associated with reduced rainfall over western Tasmania, and during spring with increased rainfall over central and eastern New South Wales. This suggests that the positive SAM may have contributed to above average June rainfall in New South Wales, while its influence, though masked by the strong negative IOD, can also be seen in reduced rainfall in areas which typically receive rain from systems embedded in westerly airflow (i.e. southwest Western Australia, southeast South Australia, western to central Victoria, and western Tasmania). In September the signal is again seen in below average rainfall in western Tasmania and above average rainfall over much of New South Wales.

From late October the SAM entered a strongly negative phase, with a monthly value for November of –1.51, and remained generally negative for the remainder of the year. Shifting the westerly winds to the north during this period means less moist onshore flow from the east, and this may have contributed to decreased rainfall over the eastern mainland.

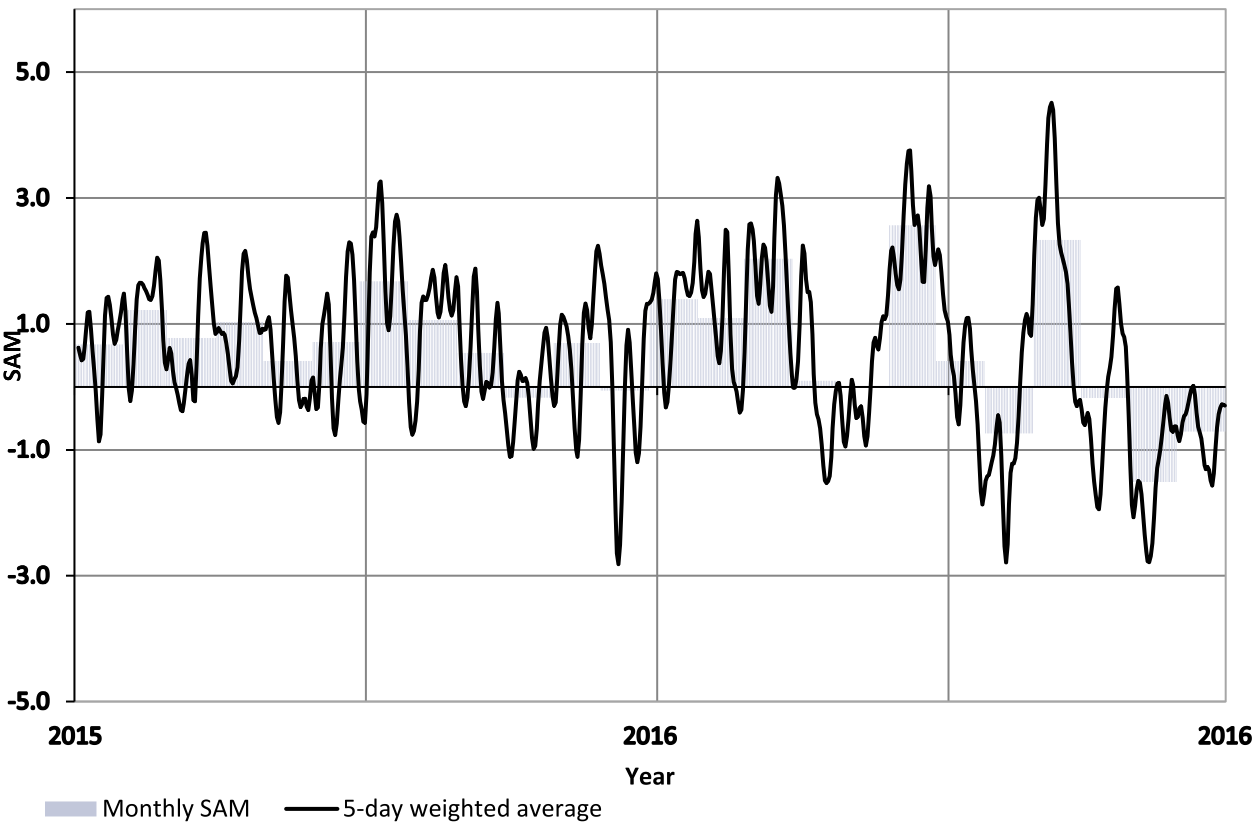

Fig. 7 Standardised AAO (SAM) index for January 2015 to December 2016, showing both monthly and 5-day weighted average. The daily values have been standardized by the standard deviation of the monthly AAO index from 1979–2000, as provided by NOAA's Climate Prediction Center at http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aao/aao.shtml.

3 Sea surface temperatures (SSTs) in the Australian region

Sea surface temperatures (SST) in the oceans around Australia were very much warmer than average during 2016, with the annual mean SST[6] for the Australian region[7] the warmest on record at +0.73 °C above the 1961–1990 average. The previous record was +0.64 °C, set in 2010. Sea surface temperatures (SSTs) have warmed substantially around Australia, and have been persistently high in recent years. Above average annual SSTs have been observed for the Australian region in every year since 1994. There has been a total increase of approximately 1 °C since 1900, very similar to the increase in temperature observed over land.

El Niño, in combination with background global warming, led to record-warm SSTs around much of Australia during the first half of 2016, including in the Coral Sea and to Australia's northwest where widespread coral bleaching was observed. The bleaching event in the northern Great Barrier Reef was the worst on record, affecting some 1000 km of reef north of Lizard Island (Pratchett and Lough 2016), while in Western Australia it was the third time a bleaching event has ever been recorded.

SSTs were also record-warm around Tasmania and across parts of the Tasman Sea during the first half of 2016, indicative of a southward extension of the East Australian Current. This was associated with the longest and most intense marine heatwave on record for the southeast Australian region (Oliver et al. 2017).

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[6] Based on ERSST v4 data, with records commencing in 1900 for the Australian region.
[7] A boxed region around Australia from 4°S to 46°S and from 94°E to 174°E.

SSTs remained in the highest ten per cent of historical records across waters to Australia's north and east throughout the second half of the year, although the areas which were warmest on record for their respective months were much smaller.

From August onwards an area of water around the southwest of Western Australia experienced cooler than average SSTs, with a large area very much cooler than average (SSTs in the lowest ten per cent of historical observations) during September and October. These cool waters were caused by southwesterly winds; those winds were the result of an atmospheric circulation set up by very warm water south of Indonesia.. This effect can also be seen in cooler than average air temperatures in southwest Western Australia across much of the year.

For the Australian region as a whole, SST anomalies for each month from January to July were the highest on record for their respective month. March was not only the warmest March on record, but also had the largest monthly positive anomaly on record for Australian region SSTs for any month of the year. All of the months January to July 2016 were not only the warmest on record for their individual month, but together made up the seven largest positive anomalies on record for any month of the year.

Ocean warmth around the north and east of Australia persisted during the second half of the year, with the months August to November amongst the top ten warmest for their respective months. December was also warmer than average, but not within the top ten warmest years.

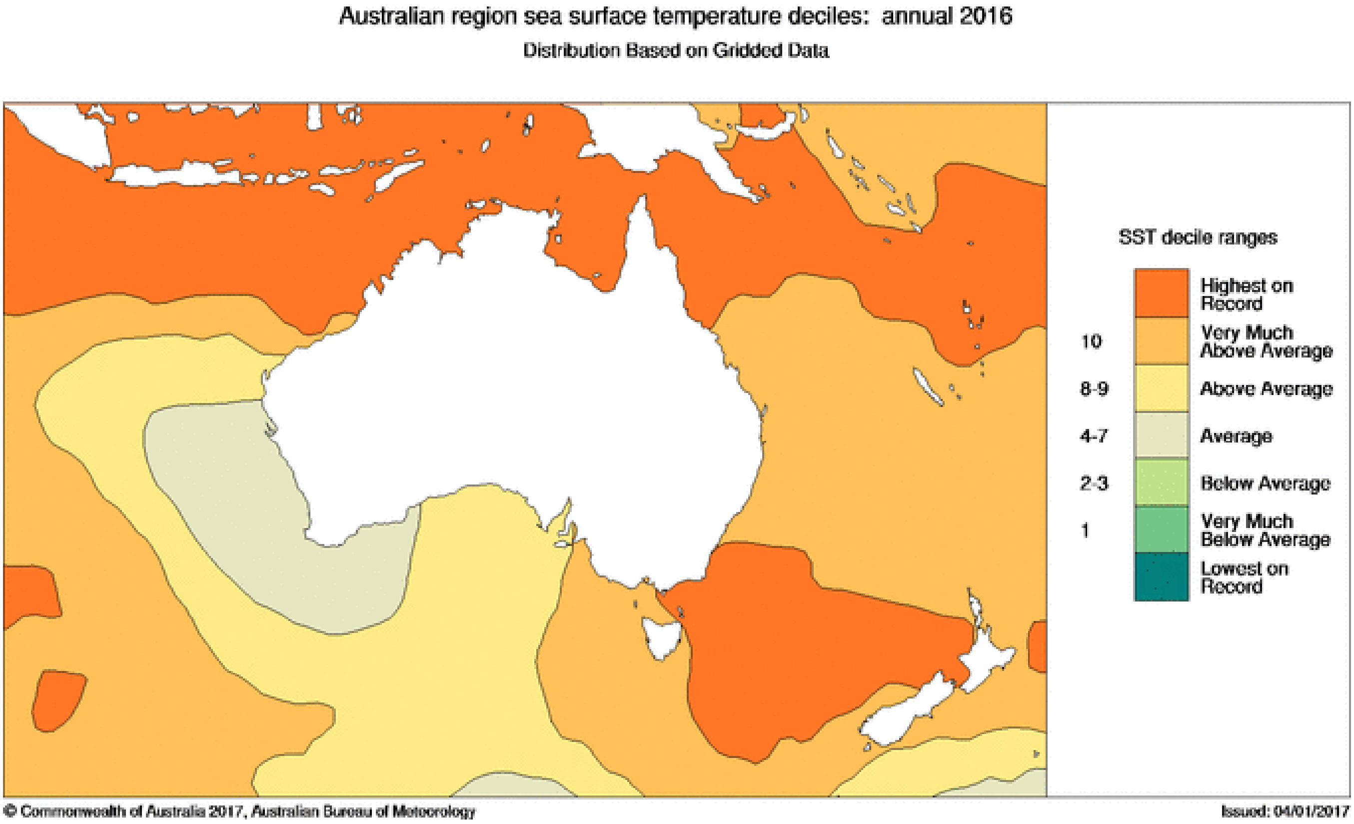

Fig. 8 2016 sea surface temperatures compared to historical records. (From the NOAA Extended Reconstructed Sea Surface Temperature dataset, ERSST v4).

4 Antarctic climate and surrounding sea ice

For much of the year nett coverage of sea ice around Antarctica was close to the 1981–2010 average[8], although there was a dramatic fall from August 2016 to December as the sea ice began retreating earlier than usual (Fig. 9).

[8] Based on satellite passive-microwave ice concentration data (Cavalieri et al. 1996, updated yearly).

Record low monthly mean sea ice extent was recorded for the months from October through December. Quite a number of record low individual daily values were broken, with 74 days of record low extent between September and December 2016, with daily values from early November to the end of the year all lowest on record. These low values are a considerable change from the record high values observed from 2012 to 2014, and also a departure from the small but statistically significant increase in nett extent since satellite records began in 1979.

The total sea ice cover is composed of regionally variable cover that forms, melts and advects throughout the year in response to large-scale ocean and atmospheric patterns and more localised factors such as fresh water input, iceberg or ice-tongue positions and interactions between ice, oceans and atmosphere. Particularly low sea ice extent was observed from August onwards in the eastern Weddell Sea and western Indian Ocean sector, followed by a sharp reduction in the western Ross Sea from October onwards. These sectors were affected by warmer than average sea surface temperatures that moved south in the Indian and Pacific oceans (Fig. 10). From late October through to the end of 2016, there was a decrease in the westerly wind strength around the continent (as indicated by the negative SAM index) and an influx of warmer than average temperatures across the sea ice zone and the continent.

Warmer than average sea surface temperatures were quite likely responsible for Macquarie Island's record rainfall in 2016 (1281.0 mm), which replaced the previous record of 1272.6 mm (2015) and was considerably higher than the annual average of 986.3 mm.

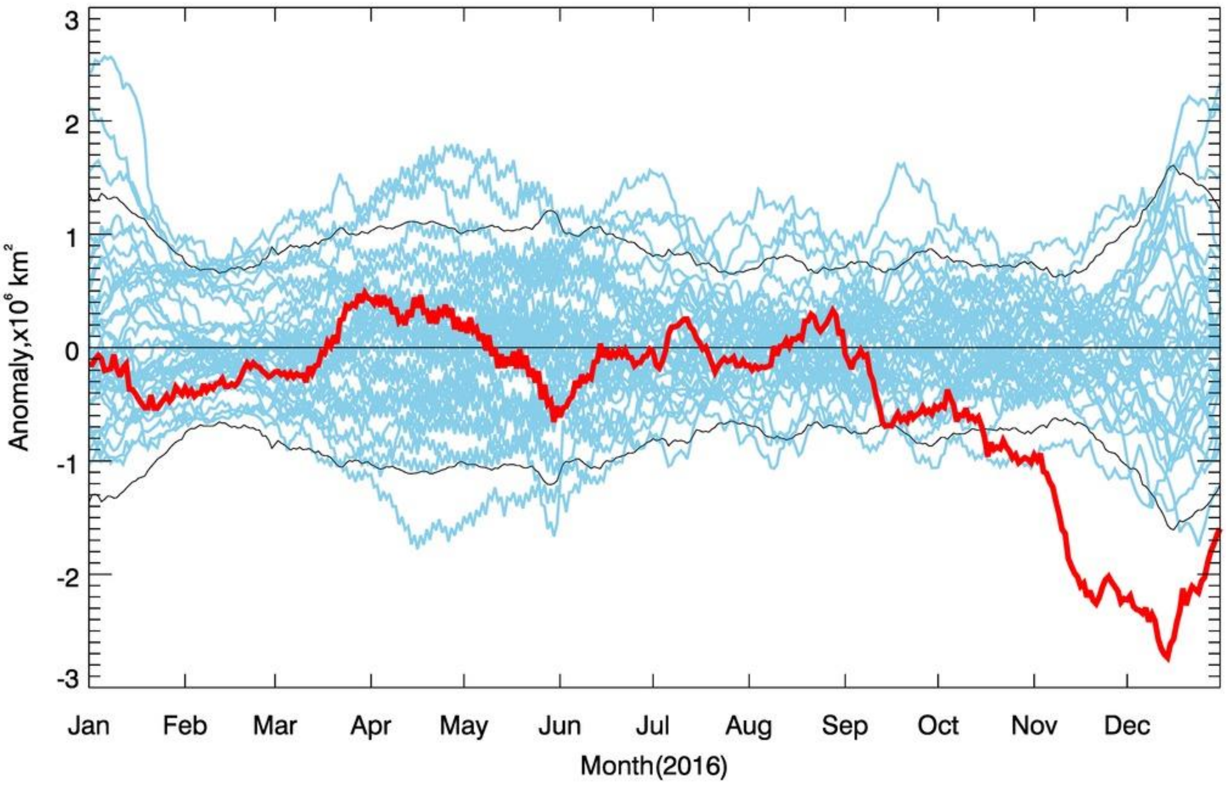

Fig. 9 Daily anomaly (millions of square kilometres) Southern Hemisphere sea ice extent (red line) for 2016 (compared to 1981–2010 mean). Thin blue lines represent the historical daily values of extent for each year from 1979 to 2015, while the thin black lines represents ±2 standard deviations of extent. Observations based on satellite passive-microwave ice concentration data (Cavalieri et al. 1996, updated yearly).

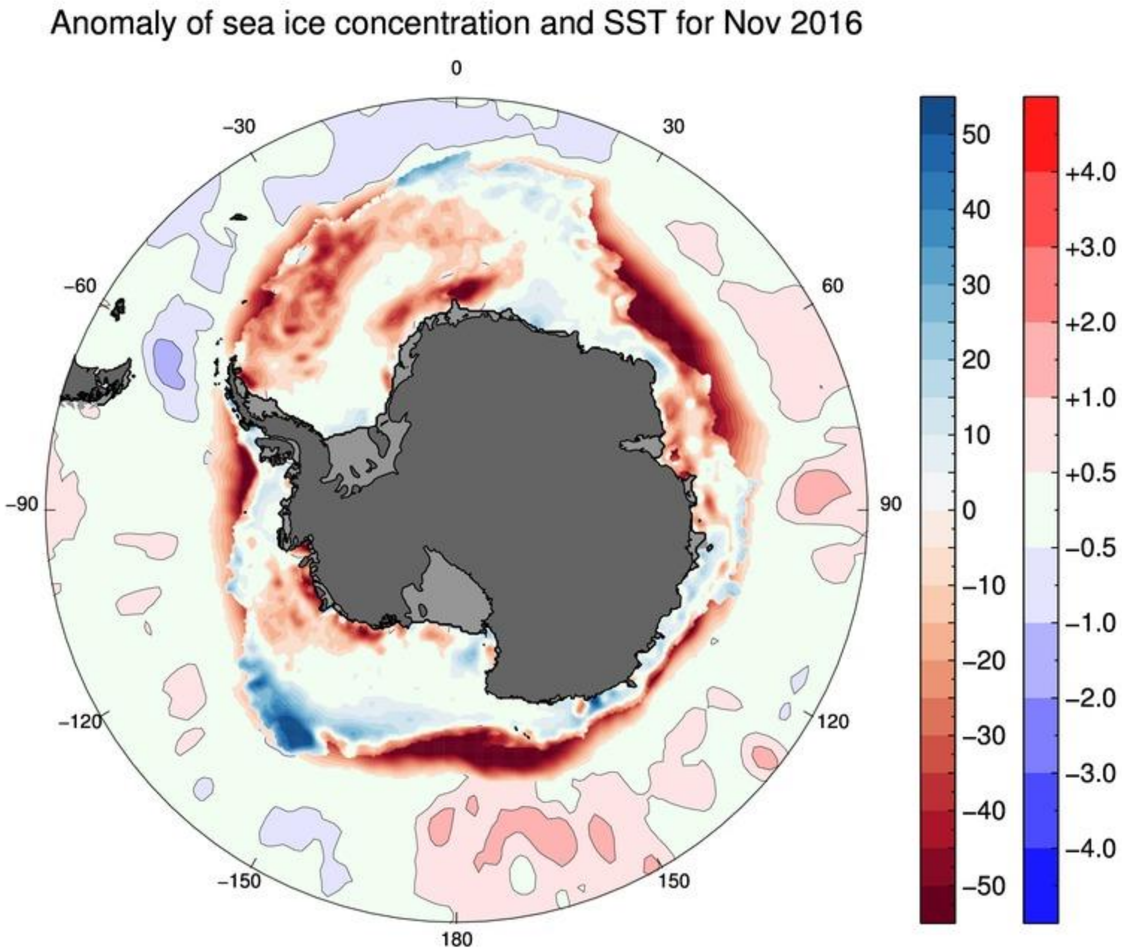

Fig. 10 Combined sea ice concentration anomaly and sea surface temperature anomaly for November 2016. Surrounding Antarctica, sea ice concentration anomaly as a percentage relative to the mean over 1981–2010 using the right hand scale. Away from the continent, sea surface temperature anomaly in °C using the left hand scale. (Reynolds et al. 2002; Smith et al. 2008).

5 Sea level, around Australia and globally

Globally, mean sea level has been rising at a rate of about 2.6–2.9 mm per year (over the years 1993–2013) (Watson et al. 2015). This rise of mean sea level is the result of a combination of thermal expansion of the oceans as they warm, the addition of fresh water to the ocean from glaciers and the ice sheets of Greenland and Antarctica, and exchange of freshwater with terrestrial water storages. Sea level, and changes in sea level, are not uniform around the globe and are influenced, at different timescales, by natural climate variability such as El Niño–Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (Salinger et al. 2001) and associated changes in winds and ocean currents.

As a result of this natural variability, rates of sea level rise to the north, west and southeast of Australia over the satellite measurement period (1993 to present) have been between 5 and 8 mm/year, well above the global average, and rates of sea level rise on the central east and southern coasts of the continent have been closer to the global average (Fig. 11).

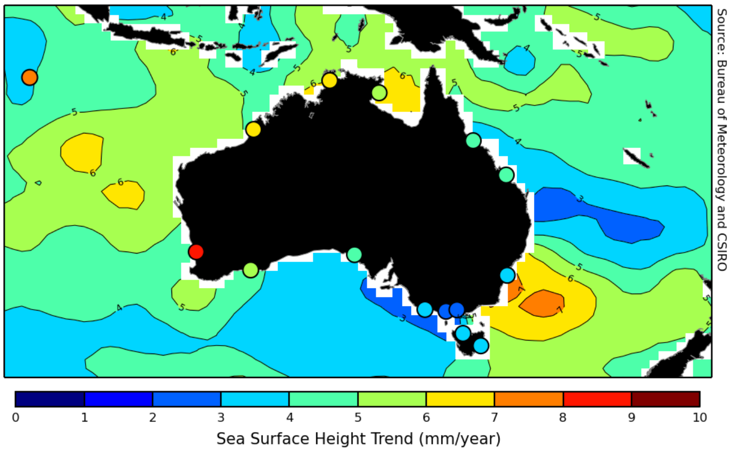

Fig. 11 The rate of sea surface height rise measured relative to the land by coastal tide gauges (coloured dots[9]), and relative to the centre of the earth by satellites (contours[10])

These large-scale drivers also have a global effect (Fig. 12). ENSO has been a large driver of sea level trends in recent decades. The strong La Niña of 2011 resulted in high rainfall over areas including Australia, with the resultant above-average water storage on land producing a notable dip in global sea level, followed by a strong rise through 2012.. The development of El Niño in early 2015 propelled the rate of global sea level rise to well above the long-term trend. This above-trend response continued into 2016.

Care must be taken when interpreting sea level trends from individual tide gauges. For instance, the greater apparent sea level rise compared to satellite measurements at Hillarys, near Perth, and in the Cocos Islands is thought to be associated with sinking of the coastal tide gauge, possibly due to compaction and/or ground water extraction. The local sea level rise relative to the land affects the coastal environment, but may not be directly comparable with satellite measurements of sea level relative to the centre of the Earth.

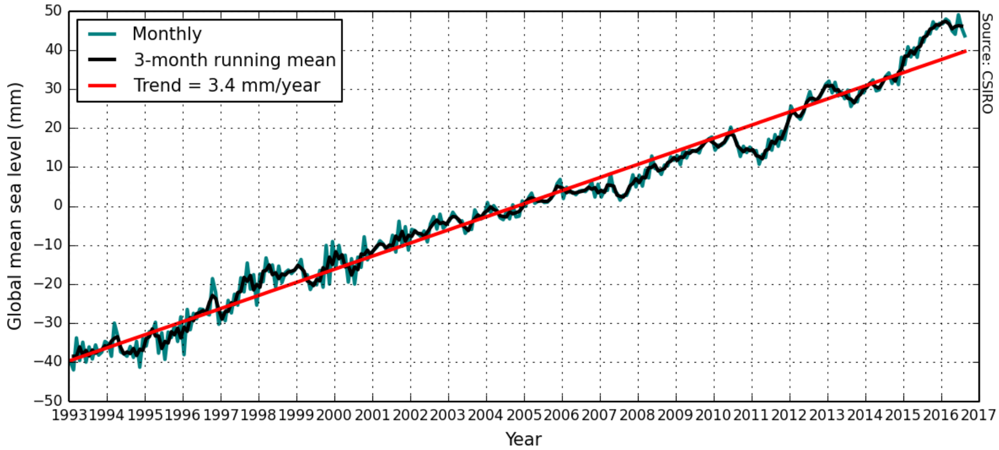

Fig. 12 Global sea level, anomalies relative to average over observational period January 1993 to August 2016. The black line shows a 12-month moving mean. Data are TOPEX/Poseidon, Jason-1 and Jason-2 satellite altimeter data, processed by CSIRO to remove the seasonal cycle.

[9] Australian Baseline Sea Level Monitoring Project tide gauge data from early 1990s to October 2016. The rates are relative to the sensor benchmark and have not been corrected for land movement or other parameters.
[10] January 1993 to August 2016. Satellite observations show sea level relative to the centre of the Earth and have had the seasonal signal removed and small corrections applied for changes in atmospheric pressure.

6 Australian region

6.1 Temperature

Australia’s annual mean temperature for 2016 was 0.87°C above the 1961–1990 average, making it the fourth-warmest year on record (national observations commence in 1910). Mean minimum temperatures were 1.03 °C above average, second-warmest behind the +1.16 °C anomaly from 1998. Maximum temperatures were 0.70 °C above average,

The mean temperature for the eleven years from 2006 to 2016 was the second-highest on record at 0.56 °C above average. Only one year during that period was cooler than average (2011), and seven of Australia's ten warmest years have occurred since 2005.

Warmth was persistent over Australia throughout 2016, with national average maximum temperatures cooler than average for only September and October, and minimum temperatures cooler than average for only October. Mean temperatures from February to July were amongst the nine warmest on record for their respective months, with mean temperature anomalies ranging from +0.92 °C to +2.00 °C.

Following a much warmer than average summer, there were frequent warm spells during autumn, contributing to Australia’s warmest March and warmest autumn on record. Autumn was marked by long runs of days with above average temperatures, as well as many record-high temperatures when a prolonged heatwave affected much of Australia during late February and the first half of March.

Winter was also warmer than average, and while spring remained warm for the northern tropics parts of southern Australia were cooler than average in September and October. November saw a return to above average temperatures over much of Australia, and December brought a warm finish to the year for the eastern states and South Australia.

The warmth around the north and east coasts of Australia brought a record-warm year for several of Australia’s major cities. Darwin and Sydney had their warmest years on record for both maximum and minimum temperature, whilst Hobart had its warmest nights on record and warmest annual mean temperature, and for Brisbane the annual mean temperature was warmest on record. It was the equal third-warmest year for Canberra annual mean temperature. Perth had its coolest year since 2005. Adelaide was a little warmer than average, and all sites across metropolitan Melbourne were warmer than average for the year.

Annual mean temperatures were above to very much above average for the majority of Australia, and record warm around the northern coastline, most of the eastern coastline, and southern and central Tasmania. Annual mean temperatures were in the highest ten per cent of historical observations for the remainder of Tasmania, much of New South Wales, and the majority of northern Australia. Temperatures were cooler than average for a small area of central southern Western Australia.

Maximum temperatures (Fig. 13) were in the highest ten per cent of historical observations around the north of Australia, the eastern seaboard and southern Victoria, and Tasmania; covering 33.3 per cent of the country’s total area (see Table 1). Annual maxima were above average for most of the remainder of the north, the eastern states and eastern South Australia. Annual mean maxima were the warmest on record for large areas of the far tropical north and in a narrow margin along most of the east coast.

Annual mean minimum temperatures (Fig. 14) were in the highest ten per cent of historical observations over a broad swathe of Australia (72.1 per cent of total area, see Table 1), and the warmest on record for Tasmania, most of Victoria and areas of southern to southeastern New South Wales, an area of Queensland away from the south and Cape York Peninsula, and areas of the western Top End and northwestern Australia. Only the southern half of Western Australia experienced annual minima close to the long-term average.

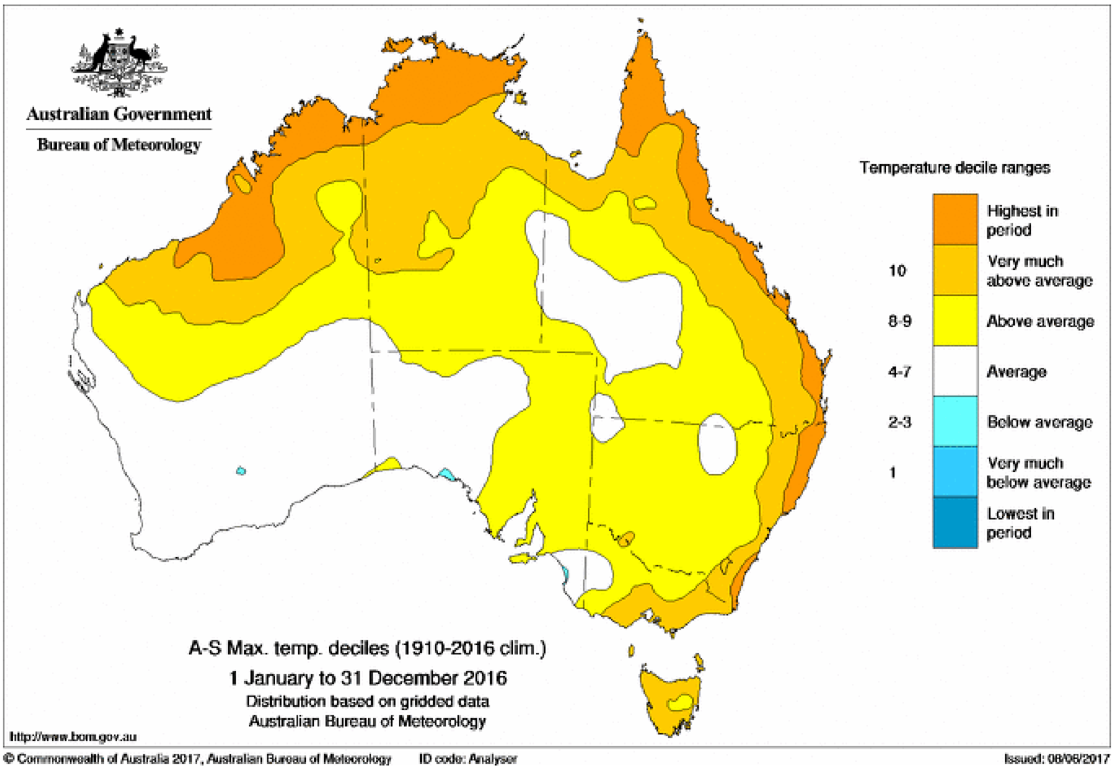

Fig. 13 2016 annual maximum temperature deciles based on gridded analysis over 1910–2016.

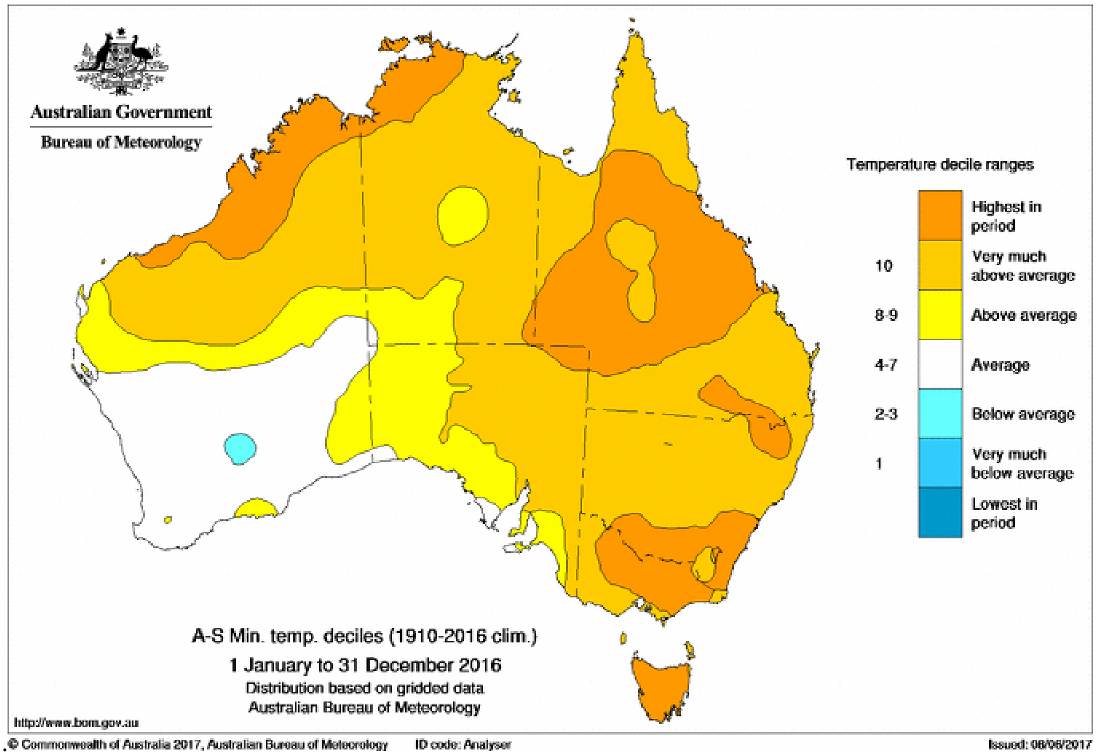

Fig. 14 2016 annual minimum temperature deciles based on gridded analysis over 1910–2016

Table 1 Percentage areas in different categories for 2016, using the gridded ACORN-SAT dataset[11], relative to 1910–2016. Areas in "decile 1" include those which are "lowest on record". Areas in "decile 10" include those which are "highest on record".

Region	*Maximum temperature*				*Minimum temperature*			
	Lowest on record	Decile 1	Decile 10	Highest on record	Lowest on record	Decile 1	Decile 10	Highest on record
Australia	0.0	0.0	33.3	11.0	0.0	0.0	72.1	23.1
Queensland	0.0	0.0	44.3	14.8	0.0	0.0	100.0	51.0
New South Wales	0.0	0.0	20.6	7.7	0.0	0.0	100.0	24.3
Victoria	0.0	0.0	39.2	0.0	0.0	0.0	100.0	60.4
Tasmania	0.0	0.0	82.0	0.0	0.0	0.0	100.0	99.1
South Australia	0.0	0.0	0.0	0.0	0.0	0.0	53.7	2.9
Western Australia	0.0	0.0	30.6	12.0	0.0	0.0	41.6	12.9
Northern Territory	0.0	0.0	53.3	16.9	0.0	0.0	83.6	10.3

[11] A high-quality subset of the temperature network is used to calculate the spatial averages and rankings shown. This dataset is known as ACORN-SAT (see http://www.bom.gov.au/climate/change/acorn-sat/ for details).

Table 2 Summary of maximum temperature ranks and extremes on a national and State basis for 2016. The ranking in the last column goes from 1 (lowest) to 107 (highest) and is calculated over the years 1950–2016[12].

Region	*Highest annual mean maximum temperature*	*Lowest annual mean maximum temperature*	*Highest daily temperature*	*Lowest daily maximum temperature*	*Area-averaged anomaly*	*Rank of area-averaged anomaly (1 to 107)*
Australia	37.5 °C at Wyndham Aero (WA)	8.4 °C kunanyi (Mount Wellington Pinnacle) (Tas.)	47.8 °C at Mardie on 12 February and Emu Creek Station on 13 February (both WA)	–5.8 °C at Thredbo AWS on 13 July (NSW)	0.70 °C	99
Queensland	35.0 °C at Century Mine	21.8 °C at Applethorpe	46.9 °C Birdsville Airport on 2 December	6.8 °C at Applethorpe on 6 July	0.81 °C	97=
New South Wales	28.6 °C at Mungindi Post Office	8.5 °C at Thredbo AWS	46.0 °C at Hay Airport AWS on 13 January	–5.8 °C at Thredbo AWS on 13 July	0.91 °C	91
Victoria	24.8 °C at Mildura Airport	9.4 °C at Falls Creek	45.6 °C at Echuca Aerodrome on 13 January	–4.6 °C at Mount Hotham on 24 June and 13 July	0.74 °C	96=
Tasmania	19.0 °C at Launceston (Ti Tree Bend)	8.4 °C kunanyi (Mount Wellington Pinnacle)	36.8 °C at Grove (Research Station) on 13 January	–3.6 °C kunanyi (Mount Wellington Pinnacle) at 23 July	0.67 °C	100
South Australia	29.2 °C at Moomba Airport and Oodnadatta Airport	17.0 °C at Mount Lofty	45.9 °C at Oodnadatta Airport on 1 December	4.6 °C Mount Lofty on 12 July	0.43 °C	78=
Western Australia	37.5 °C at Wyndham Aero	19.4 °C at Shannon	47.8 °C at Mardie on 12 February and Emu Creek Station on 13 February	8.8 °C at Rocky Gully on 8 August	0.56 °C	88
Northern Territory	36.8 °C at Bradshaw	29.5 °C at Alice Springs Airport	44.8 °C at Rabbit Flat on 4 January	10.0 °C at Arltunga on 13 July	0.89 °C	99

[12] A high-quality subset of the temperature network is used to calculate the spatial averages and rankings shown. These averages are available from 1910 to the present. Rankings that tied (at the two decimal place precision shown) are marked with =.

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Table 3 Summary of minimum temperature ranks and extremes on a national and State basis for 2016. The ranking in the last column goes from 1 (lowest) to 107 (highest) and is calculated over the years 1950–2016.

Region	*Highest annual mean minimum temperature*	*Lowest annual mean minimum temperature*	*Highest daily minimum temperature*	*Lowest daily temperature*	*Area-averaged anomaly*	*Rank of area-averaged anomaly (1 tp 107)*
Australia	27.0 °C at Troughton Island (WA)	1.6 °C at Thredbo AWS (NSW)	33.4 °C at Telfer Aero on 4 January (WA)	–10.4 °C at Thredbo AWS on 7 August (NSW)	1.03 °C	106
Queensland	25.9 °C at Coconut Island	9.6 °C at Applethorpe	33.2 °C at Birdsville Airport on 12 January and Boulia Airport on 2 February	–4.5 °C at Stanthorpe (Leslie Parade) on 26 June and 30 July	1.61 °C	107
New South Wales	17.0 °C at South West Rocks (Smoky Cape Lighthouse)	1.6 °C at Thredbo AWS	31.4 °C at Fowlers Gap AWS on 28 December	–10.4 °C at Thredbo AWS on 7 August	1.24 °C	107
Victoria	12.9 °C at Gabo Island Lighthouse	3.1 °C at Falls Creek	29.0 °C at Walpeup Research on 26 December	–8.0 °C at Mount Hotham on 13 and 14 July	1.06 °C	107
Tasmania	12.2 °C at Swan Island	1.9 °C at kunanyi (Mount Wellington Pinnacle)	21.8 °C at Flinders Island Airport on 24 February	–9.0 °C at Liawenee on 1 June	1.08 °C	107
South Australia	16.1 °C at Moomba Airport	8.6 °C at Keith (Munkora)	31.8 °C at Roxby Downs (Olympic Dam Aerodrome) on 13 January and Moomba Airport on 27 December	–5.0 °C at Yunta Airstrip on 16 July	0.73 °C	100=
Western Australia	27.0 °C at Troughton Island	8.1 °C at Newdegate Research Station	33.4 °C at Telfer Aero on 4 January	–4.5 °C at Eyre on 18 September	0.66 °C	100=
Northern Territory	26.7 °C at McCluer Island	13.9 °C at Alice Springs Airport	31.9 °C at Victoria River Downs on 10 December	–4.5 °C Kulgera 16 July	1.10 °C	104

6.2 Rainfall

Australian mean rainfall for 2016 was nineteen per cent above the 1961–1990 average, with an area-average total of 551.42 mm—well above the average of 465.2 mm. Compared to rainfall since 1900 (117 years), this makes 2016 the 13th-wettest year on record (see Table 4).

Annual rainfall was above average for most of Australia, although below average for areas of the coast in the Gascoyne and Pilbara in Western Australia, pockets of the coastal Top End, much of the Cape York Peninsula in Queensland, and also for parts of coastal southeast Queensland and northeastern New South Wales.

Rainfall for the year was in the highest ten per cent of historical observations (decile 10) for most of Tasmania and New South Wales inland of the Great Dividing Range, areas of northern and western Victoria, parts of agricultural South Australia, and very large areas of Central Australia extending from western Queensland, across the north of South Australia and south of the Northern Territory, and adjacent parts of central inland Western Australia. Collectively, rainfall was in decile 10 for 33.9 per cent of Australia's total area (see table 5).

Tasmania experienced its second-wettest year since 1900, and South Australia its third-wettest. Victoria and New South Wales ranked 13th- and 14th-wettest respectively. This was a dramatic change for Victoria and Tasmania, both of which had low annual rainfall during 2014 and 2015, and commenced 2016 with large areas of long-term rainfall deficiencies.

Annual rainfall was below average for the north of the Cape York Peninsula in Queensland, areas of the Top End and south of the Gulf of Carpentaria in the Northern Territory, areas along the northwest coast of Western Australia and on the coast of southeast Queensland and northern New South Wales.

Adelaide had its second-wettest year on record and its wettest since 1992. Sydney, Canberra and Hobart had above average rainfall, whilst Perth and Melbourne received close to average rainfall. Both Darwin and Brisbane were significantly drier than average for 2016. However, Darwin's year was a mix of above and below average rainfall; it had its driest January–April period on record, then its wettest dry season since 1988, and finally October–December rainfall more than 150 per cent of the average.

The 2015–16 northern wet season (October 2015 to April 2016) was the driest in more than 20 years, and the fourth drier-than-average wet season in a row. December 2015 was very wet, largely as a result of a single low pressure system, but January in particular was dry for the far north of Australia, with small pockets experiencing their driest January on record. As well as infrequent and generally weak periods of monsoonal rainfall, the season saw far fewer tropical cyclones than average but an elevated number of tropical lows, which are systems one step below a tropical cyclone (see section 6.4).

January to April rainfall was below average for much of eastern Australia as well as for the north of the country. This dry start to the year saw the persistence of drought conditions across large areas of western and central Victoria, southeastern South Australia, Tasmania, and large areas of inland Queensland.

As the 2015–16 El Niño broke down during autumn, and a negative Indian Ocean Dipole developed in May, conditions turned dramatically wetter. After Australia's ninth-driest April on record, May came in as sixth-wettest.

Very much above average rainfall continued during winter and spring, providing relief from prolonged dry conditions which were widespread earlier in the year in Queensland and southeastern Australia. Satellite imagery shows that the wet and warm southern growing season brought significant grass growth in 2016. Conditions were favourable for crop production, with ABARES noting a record breaking wheat crop for 2016 (ABARES 2017). Historically, increased wheat production is strongly associated with those years experiencing mild and wet conditions and a negative Indian Ocean Dipole.

All six months from May to October had above average rainfall for the country. June and September were exceptionally wet, both second-wettest on record for their respective months for the country as a whole. Winter was the second-wettest on record, with just over half of Australia receiving rainfall totals in the highest ten per cent of historical records for the June–August period. The only region to experience below-average rainfall during winter was southwest Australia, where the long-term rainfall decline is the dominant factor. May to September was also the wettest May–September on record (Figure 17).

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Only southwest Western Australia, experienced below average rainfall during May to September. There has been a general decline in rainfall in this area, especially since the 1970s (BoM 2017).

Rainfall for October was near-average over much of Australia. With the IOD moving from a negative event to neutral, November to December rainfall continued to be above average across most of the northwest and central Australia, while much of eastern Australia experienced below average rainfall. A tropical low at the end of the year brought very much above average December rainfall across South Australia, the Northern Territory and the east of Western Australia.

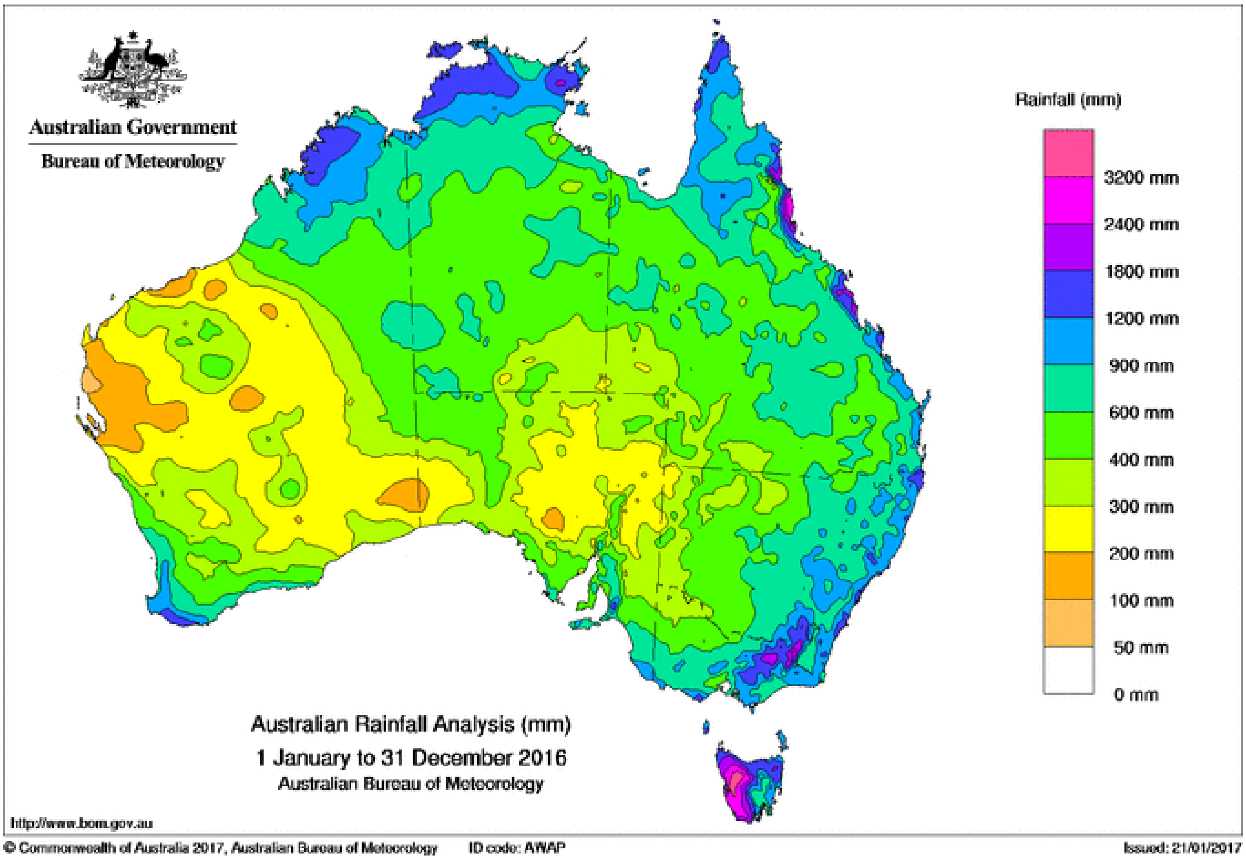

Fig. 15 2016 annual rainfall totals (mm) for Australia.

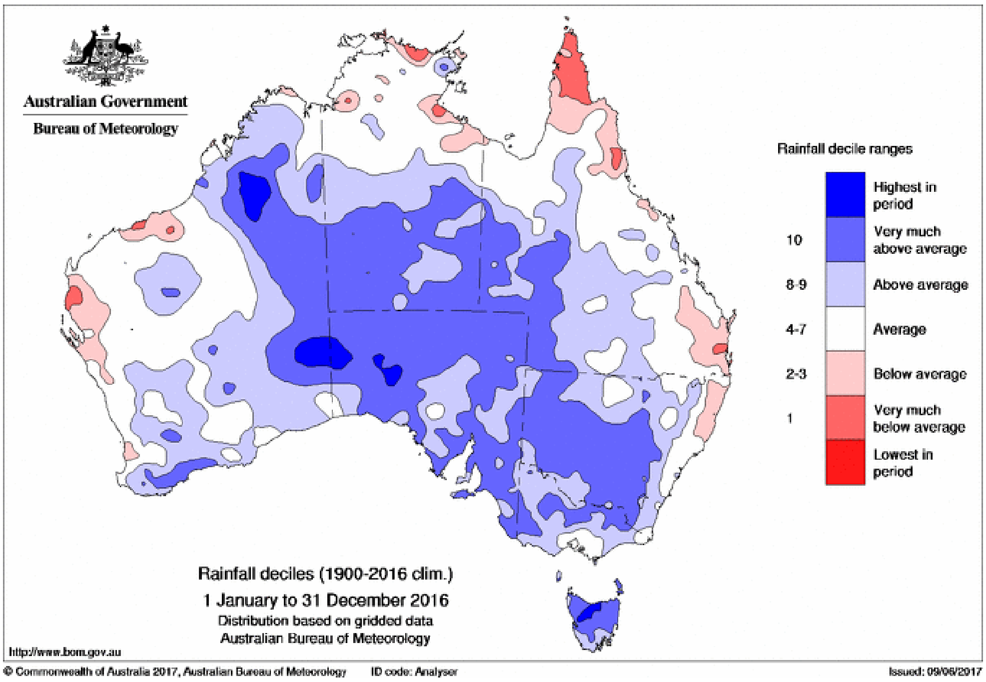

Figure 16 Rainfall deciles for Australia for 2016, based on the 1900–2016 distribution.

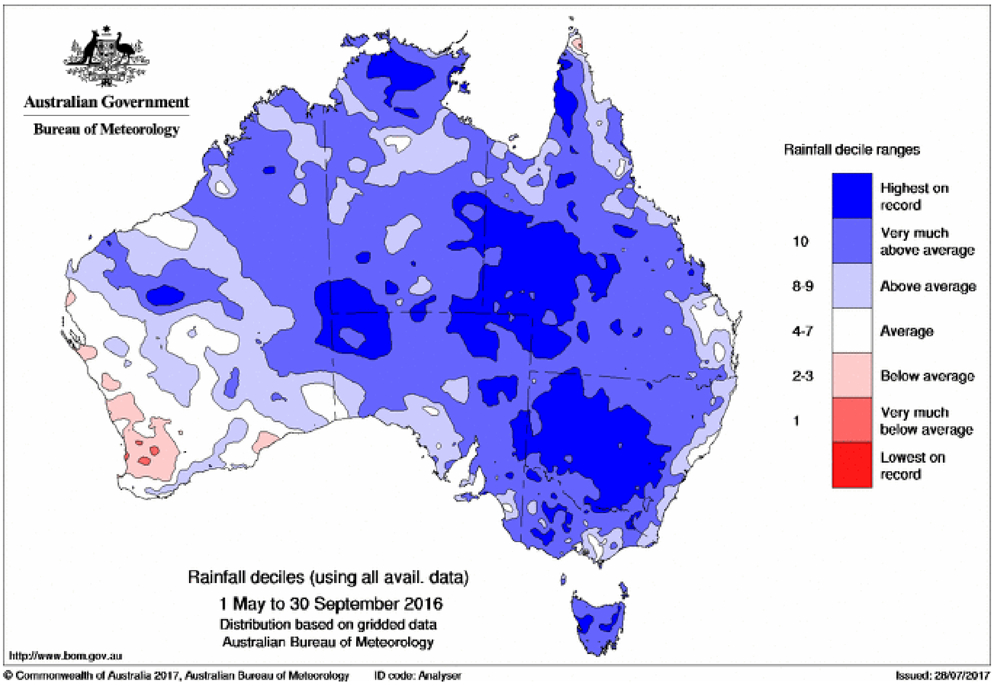

Figure 17 Rainfall deciles for Australia for the five months May to September 2016, based on the 1900–2016 distribution.

Table 4 Summary of rainfall ranks and extremes on a national and State basis for 2016. The ranking in the last column goes from 1 (lowest) to 117 (highest) and is calculated over the years 1900–2016.

Region	*Highest annual total*	*Highest daily total*	*Area-averaged rainfall*	*Rank of area-averaged rainfall (1 to 117)*	*Difference from mean*
Australia	6341 mm at Bellenden Ker Top Station (Qld.)	430.0 mm at Coramba (Glenfiddich) on 5 June (NSW)	551.4 mm	105	+19%
Queensland	6341 mm at Bellenden Ker Top Station	412.6 mm at Miara on 5 January	641.4 mm	70	+3%
New South Wales	2928 mm at Perisher Valley AWS	430.0 mm at Coramba (Glenfiddich) on 5 June	660.9 mm	105	+20%
Victoria	2105 mm at Mount Buller	158.6 mm at Mount Hotham on 30 December	787.9 mm	104	+19%
Tasmania	3709 mm at Lake Margaret Power Station	278.0 mm at St Marys (Cameron Street) on 22 June	1819.5 mm	116	+31%
South Australia	1791 mm at Uraidla	130.8 mm at Kalamurina on 1 January	373.5 mm	115	+66%
Western Australia	1443 mm at Northcliffe	225.6 mm at Broome Airport on 23 December	425.1 mm	99	+25%
Northern Territory	1901 mm at Walker Creek	231.6 mm at Walungurru Airport on 26 December	636.0 mm	94	+18%

Table 5 Percentage areas in different categories for 2016 annual rainfall, using the gridded AWAP dataset[13], relative to 1900–2016. "Severe deficiency" denotes rainfall at or below the 5th percentile. Areas in "decile 1" include those in "severe deficiency", which in turn include those which are "lowest on record". Areas in "decile 10" include those which are "highest on record".

Region	*Lowest on record*	*Severe deficiency*	*Decile 1*	*Decile 10*	*Highest on record*
Australia	0.0	0.3	1.4	33.9	1.6
Queensland	0.0	0.8	4.2	16.1	0.0
New South Wales	0.0	0.0	0.2	49.2	0.0
Victoria	0.0	0.0	0.0	37.0	0.0
Tasmania	0.0	0.0	0.0	76.9	20.8
South Australia	0.0	0.0	0.0	75.1	3.5
Western Australia	0.0	0.0	0.7	22.0	2.9
Northern Territory	0.0	0.5	1.2	36.9	0.0

6.3 Drought

Victoria, southeast South Australia, and Tasmania had each received below average annual rainfall during 2014 and 2015, and commenced 2016 with large areas of long-term rainfall deficiencies. Deficiencies on timescales from one to four years were also present across large areas of inland and central northern Queensland and parts of the South West Land Division in Western Australia.

Under the influence of a very strong El Niño, a dry start to 2016 saw persistence of these deficiencies during the first four months of the year.

Rainfall in March eased deficiencies in parts of northern and western Queensland, and parts of South Australia away from the southeast, but it wasn't until May when the shifting climate drivers saw more widespread above average rainfall and a subsequent decrease in areas with marked rainfall deficiencies.

May's rainfall largely cleared deficiencies affecting Tasmania and reduced the severity of deficiencies in northern Victoria. Continued rainfall saw further reductions in deficiencies across these regions as the year progressed, although were slow to clear from southeast South Australia and western to central southern Victoria, and from the South West Land Division in Western Australia where a long-term drying trend has been detected (BoM 2017).

By the conclusion of the record-wet May to September period remaining deficiencies had been cleared for most periods out to 24 months.

6.4 Tropical cyclone season 2015–16, and the first part of 2016–17

It was a very quiet season for tropical cyclones (November 2015 to April 2016), with only three recorded in the Australian region, compared to a long-term average of 11, and the lowest number since satellite records began in the 1970s. There were no severe (category 3) cyclones, and only one cyclone made landfall (tropical cyclone *Stan* in Western Australia).

By the end of 2016, the 2016–2017 tropical cyclone season had only seen one cyclone: *Yvette*, which had weakened to tropical low strength before making landfall near Broome on 25 December.

[13] The analysis method used to calculate the spatial averages and rankings is described in Jones et al. 2009. These averages are available from 1900 to the present. Rankings that tied (at the two decimal place precision shown) are marked with =.

6.5 Notable events

El Niño, in combination with background global warming, led to record-warm SSTs around Australia during the first half of 2016. Coral bleaching in the northern Great Barrier Reef was the worst on record, affecting some 1000 km (Pratchett and Lough 2016), while in the reefs to Australia's northwest Kimberley coast it was only the third time a major bleaching event has ever been recorded (Schoepf 2016). SSTs were also record-warm around Tasmania and across parts of the Tasman Sea, in part driven by a southward extension of the East Australian Current. This was associated with the longest and most intense marine heatwave on record for the southeast Australian region (Oliver et al. 2017), with outbreaks of disease in aquaculture and the loss of cold water kelp forests along the Tasmanian east coast.

The very dry and warm conditions with low cloudiness during the northern Australian 2015–16 wet season also contributed to widespread mangrove deaths along the northern coastline (Duke et al. 2017).

Excessive heat was not restricted to the oceans: during late February and the first half of March a prolonged heatwave affected much of Australia, especially the southeast. This was attributed to weak monsoonal rainfall over northern Australia leading to a build-up of heat in the interior, and by the first week of March this had extended to cover almost all of Australia, with numerous daily records set.

In northwest Tasmania extensive bushfires occurred during January and February following an extended dry period; about 123 800 ha burnt mostly in remote areas, with smoke on occasion reaching Hobart and southern Victoria. There were also significant fires at the start of 2016 near Lorne in Victoria, and in southwest Western Australia affecting Yarloop and Waroona. These events led to the loss of many houses with a number of deaths.

An East Coast Low caused major coastal flooding and erosion in New South Wales in early June, with major flooding also affecting Victoria and large parts of Tasmania.

There were also significant storm and wind events which affected the southeast during the wet period. In the Murray–Darling Basin, already wet soils and high river levels meant excessive rain caused flooding in many areas of inland New South Wales and the north and west of Victoria throughout September and October, with flooding also affecting some parts of southeast South Australia.

In Queensland, flooding occurred from June to September in western, central and southern Queensland following the state's second-wettest winter on record. Waters in this inland drainage basin can take many months to progress through the system, meaning flooding in the western parts of Queensland can span multiple months.

Significant flooding also occurred in Tasmania during January and in each month of spring.

As well as the rain, spring saw a number of damaging severe storms, with the most notable occurring in South Australia in late September when severe thunderstorms and multiple tornados caused widespread damage (BoM 2016) and on 21 November when widespread thunderstorms affected Victoria, igniting grassfires in the north and triggering thousands of incidents of thunderstorm asthma—the worst such event recorded in Australia[14].

A tropical low at the end of the year brought exceptional rainfall to a number of regions from the northwest to the southeast of Australia. This caused flooding in the Kimberley, flash flooding around Uluru in Central Australia, and around Adelaide, Melbourne and Hobart. Southeast Australia also experienced exceptional humidity during the event.

Further detail on these and other significant events are carried in the Monthly Weather Reviews, Special Climate Statements, and the Annual Climate Statement available from http://www.bom.gov.au/climate/current/.

[14] http://www.theage.com.au/victoria/ninth-thunderstorm-asthma-death-20170125-gtyfbj.html and https://www2.health.vic.gov.au/Api/downloadmedia/%7B188CEBBE-EEEB-4127-903C-8E94036E854D%7D

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