Earth Systems and Climate Change Hub

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# Climate drivers of the 2015 Gulf of Carpentaria mangrove dieback

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# Acknowledgements

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# Executive summary

**At a glance**

ESCC Hub researchers investigated the oceanic and atmospheric conditions leading up to the major mangrove dieback in late 2015 to identify potential stressors that contributed to the tree deaths. They found that it was most likely a result of a combination of very dry conditions and lower than average sea level. In combination, it appears that these conditions were unprecedented since at least 1971, and linked to the strong El Niño of 2015/16.

More detailed attribution studies are necessary to determine what role, if any, human-induced climate change played in the 2015 dieback event. This would help inform natural resource policy-makers, planners and associated decision-makers about the causes of such events and how they may change into the future.

## Mangroves and the 2015 dieback

Work conducted by Duke et al. (2017) as part of a joint NESP project between the Northern Australia Environmental Resources Hub and Tropical Water Quality Hub showed that approximately 7400 hectares of mangroves suffered dieback across a 1000 km front along the southern Gulf of Carpentaria in late 2015.

Mangroves are a vitally important part of the local ecosystem, providing homes and nurseries for an array of aquatic life, protecting coastlines from extreme weather and erosion, filtering out sediment from river run-off to protect coral reefs and sea grass, as well as absorbing and storing large amounts of carbon dioxide. The total value of these services is conservatively estimated to be AU$1.7 billion annually (Lovelock et al. 2015), a value likely diminished by the dieback event.

Mangrove trees require moisture from a combination of sources, including sea water. They can become stressed when sea levels are low and their roots are exposed for long periods of time. High temperatures can also exacerbate moisture loss, leading to further stress. In the absence of other disturbances such as pollution or tropical cyclones, hypersalinity can kill them.

## Timing of the event

While the main dieback occurred late in 2015, satellite data suggests that the trees were already not as green and vigorous as usual at the end of the preceding wet season (March-April 2015) and throughout 2015. This suggests that the dieback may have been the result of cumulative stress.

## Climate drivers

Local sea levels were unusually low for most of 2015. As sea levels dropped at the start of the dry season, ocean salinity levels were high. An early end to the 2014/15 wet season, below-average vapour pressure, and below-average top layer soil moisture since February 2015 point to moisture loss as a major factor.

Near surface land temperatures in the region were also high through most of 2015, with maximum temperatures at least in the top 20% from February to September, and November the warmest on record for much of the affected coastline.

The coincidence of unusually hot and dry conditions with low sea level likely provided a stressful environment for the mangroves. This cumulative stress during most of 2015 almost certainly contributed to the major dieback near the end of 2015.

The combination of dry and warm conditions in the six to nine months preceding the dieback has not been experienced since records began in 1971.

## Did climate change play a role?

The unusually low sea levels contributing to the dieback were largely a result of the strong El Niño in 2015/16. While the combination of these low sea levels and very dry conditions underpinned the mangrove dieback, detailed attribution studies are necessary to determine what role, if any, human-induced climate change played in this event.

## Next steps

There are still many questions with respect to understanding why the major mangrove dieback occurred, if it has happened before and if climate change played a part.

Development of a climate-based mangrove stress index could be used to identify (and consequently study) dieback events that may have occurred in the past, and assess potential dieback conditions in the future. Such an index would serve as an important management tool for mangrove communities and possibly other vulnerable ecological communities.

Better understanding of the climate drivers of events such as this one will help inform natural resource managers, policy-makers, planners and associated decision-makers about current and future risks.

# 1 Introduction

Late in 2015, approximately 7400 hectares of mangroves died along 1000 km coastline of the Gulf of Carpentaria (Figure 1; Duke et al. 2017). There was great interest in the media (Scobell 2016; Slezak 2016; van Oosterzee and Duke 2017; Wild 2016). Stark photos reveal the dramatic extent of the deaths (Duke, 2017). Mangroves are a vitally important part of the local ecosystem, providing homes and nurseries for an array of aquatic life, protecting coastlines from extreme weather and erosion, filtering out sediment from river run-off to protect coral reefs and sea grass, as well as absorbing and storing massive amounts of carbon dioxide (Gilman et al. 2008; Hamilton and Snedaker 1984; Lovelock et al. 2015; Phillips 2015). The total value of these services is conservatively estimated to be AU$1.7 billion annually (Lovelock et al. 2015), a value likely diminished by the dieback event. Climate factors and low sea levels are suggested as the likely cause (Duke et al. 2017; Hope et al. 2017; Oliver et al. 2017; van Oosterzee and Duke 2017). The exact timing of the dieback has implications for which aspects of the climate were particularly relevant given the strong seasonal cycle in rainfall and sea level in the region. We explore the hypothesis that there was cumulative stress, and thus examine the climate during the year prior to the dieback event.

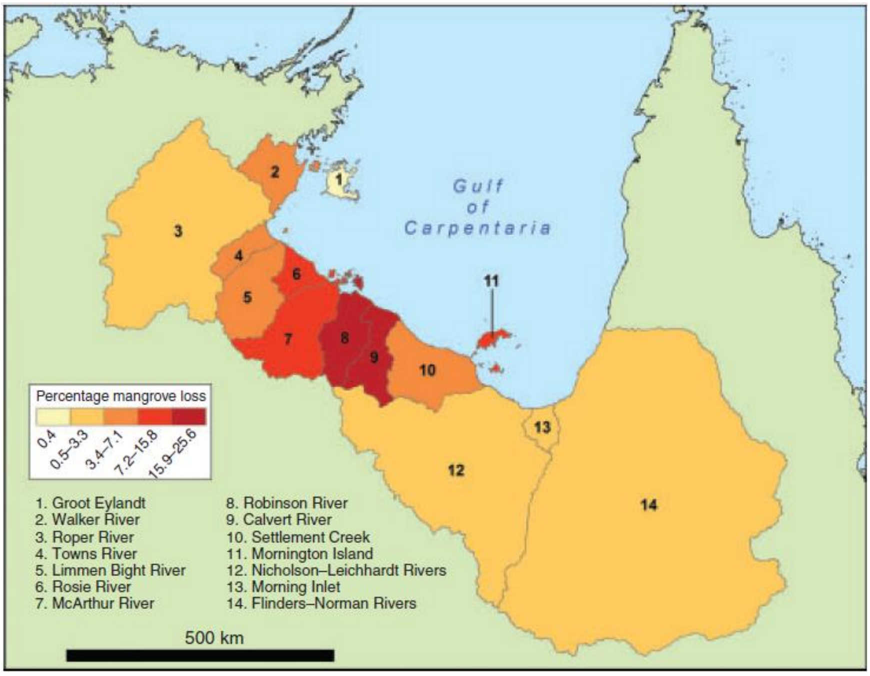

Figure 1: Proportional losses of mangroves for 14 catchment areas bordering the southern shorelines of the Gulf of Carpentaria. From Duke et al. 2017, their Figure 10

## 1.1 Mangrove physiology and stressors

Mangrove trees obtain moisture from a combination of sources, including sea water (Lovelock et al. 2017). They can become stressed when in hypersaline conditions or when moisture sources are reduced (M Ball, Australian National University, pers. comm. February 2017). This can occur when sea levels are low and their roots are exposed for long periods of time. High temperatures can also exacerbate moisture loss, leading to further stress. In the absence of other disturbances such as pollution or tropical cyclones, hypersalinity can ultimately kill them (L Hutley, Charles Darwin University, pers. comm. January 2017).

Most species of mangroves can tolerate a mix of fresh and salt water, however, there is a wide range of salt tolerances between species. Furthermore, those species that can tolerate a large range of salinities have slower growth than the less tolerant species, even when conditions are optimal. This results in a distribution of mangrove species along a salinity gradient of a coastline that are all on the upper edge of their salinity tolerance (Ball 1988; Duke et al. 1998). Consequently there are mangroves that are vulnerable to sudden increases in salinity throughout their distribution, not just in the most saline areas at the seaward edge of the forests.

With their shallow roots, mangroves are vulnerable to lower than normal sea levels, which might dry out the soil. Such conditions could trigger a change in the environment from mangrove forest to saltmarsh, where only a few specialised plants can grow in the drier, more saline soils (Goudkamp & Chin 2006). This is likely only to be a major issue late in the dry season where it would be compounded by an extended lack of rainfall (Ball 1998).

Higher air temperatures have been found to be a stressor. Reef et al. (2016) found that certain mangrove species (not the same as found along the Gulf of Carpentaria) cannot efficiently photosynthesise over 35°C, particularly if they are stressed by other factors. The Gulf Country often exceeds this threshold during the wet season, but not during the dry season on average.

## 1.2 This study

Initial investigations into the late 2015 event indicated that climate conditions were to blame. Media reports based on information from James Cook University focused on the short wet season that preceded the dieback, and the elevated temperatures that had persisted for several months leading up to the event. The temperatures through the dry season in 2015 were generally higher than average, with particularly high temperatures at the beginning of the dry season in March (Bureau of Meteorology 2015), and at the end of the dry season in November. High sea-surface temperatures and low sea level have also been discussed as contributing factors (Duke et al. 2017). The purpose of this study is to further investigate climate variables as possible causes of the event.

Estimating the conditions faced by the mangroves is made difficult by their location on the coast. Data sources from streamflow recording sites, weather stations or marine buoys record measurements on either the land, the sea, or in the atmosphere. However, when estimating the moisture available to mangroves we have to consider all of these contributing factors. Direct rainfall, river flow, sea level, vapour pressure and soil moisture are the primary variables of concern in this study. Ocean salinity and air and ocean temperatures are also considered.

# 2 Examination of climate drivers

## 2.1 Method

### 2.1.1 Study area

The area shown in the left-hand panel of Figure 2 is the area over which rainfall was totalled. It covers the relevant river basins, so total rainfall over this area can be used to infer stream flow. Actual stream flow measurements are available for the Roper, McArthur, Leichhardt, Flinders, and Norman rivers near the coast, though unfortunately they are not included in this report due to time constraints. Other variables for which local conditions are more relevant, such as vapour pressure and soil moisture, are averaged over the area closer to the coast (Figure 1, right panel).

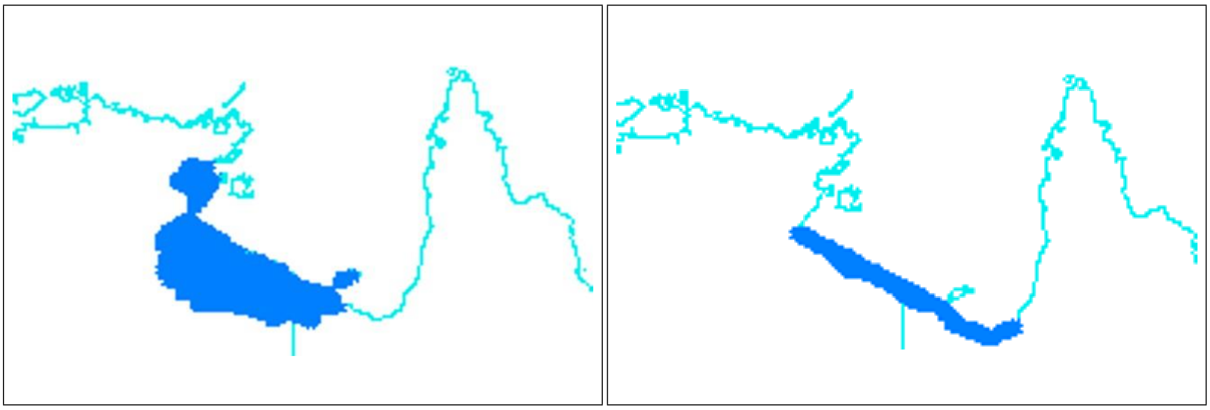

Figure 2: The river basin (left) and coast (right) areas used to create time series. Total rainfall was summed over the river basin area, which encompasses all river basins along the coast from the Walker River to Settlement Creek and Mornington Island except the Roper River basin. For more direct estimates, vapour pressure, soil moisture and NDVI were averaged over the coast area.

### 2.1.2 Data sets

Several datasets were examined in this study.

The Normalised Difference Vegetation Index (NDVI) was used to determine the ‘greenness’ of the region, and so identify the timing of the dieback. The NDVI is calculated by the Bureau of Meteorology based on US satellite data. The climate baseline, or climatology, used for NDVI was the 15-year period from February 1995 to January 2010.

The 2016 Bluelink ReANalysis (BRAN) experiment, a full 3-D ocean simulation, was used as an indicator of sea level and sea-surface salinity (BlueLink 2016). To produce time series, a geographically weighted area average was taken for a box defined by the coordinates 16.8–14.5°S, 135.0–138.8°E. Note that this is not the same box seen in the ocean panel plots (Figure 4), instead being more closely focused on the southern coastline of the Gulf. Note also that the actual salinity levels that the mangroves are exposed to would be dependent on both the nearby sea-surface salinity and the amount of freshwater from rainfall and rivers.

Satellite altimeter data (CSIRO 2016) provided another source of sea-level information, albeit at a much lower resolution (1° compared to BRAN’s 0.1°). The same region defined above was used for area averages. National Tidal Unit data from the Karumba and Groote Eylandt tide gauges (NTU 2016) were also acquired. The standardised anomalies of these sources had their six-month moving average taken, along with that of the BRAN data, and all four time series were plotted so that their agreement was made apparent. Note that the climatology used for the BRAN, CSIRO, and tide gauge data was 1994–2013, a non-standard period, but an unfortunate necessity as that is as far back as satellite data goes.

Hourly sea-level data from the Milner Bay station, Groote Eylandt was used to examine sea-level drivers. Tides were removed from the hourly sea-level data using a harmonic analysis toolbox (t_tide) and then daily averages were computed from the residuals. The seasonal cycle was calculated by harmonic regression of the annual and semi-annual cycle onto the daily data; this seasonal cycle was removed to calculate daily anomalies.

Data from the Australian Water Availability Project (AWAP) was used to determine rainfall, temperature, and vapour pressure. The data was averaged over relevant regions defined in Figure 2 and mentioned in the text.

The Australian Water Resource Assessment–Land (AWRA-L) v5.0 was used to provide information on top layer (0–10 cm) soil moisture. While not fully representative of the actual soil moisture experienced directly by the mangroves (which would be strongly affected by sea level and stream flow), it is a contributing factor. Note that the climatology used for the AWAP and AWRA-L data was 1971–2000.

To judge the historical precedence and relative extremity of the various conditions during 2015, absolute anomalies (calculated by simply subtracting the climatology from the data) were standardised. The standard deviation of each month was calculated during the climatology period. The absolute anomalies were then divided by these values, meaning that the anomalies in this study are in units of standard deviation. While this is not the same as the percentile analysis used for maps, a standardised anomaly value of ±1.96 can be considered approximately the 95th percentile of the period over which the climatology was taken.

## 2.2 Timing of the event

The timing of the dieback has implications for which aspects of the climate were particularly relevant. To gauge the temporal extent of the dieback we first explore a measure of the greenness of the region.

Satellite observations of the greenness of the region using the Normalised Difference Vegetation Index (NDVI) averaged over the coastal averaging region shown in Figure 2 highlight a strong seasonal cycle (pink line of Figure 3). The NDVI values peak late in the wet season, then decline through the dry season. This indicates that every year the trees experience growth and decline phases, probably tied to the moisture availability (D. Burrows, TropWATER, pers. comm. March 2017).

There were three years (2011, 2012 and 2013) with very high NDVI values, suggesting vigorous growth through this time (Figure 3). In 2014, the seasonal pattern of NDVI was near normal, but by the end of year it had dropped below normal values. At the start of 2015, the NDVI began to follow the usual climatological increase, but failed to achieve anywhere near the usual peak values at the end of the wet season (through March and April). The drop to seasonally low values began months earlier than usual, with the dramatic, unprecedented low levels in totals as well as anomalies occurring at the end of 2015.

Duke et al. (2017) suggests that the main dieback occurred late in 2015, but the NDVI suggests that the trees were already not as green and vigorous as usual at the end of the preceding wet season and throughout the preceding dry season. This suggests that the dieback may have been the result of cumulative stress, so we examined the climate during the year prior to the dieback event.

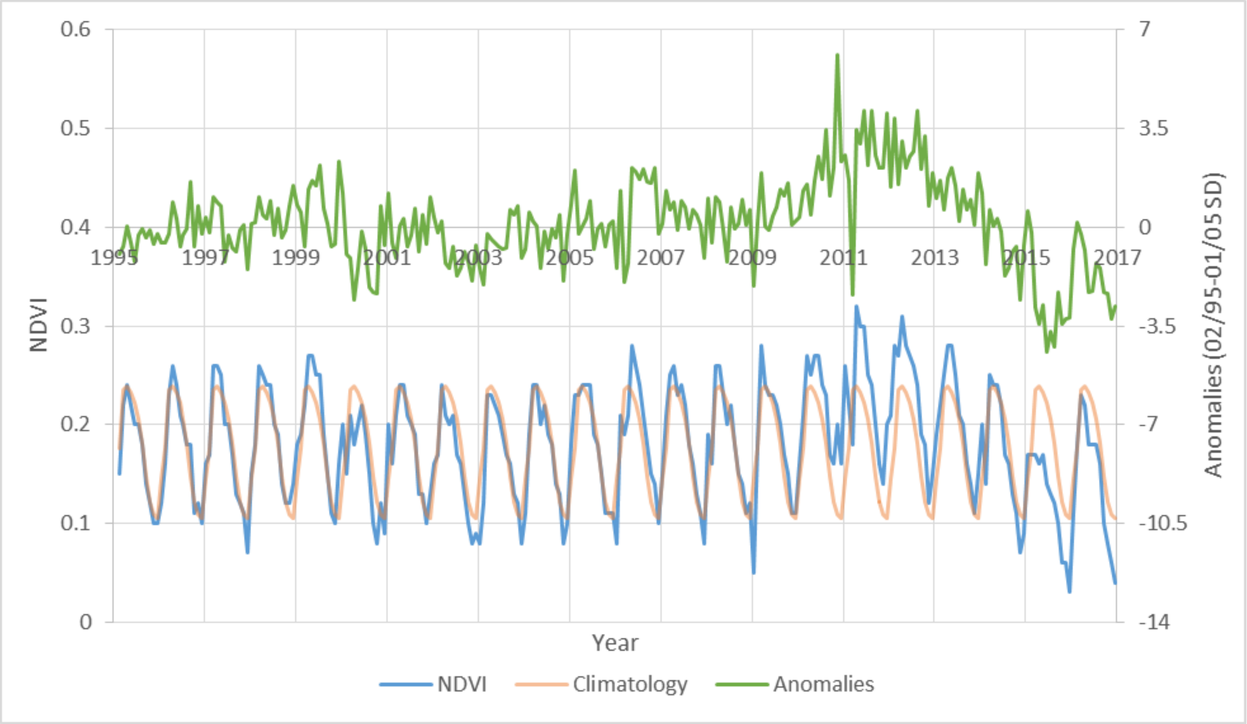

Figure 3: The NDVI, its 02/1995 to 01/2005 climatology, and its standardised anomalies in the coast area of the Gulf of Carpentaria. Note the significant positive anomalies in 2011–2013, and their gradual decline back to normal values in late 2014, followed by a massive and unprecedented decline through 2015. Worthy of note is that this decline begins early in 2015, not late in the year.

## 2.3 Climate drivers

### 2.3.1 Sea level

There is a strong seasonal sea-level cycle in the Gulf of Carpentaria with low levels in the dry (winter) season and high levels in the wet (summer) season. The seasonal range at Milner Bay of Groote Eylandt is 57 cm (Figure 4, blue line). Absolute sea levels in the 2015 dry season were very low (Figure 4, black lines), the lowest levels since 1997. In addition, relatively low levels persisted after the end of the dry season with October 2015 maintaining levels near the dry season minimum, and continued low sea levels from January to April 2016.

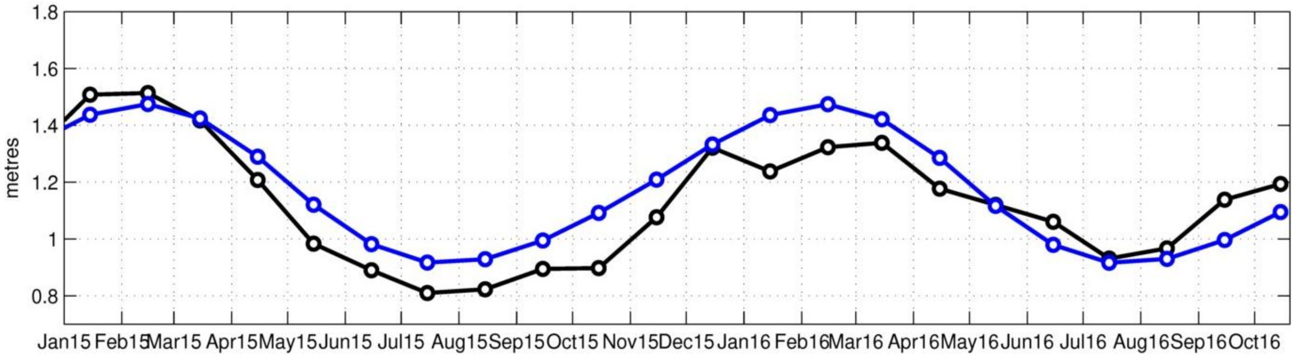

Figure 4: Groote Eylandt sea levels for 2015 and 2016. Monthly averages are shown for the absolute sea level anomalies from 2015 and 2016 (black lines) and the average seasonal cycle (blue lines). The sea level was very low through most of 2015 and into 2016.

The spatial patterns of the seasonal cycle and anomalous sea levels in 2015 are shown in Figure 5. It is apparent that the Gulf experienced unusually low sea levels in 2015, from April to November (the usual local dry season). Sea level is normally relatively low during the dry season (as is apparent in the climatology plots of the figure), so negative anomalies during this time would be particularly stressful on the mangroves.

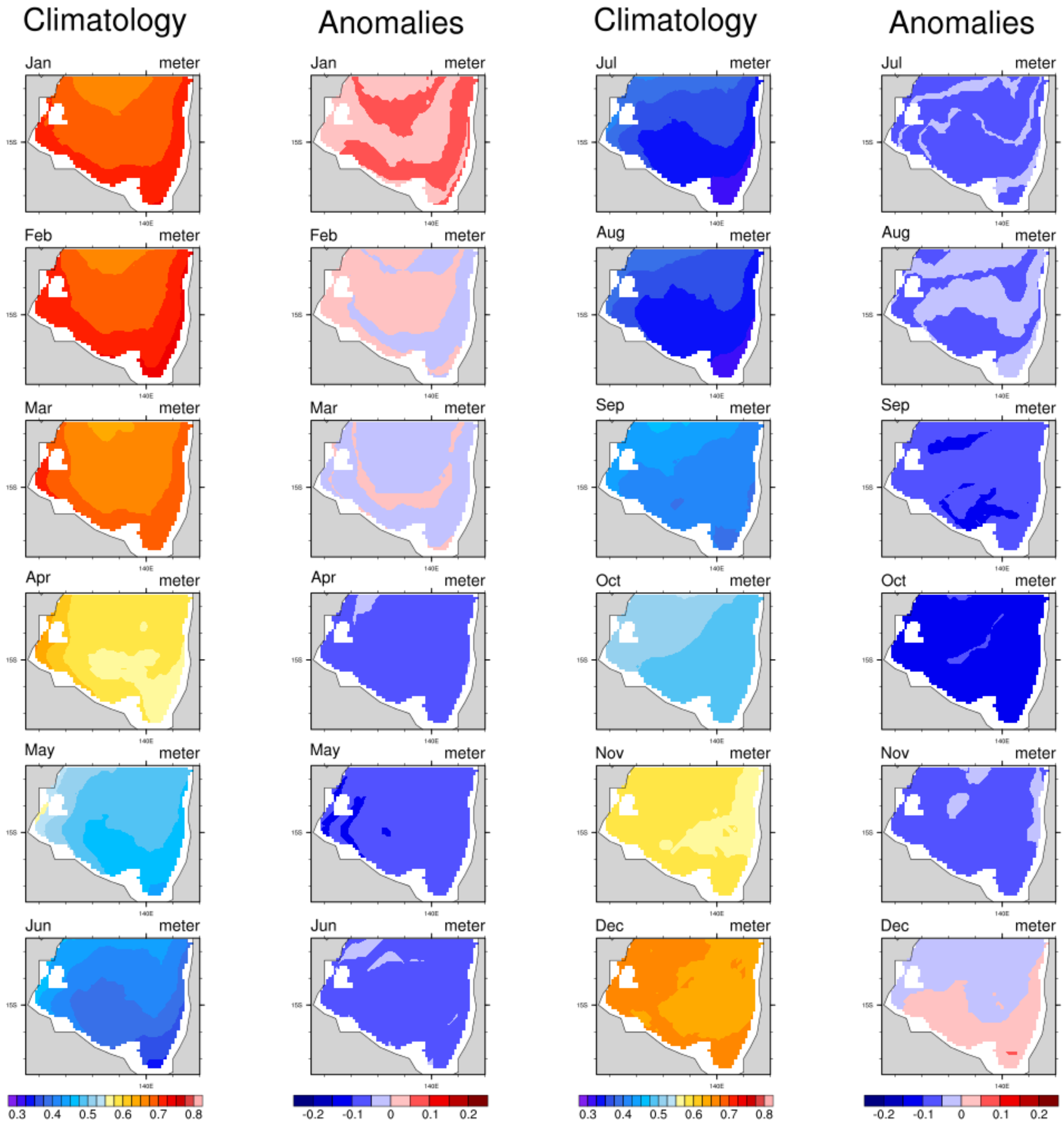

Figure 5: A panel plot indicating the monthly climatologies (1994–2013) and 2015 anomalies for sea level (m; from BRAN). In 2015, the sea level was unusually low from April until November, a period which historically (from the climatology) experiences a lowered sea level.

Figure 6 illustrates the monthly mean sea-level anomalies in the Gulf of Carpentaria, near the south-west coastline (defined in section 2.1.2). There is strong agreement between all four sources of sea-level data. Sea levels were unusually low in late 2015. October 2015 (–19.7 cm) and January 2016 (–19.6 cm) were the lowest since 1997/98 (when they were in the range –23.6 cm to –25.8 cm). Anomalies were close to these levels at the end of 2002 and end of 2007; nonetheless, October 2015 and January 2016 were far lower than was typical over the last decade.

Another noteworthy feature of the plot is the extended period of elevated (or at least non-depressed) sea levels from 2008 to 2015. Through recent decades, while global sea levels have been rising at about 3 mm per year, the average sea level in the Gulf has been rising at a faster rate (9–10 mm/year during 1993–2010, CSIRO and the Bureau of Meteorology 2015) which means the drop in 2015 was from a higher baseline than in 1997/98. Sea level in the Gulf is strongly affected by the El Niño Southern Oscillation (ENSO; see Section 3.2).

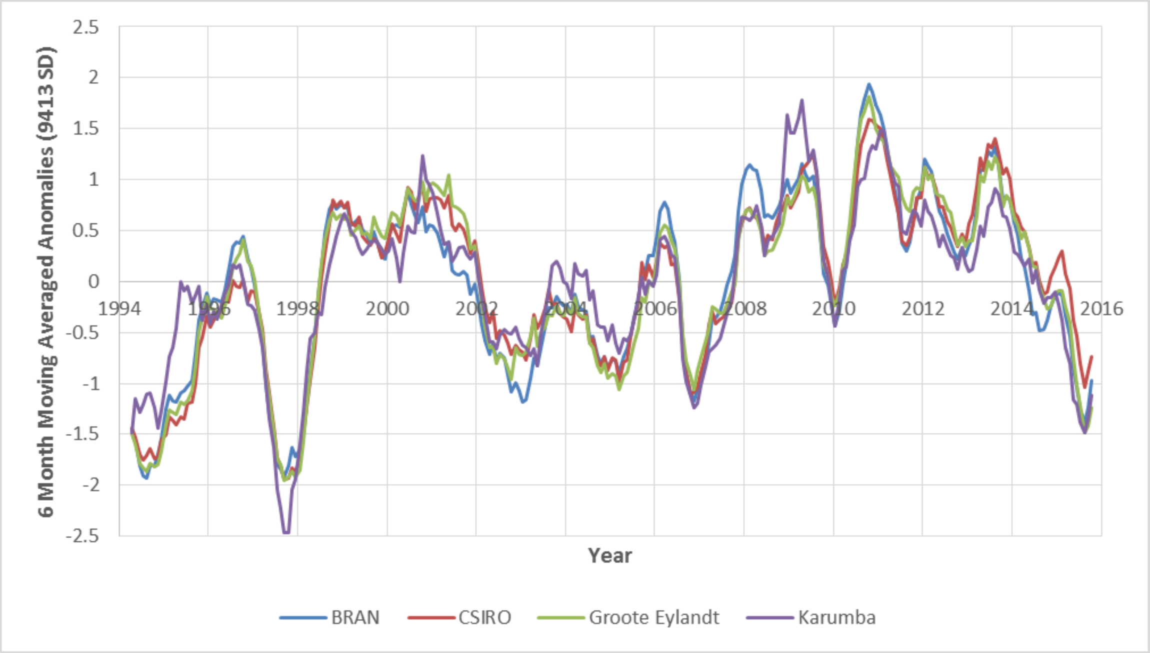

Figure 6: A time series showing the standardised anomalous sea level in the Gulf of Carpentaria (16.8–14.5°S, 135.0–138.8°E). Sea level was determined by taking the six-month moving average of each of the four sea level data sources. Their strong agreement is apparent. Key features are a significant drop in late 2015, an extended period of elevated sea levels from 2008 to 2015, and a more significant drop in 1997.

## 2.3.2 Sea surface salinity

The sea surface salinity anomalies are shown in Figure 7. There is high salinity in 2015; however, there are many previous instances of similarly high salinity in this data. Figure 8 shows that in 2015, the water was most anomalously saline in March and April, when the climatology would have salinity approaching its minimum.

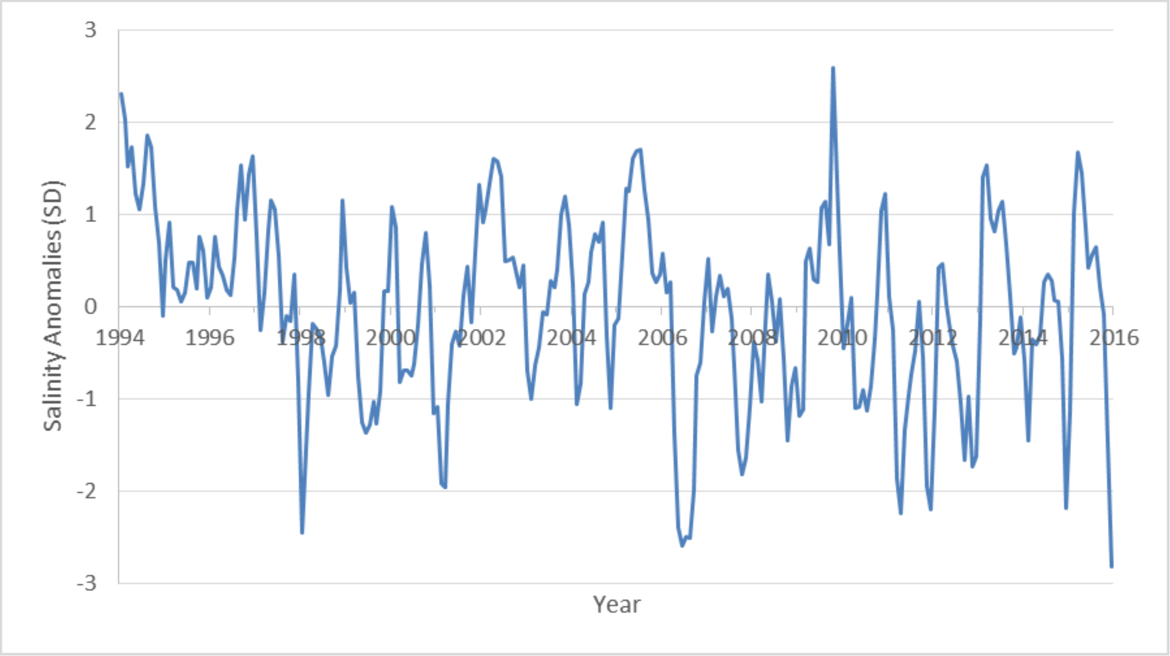

Figure 7: A time series of the standardised salinity anomalies in the Gulf of Carpentaria (16.8–14.5°S, 135.0–138.8°E) using the BRAN data. Note the large positive anomaly in 2015, but also note that similar positive anomalies occur many times in the data.

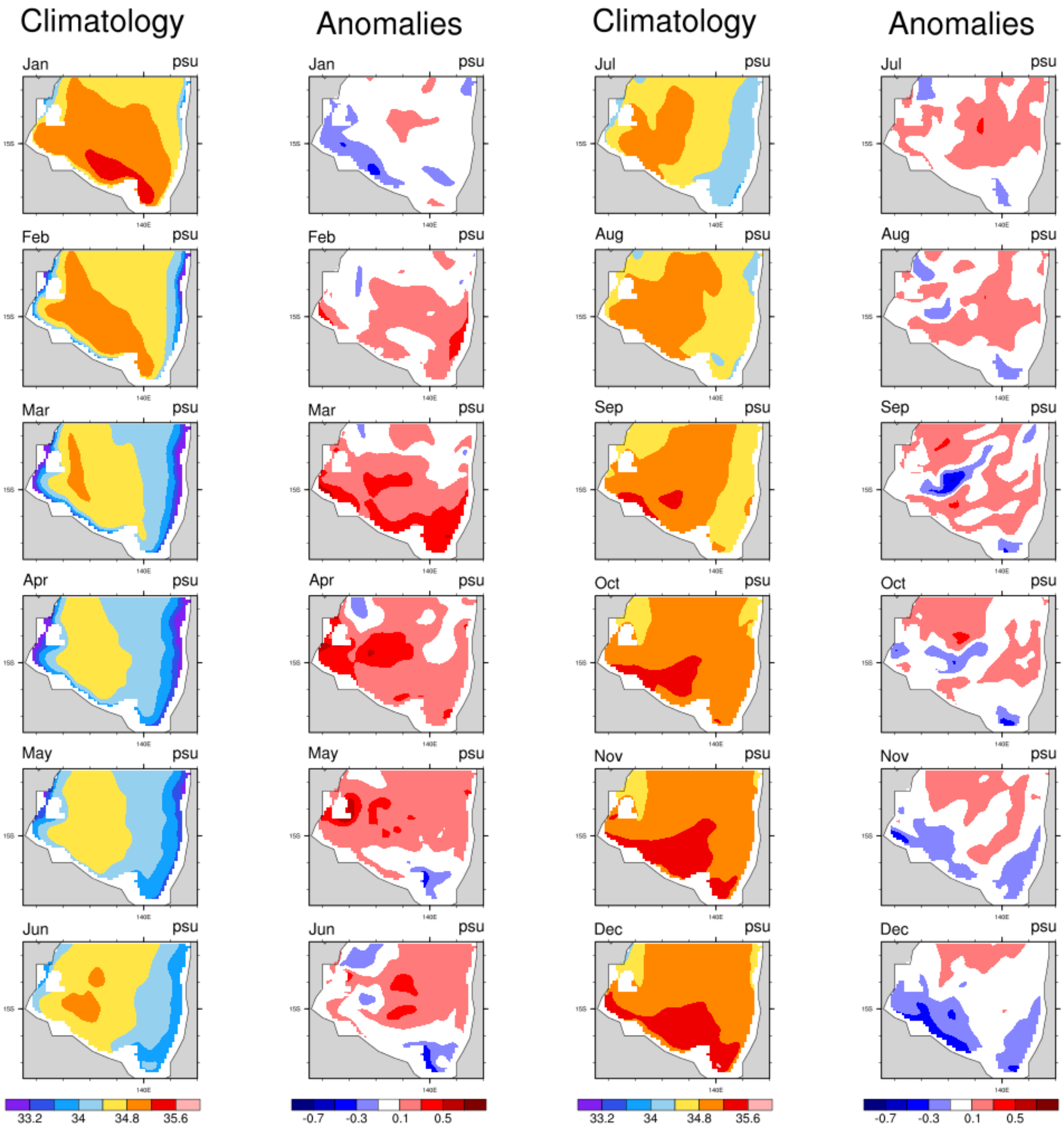

Figure 8: A panel plot showing the monthly climatologies (1994-2013) and 2015 anomalies of salinity in the Gulf of Carpentaria from the BRAN data (psu).

## 2.3.3 Sea surface temperature

The sea surface temperatures follow a strong seasonal cycle, peaking around December with the coolest temperatures around August. The seasonal variation is about 7°C. NCEP/NCAR reanalyses, averaged over the same box as the other ocean datasets, show that the seas in the Gulf were not unusually warm throughout 2015, although there were warm peaks in March of 2015 and 2016 (Figure 9). It does not seem that high ocean temperatures played a strong role in the dieback.

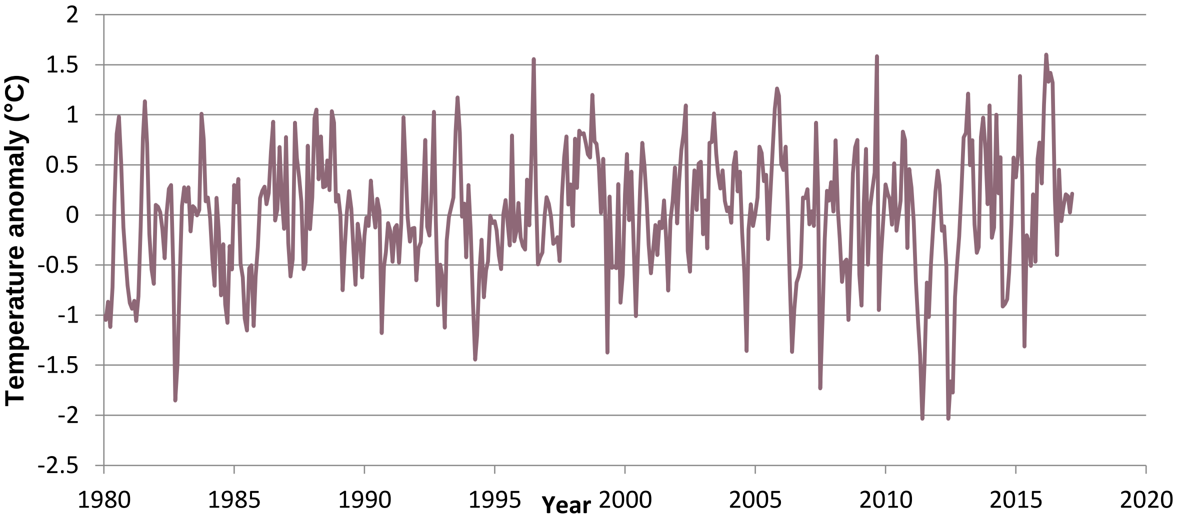

Figure 9: Sea surface temperature monthly anomalies (in °C, not units of standard deviation), from NCEP/NCAR reanalyses, averaged over 16.8–14.5°S, 135.0–138.8°E. The seas in the Gulf were not unusually warm throughout 2015, although there were warm peaks in March of both 2015 and 2016.

### 2.3.4 Rainfall

The AWAP rainfall data showed that the 18 months preceding the dieback event were very dry, as seen in Figure 10. Looking at the time series in Figure 11, it is clear that the 2014/15 wet season ended earlier than normal. The exact way one chooses to define the end of the wet season is not so important here, only the fact that rainfall was far below normal in February and March. A decile map of rain from February to October paints a more informative picture (see Figure 12). The time series also shows that over the whole wet season, a lower than usual amount of rain fell. This implies that stream flow during 2015 was significantly lower than usual.

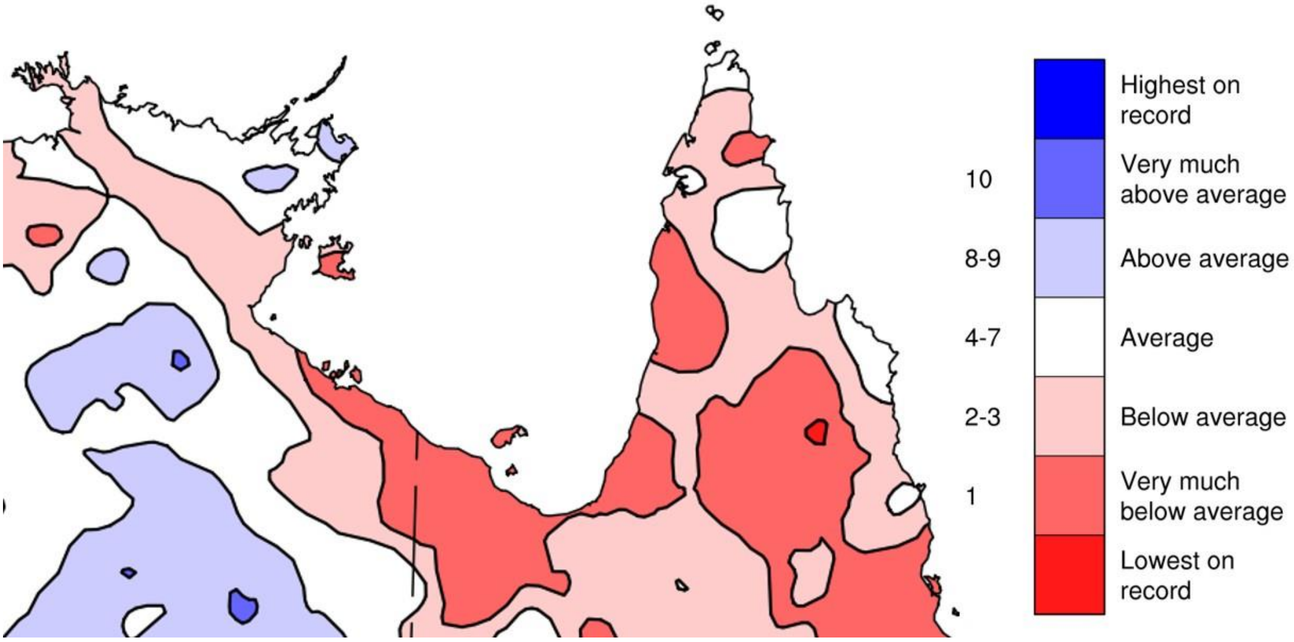

Figure 10: A decile map of rainfall in Gulf Country from 1 May 2014 to 31 October 2015 (18 months). The coast and river basin areas had very much below average rainfall, but nothing at historically unprecedented levels.

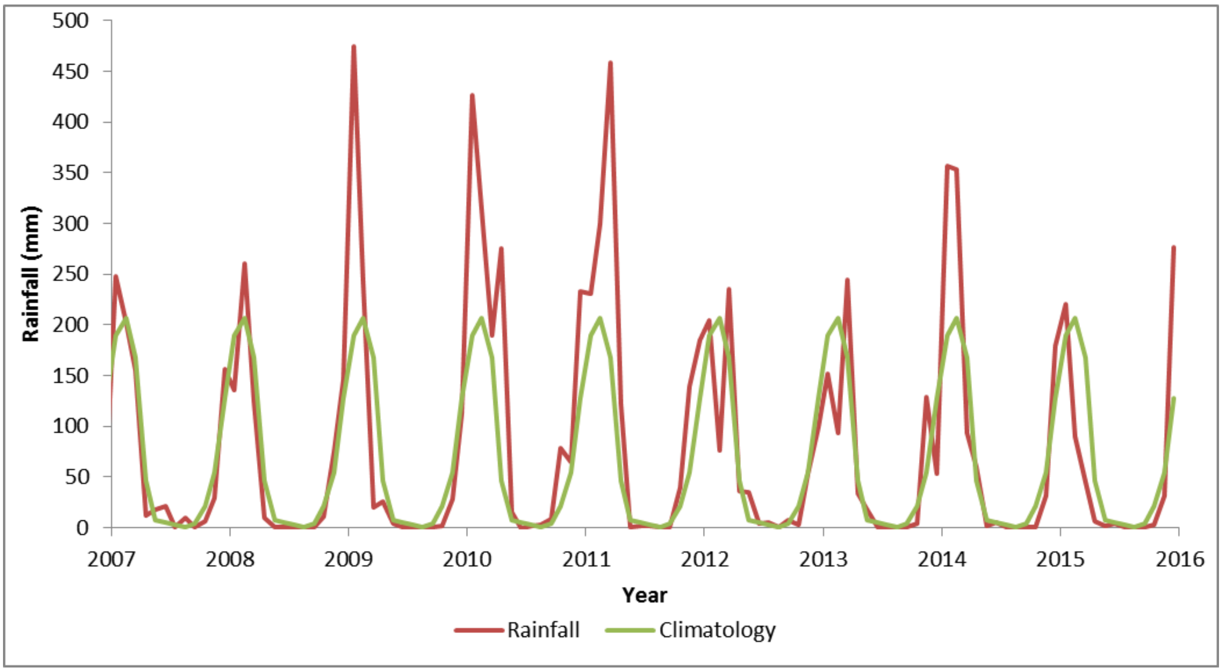

Figure 11: Time series showing the total monthly rainfall in the river basins connected to the primary mangrove dieback areas (see Figure 2, left panel), along with the 1971–2000 climatology. Stream flow can be inferred from this. Note that the 2015 wet season clearly ‘ended early’, and that the 2009, 2010 and 2011 wet seasons were particularly wet.

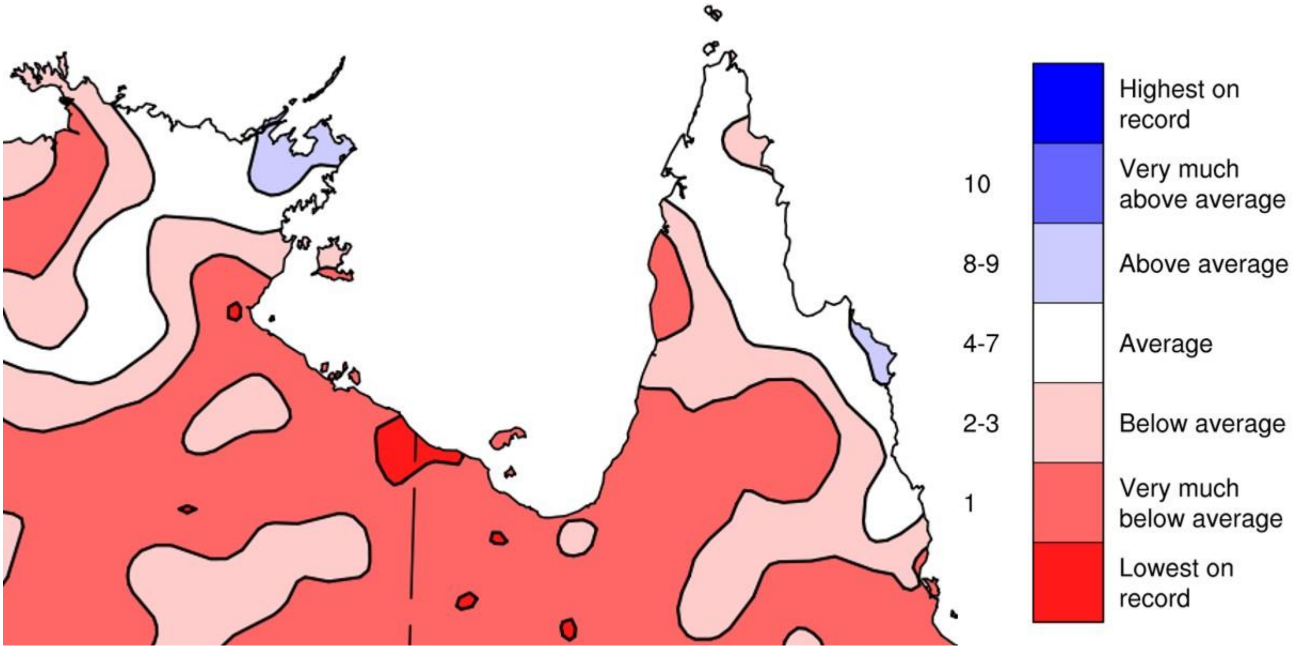

Figure 12: A decile map of rainfall in Gulf Country from 1 February to 31 October 2015 (9 months). A very large area had very much below average rainfall, and the lowest rainfall on record for this period was recorded on the state border in the middle of the mangrove dieback region.

### 2.3.5 Vapour pressure

The early-ending wet season affected the remaining rain-dependent variables. Vapour pressure is used as an indicator of air humidity in this analysis, but other variables might be considered in a subsequent study.

AWAP 9 am vapour pressure data shows that the nine months preceding the dieback had very low 9 am vapour pressure (Figure 13), though about half the coastline was in the second and third deciles, thus the conditions in 2015 were not unprecedented. Figure 14 shows a similar picture, but for 3 pm vapour pressure, and the south-west coastline is almost entirely in the first decile (very low). Time series were also plotted with six-month moving means (Figure 15).

Analysis of humidity measures of relevance to mangrove growth will form the basis of further study.

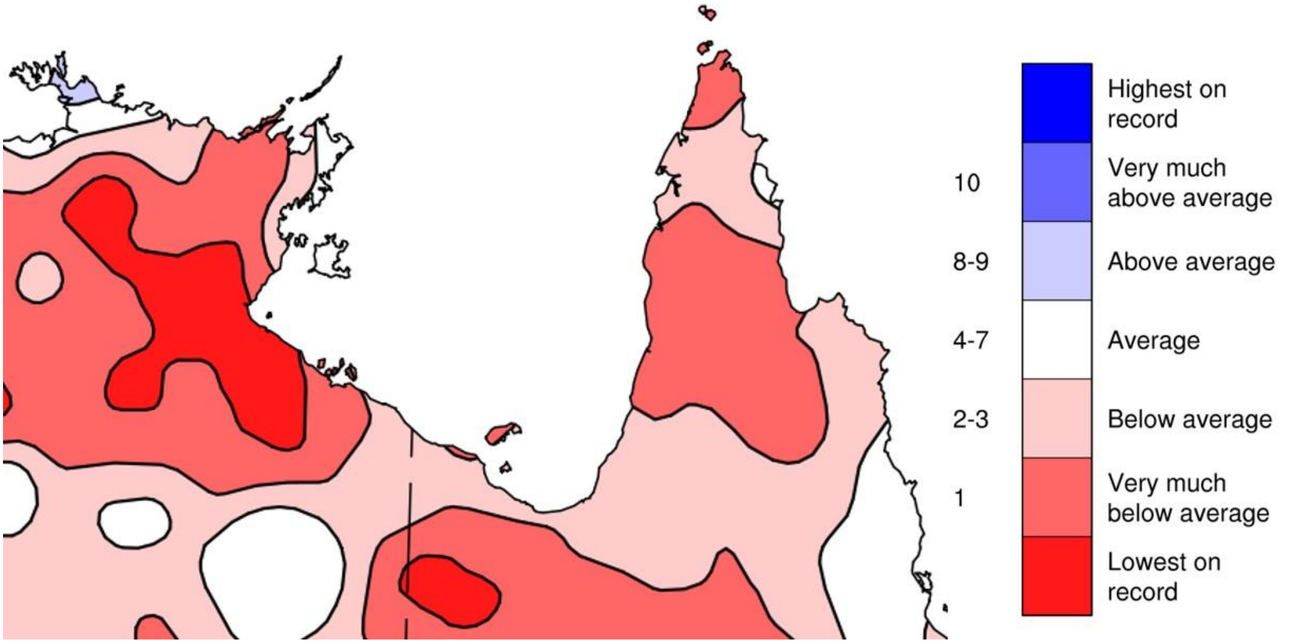

Figure 13: A decile map of 9 am vapour pressure from 1 February to 31 October 2015 (9 months). A medium-sized area on the west side of the Gulf had the lowest 9 am vapour pressure on record for this period, however the southern area of the Gulf was only in the second and third deciles: low, but not remarkably so.

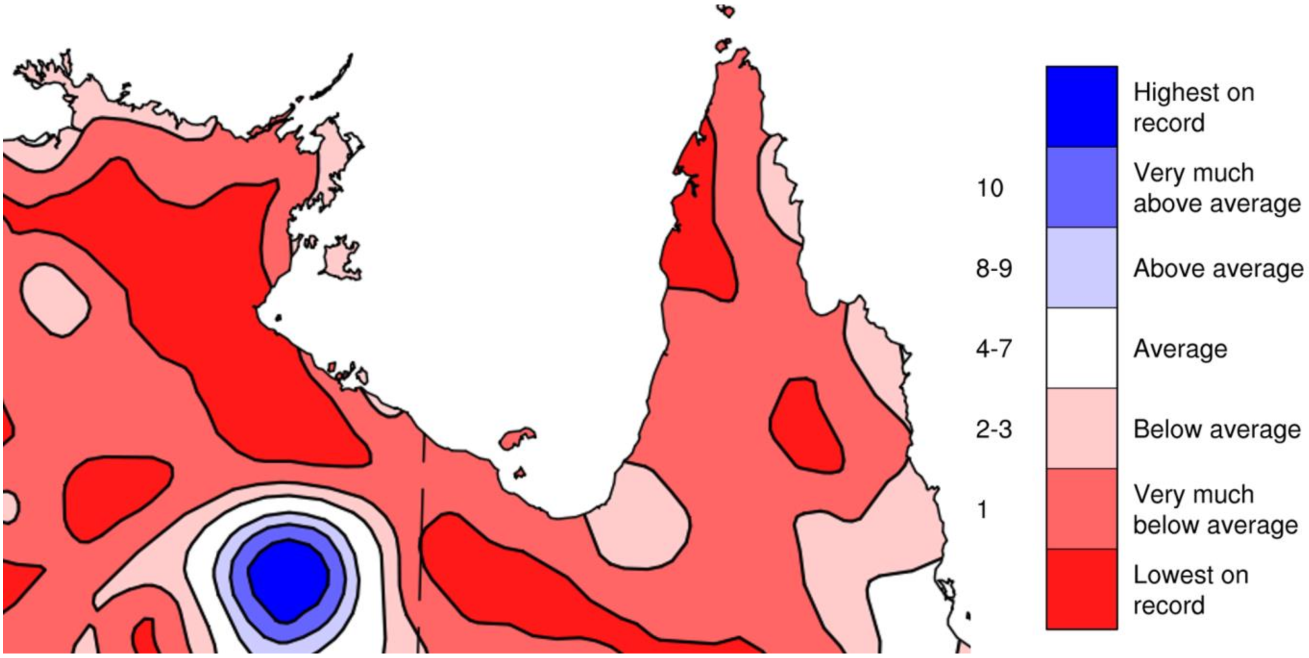

Figure 14: A decile map of 3 pm vapour pressure from 1 February to 31 October 2015 (9 months). In comparison with Figure 13, the same area on the west of the Gulf had the lowest vapour pressure on record, although the area is slightly larger here. Down the rest of the southern coast, 3 pm vapour pressure was very much below average (for the most part).

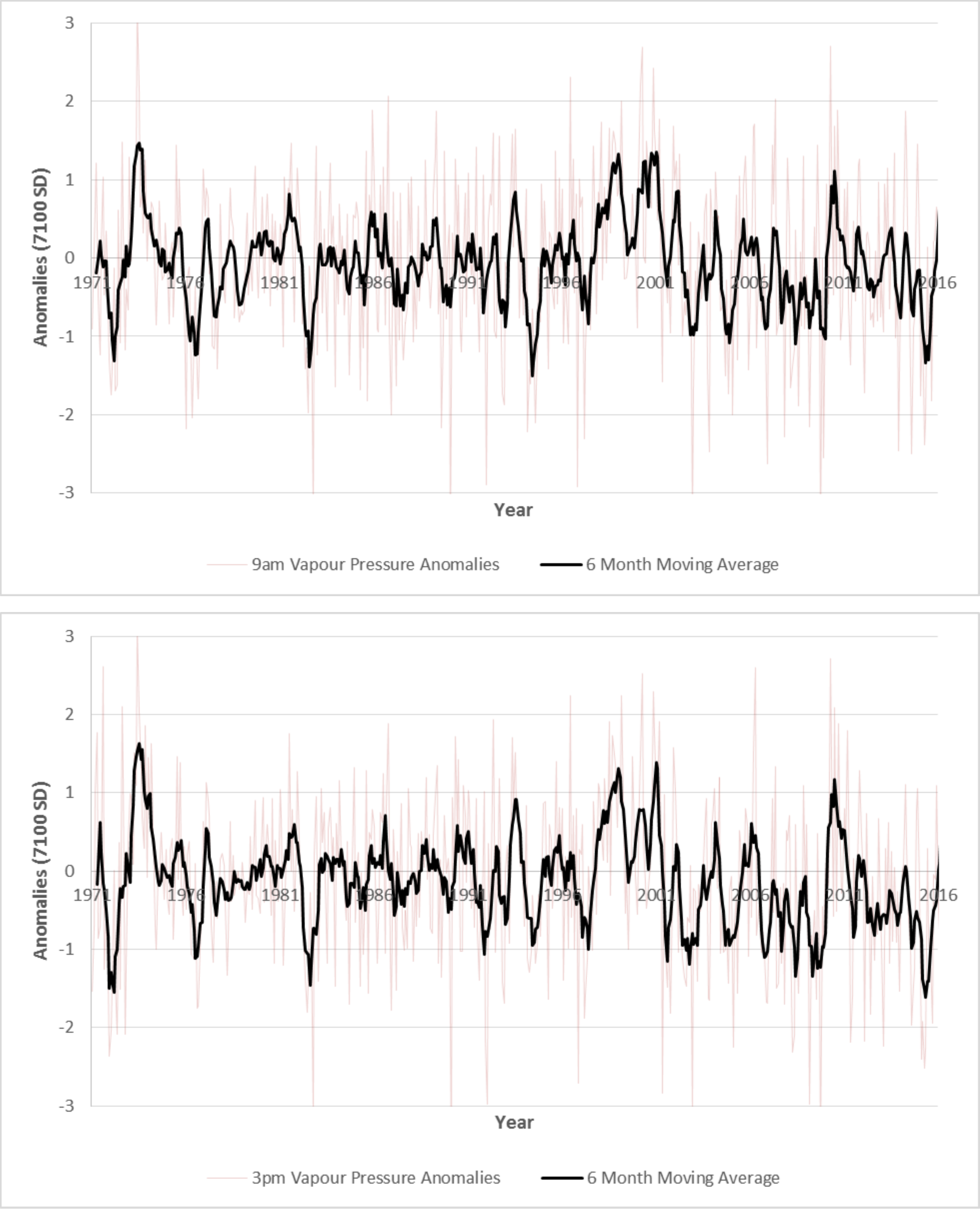

Figure 15: Times series of the vapour pressure scaled anomalies (from 1971-2000 average) in the coast area (see Figure 2, right panel) with six-month moving averages. There are only minor differences between the 9 am (top) and 3 pm (bottom) vapour pressure anomalies. Both feature significant negative spikes (low vapour pressure) in 2015.

### 2.3.6 Soil moisture

AWRA-L5.0 data shows that the top layer soil moisture was very low in the nine months preceding the dieback event, as seen in Figure 16. Soil moisture near the coast was very much below average for the nine-month period, except for a small region near the state border. This is an unexpected result given that this approximate area saw the lowest rainfall on record for the same period. A time series (Figure 17) shows that soil moisture reached an unprecedented low during 2015 in the coast area; however, this is based on a six-month moving average.

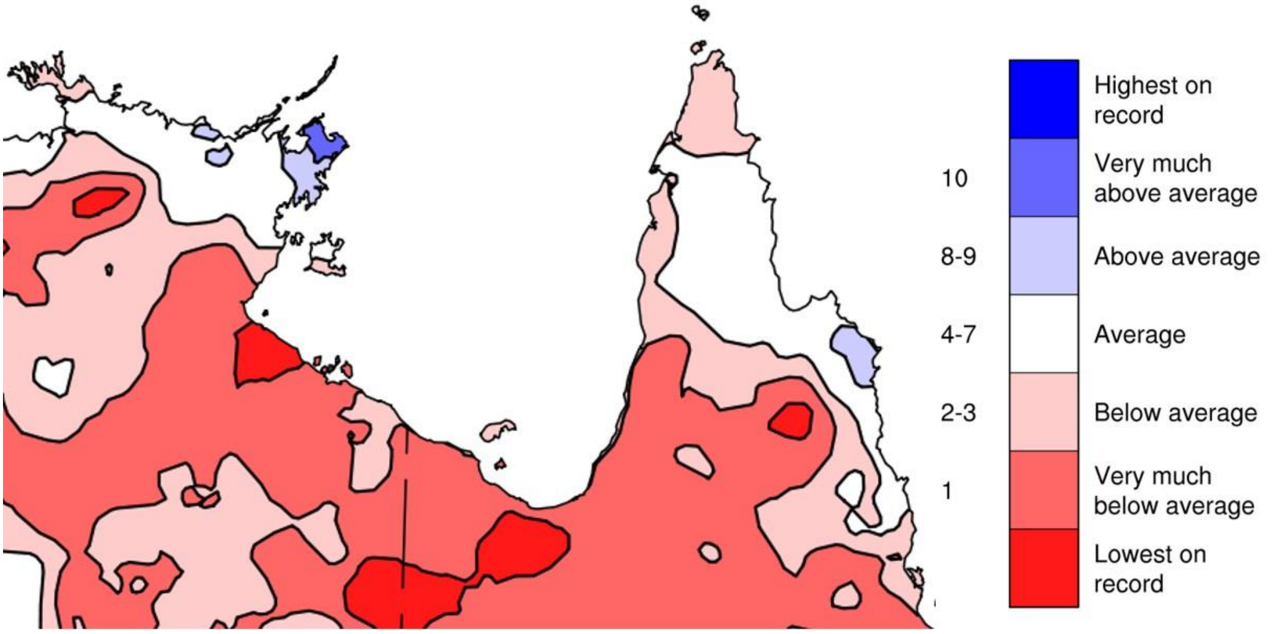

Figure 16: A decile map showing AWRA-L5.0 top layer (0–10 cm) soil moisture from 1 February to 31 October 2015. Most of the south west coast of the Gulf was very much below average except a small region near the state border (which interestingly saw the lowest recorded rainfall for the same period, see Figure 12).

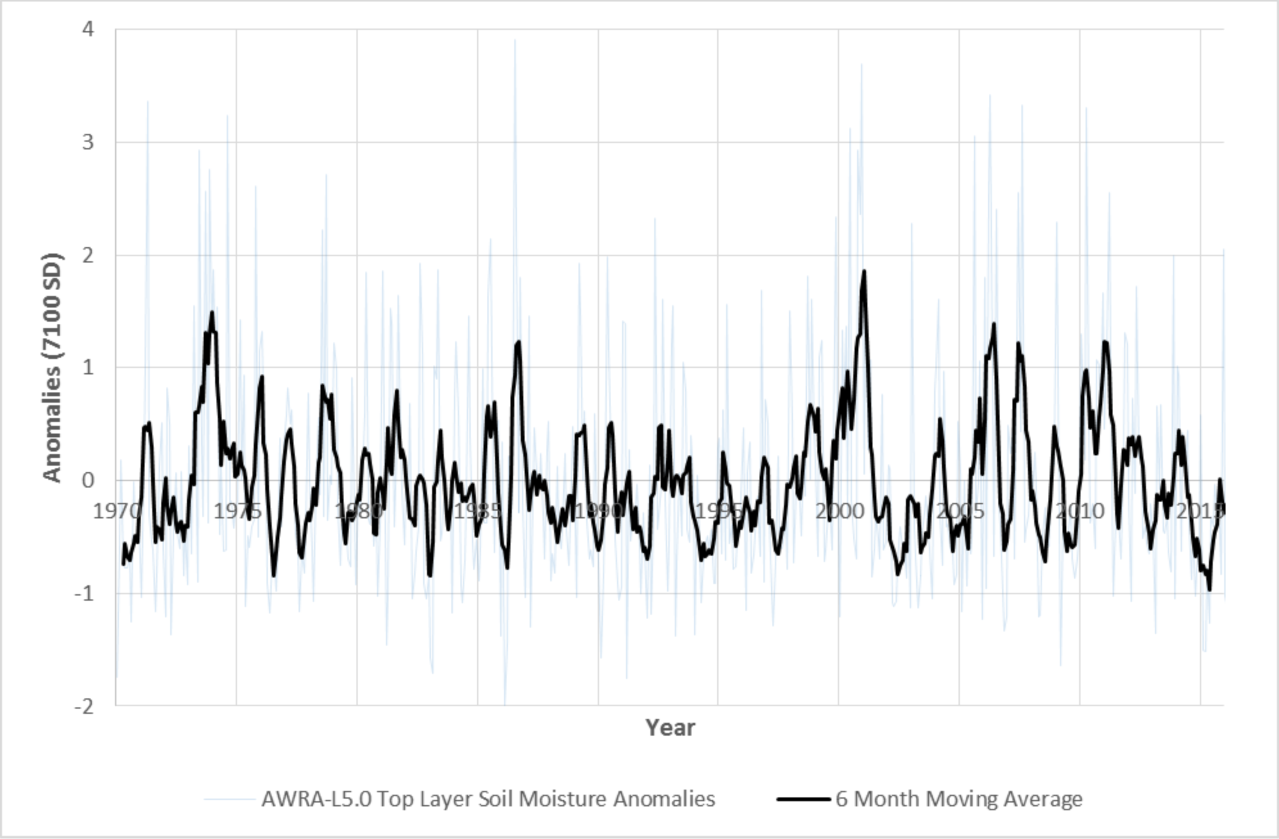

Figure 17: A time series of AWRA-L5.0 top layer (0–10cm) soil moisture scaled anomalies (from 1971-2000 average) in the coast area. Note the very large month-to-month fluctuations in the background, which results in the six-month moving average in the foreground never reaching particularly large values. Also note that because the area is so dry, the positive spikes were much larger than the negative ones.

### 2.3.7 Air temperature

The near surface air temperature was warmer than average through the dry season, and the maximum temperatures in November were the warmest on record for most of the affected coast, as were temperatures during the early decline of the wet season and the early part of the dry season (March to August) (Figure 18), although they were closer to normal through the latter part of the dry season. It will be of interest to quantify the temperature thresholds at which the main species of mangroves that inhabit the Gulf region are particularly stressed, as assessed by Reef et al. 2016 for other species.

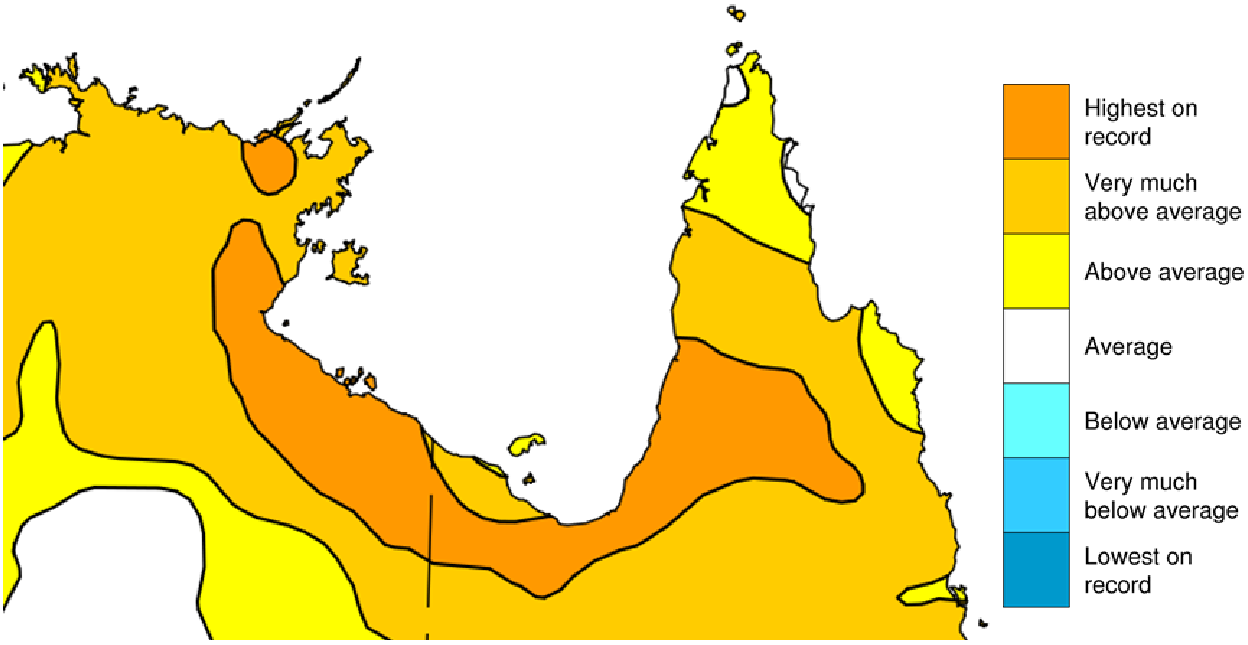

Figure 18: Average daily maximum temperature deciles for 1 March to 31 August 2015, relative to 2011 to 2015. Much of the dieback region saw temperatures that were the highest on record during these months at the start of the dry season in 2015. Temperatures were closer to normal later in the 2015 dry season.

## 2.4 Summary of the major climate drivers of the dieback

The climate conditions examined in this study describe a hostile environment for mangroves: there were unusually low sea levels for the majority of 2015, elevated salinity levels earlier in the year, and from February 2015 to October 2015 there was very low rainfall (implying low stream flow), very much below average vapour pressure, very much below average top layer soil moisture and, at the start of the dry season, above average temperatures. This combination of conditions suggests that the mangroves were starved for water. The role of temperature stress is unclear.

The timing of the unusually high salinity and unusually low sea level warrants mention. The sudden sea level drop in April 2015 occurred when the unusually high salinity was near its peak (Figure 5 and Figure 8). Furthermore, the early end to the wet season in 2015 meant that the rain had stopped sometime in March, so by April there would have been very little stream flow. The timing of all this may have allowed an unusually high amount of salt to be deposited in the soil at the start of the dry season. (An analysis of the soil in the areas where mangroves died would be required to verify this theory.) With the additional stress caused by the lack of water, the mangroves died in late 2015, having fallen just short of surviving the duration of the dry season.

## 2.5 Have these climate conditions occurred before?

An analysis of readily available datasets has revealed that some of the climatological factors have occurred before. However, some of these variables only have data that extend back to the mid 1990s or early 1970s, so the length of each dataset will also be a consideration.

2015/16 was a strong El Niño, and it appears that low sea levels occur during El Niño events in this region (Wyrtki 1984; Oliver and Thompson 2011). Some previous El Niños, such as in 1982 and 1997, show even greater sea-level decline than in 2015. However, there is evidence that the mangrove forests have extended further inland since 1997 (Asbridge et al. 2016). During this time, mean sea levels in the Gulf were rising (9-10 mm/ year during 1993–2010) which means the drop in 2015 was from a higher baseline than in 1997.

The rainfall from February to October 2015 was the lowest in records since 1971. For different averaging periods through the dry season, other years were also very dry, including 1982, 2009 and 2002.

A measure of the atmospheric moisture (vapour pressure) suggests that this too was unusually low in 2015, particularly at the beginning and end of the dry season, but not a record-low in all months. It would be of use to better define which measure of atmospheric moisture is of most relevance to the mangroves.

While some individual measures of climate or ocean variability did not reach historically unprecedented levels, it may be the coincidence of their unfavourable anomalies in 2015 that lead to the mangrove dieback.

# 3 Towards attribution: did climate drivers cause the dieback?

There are many factors to consider in determining why the mangrove dieback occurred. Answering the question ‘Why did the mangroves die?’ will take many steps. The first has been initiated in this discussion of the timing of the event and the climate drivers that are likely to have been of importance.

Of course, other factors must also be considered, such as a shift in the extent of the mangrove forests during years with generally elevated sea levels from 2008 to 2014. Asbridge et al. (2016) suggest this as a possibility.

However, even after consideration of other factors, such as the changing distribution of the forests, the combination of climate drivers (and their timing) are very likely to have underpinned the dieback event in October 2015. Understanding why these conditions occurred requires additional investigation. A first step is to define a ‘Gulf mangrove stress index’ that includes the climate variables of importance, alongside the timescales that are most relevant.

## 3.1 A Gulf of Carpentaria mangrove stress index

The evidence suggests that the key climate drivers of this event were low sea level, rainfall (and possibly also streamflow), salinity, soil moisture and humidity. Having determined these drivers, and noted that for individual variables, the low or dry conditions have occurred before, we explore whether perhaps it was a combination of conditions that compounded to make a highly stressful environment. A ‘mangrove stress index’ could combine relevant climate factors. It can be used to look back in time for previous potential dieback events, and to monitor future conditions, as currently occurs in the Great Barrier Reef (e.g. NESP Tropical Water Quality Hub).

The sea-level anomalies appear to align reasonably closely with the NDVI measure of vegetation greenness, taken as a rough indicator of mangrove health (see the six month moving averages of sea level (Figure 6) and NDVI anomalies (Figure 3)). Other factors that appear to be of importance include the range of moisture sources. Thanks to the choice of units, we can combine some of the variables we have studied. Unfortunately, the standard deviation units were technically different for those variables that relied on satellite data (sea level, salinity, NDVI, due to the necessary use of different climatology periods) so they cannot be included. Satellite derived indices also do not extend further back in time than the mid 1990s.

A preliminary analysis using rainfall, vapour pressure and soil moisture resulted in a simple ‘mangrove stress index’, with the idea being that extremely low values indicate that mangroves are stressed and at risk of dying. Adding indices of each climate variable together, and taking a six-month moving average, we found that the combination of conditions in 2015 have not been experienced in the period of available data, i.e. since the early 1970s. This lends weight to the theory that it was the coincidence of unusual climatic conditions that caused the dieback.

Although this is a beguiling result, there are strong caveats and further work is needed. One concern is that the climate variables considered are intimately linked, and their correlation means that the statistical model is currently over-fitted. Analysing and correcting for this will be done in the next phase of this work.

## 3.2 Why was the sea level low?

The cause of the strong drop in sea level implicated in this dieback event can begin to be attributed using methods already developed (Oliver and Thompson 2010, 2011).

The El Niño–Southern Oscillation (ENSO) plays a strong role in modulating sea level anomalies from year to year, with lower than average sea levels occurring largely in El Niño years (Figure 19, red shading) and higher than average sea levels in La Niña years (Figure 19, blue shading).

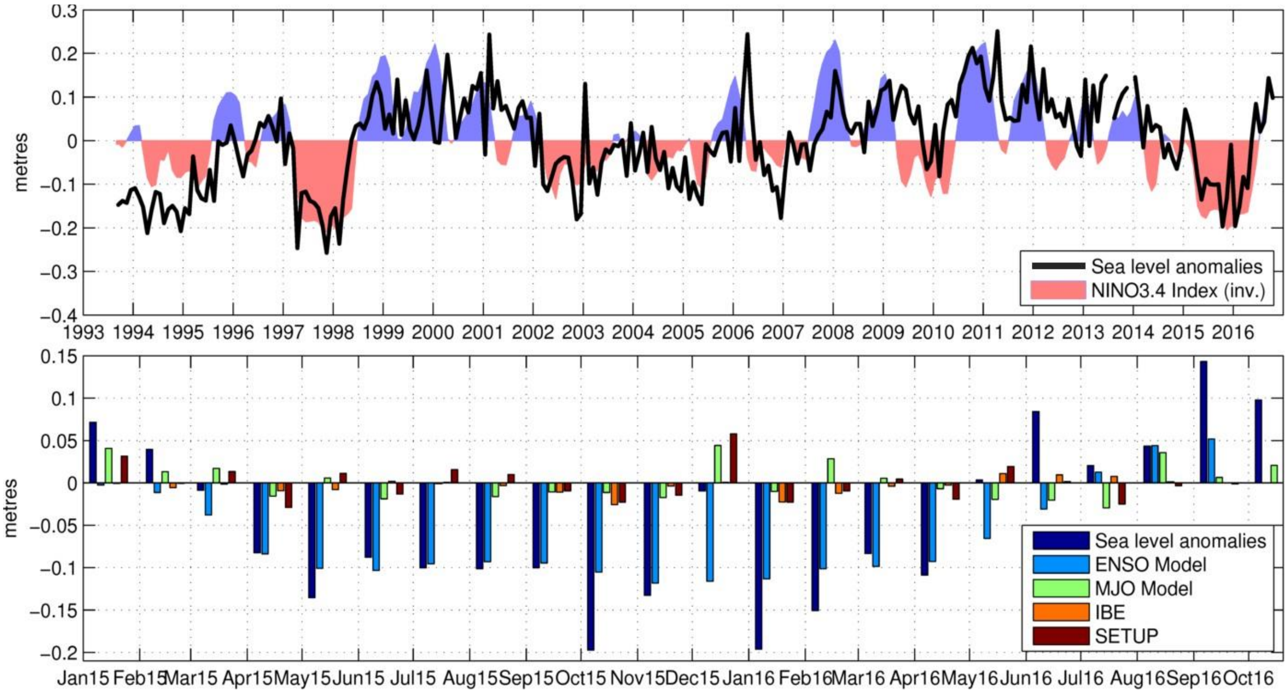

Figure 19: Groote Eylandt sea level anomalies for (top) the years 1993–2016 and (bottom) the years of 2015 and 2016. Monthly averages are shown. Top panel includes the NINO3.4 index (scaled and inverted). The bottom panel includes the contribution to sea level from the various models considered.

We considered four potential drivers of sea-level variations: (ENSO), the Madden–Julian Oscillation (MJO), the effect of sea level pressure through the inverse barometer effect, and wind-driven sea level setup. The inverse barometer effect is the effect that atmospheric pressure has directly on sea level. For instance, very high pressure, as experienced in the Gulf in 2015, directly produces lower sea level. The wind-driven sea level setup is the consequence of the interaction between the prevailing winds and the geography of the coastline – where, if they are in the right orientation, will either ‘pile-up’ water near the coast, raising local sea levels, or then can also draw the ocean away from the coast, lowering sea levels, as occurred in October 2015.

Most of the unusually low sea levels recorded in 2015/16 could be explained by ENSO (Figure 19, lower panel, dark and light blue bars). However, the particularly low levels in October 2015 and January 2016 required additional contributions from the MJO, sea level pressure and wind-driven sea level setup (green, orange, and red bars).

Full details of the attribution method and results are in the appendix to this report.

## 3.3 Was there a contribution from climate change?

More detailed attribution studies are necessary to determine what role, if any, human-induced climate change played in the 2015 dieback event. Given that an accumulation of the stressors on the mangroves over time might be important, the attribution to human-induced climate change will require methods that are more complex than many of the current methods used for more simple events, such as heatwaves (Hope et al. 2015; 2016; Lewis et al. 2014; Wang et al. 2016).

Studies on the potential changing nature of coastal ecosystems suggest that changes will occur during the 21st century (Gabler et al. 2017), so it will be of great interest to better understand the climatic factors affecting the mangrove forests of the Gulf of Carpentaria.

Climate change projections for the Monsoon North region (CSIRO and Bureau of Meteorology, 2015) include the following for a 20-year period centred on 2030 relative to a 20-year period centred on 1995:

- Annual mean sea level increase of 6-17 cm
- Annual mean temperature increase of 0.5-1.3°C
- Annual mean rainfall change of -10 to +5%
- Increased intensity of heavy daily rainfall events
- Fewer but possibly more intense tropical cyclones
- Small changes in solar radiation and humidity
- Increased evaporation rates and reduced soil moisture
- Decrease in ocean pH (acidification)

These projected changes will be superimposed on large natural variability, including extreme events. This is likely to create unprecedented extremes, with challenges for natural and human systems.

# Appendix: Sea level attribution method

A decomposition of sea level into several components was performed to trace the drivers of the low sea levels in 2015/16. Four potential drivers of sea-level variations were considered: ENSO, the Madden–Julian Oscillation (MJO), the effect of sea level pressure through the inverse barometer effect (IBE), and wind-driven sea level setup (SETUP).

The contributions from ENSO and the MJO on sea levels in the Gulf of Carpentaria are known (Oliver and Thompson 2011) and are calculated here through statistical models. The contribution from the IBE and SETUP are calculated here through theoretical arguments (although the role of winds in setting Gulf of Carpentaria sea levels on intraseasonal time scales is also well known (Oliver and Thompson 2010, 2011)). Since the influence from ENSO and the MJO can include pressure and wind effects, the influence of these modes has been removed when calculating the IBE and SETUP contributions (i.e. these are the ENSO- and MJO-independent IBE and SETUP contributions). All models were calculated using daily sea levels, pressures and winds to capture sub-seasonal variability properly; monthly averages were then taken to examine the contribution of each component by month.

### *ENSO and MJO*

The influence of ENSO and the MJO were considered jointly in a statistical model. ENSO was represented by the NINO3.4 index and the MJO by the Real-time Multivariate MJO (RMM) Index (Wheeler and Hendon 2004). A regression of sea level anomalies ($\eta$) onto these two indices was performed, with the regression coefficients estimated by ordinary least squares (OLS):

$$\eta(t) = \beta_{\mathrm{ENSO}}\mathrm{ENSO}(t) + \beta_{\mathrm{RMM1}}\mathrm{RMM1}(t) + \beta_{\mathrm{RMM2}}\mathrm{RMM2}(t) + \epsilon(t) \qquad \text{(Equation 1)}$$

The contributions from ENSO and the MJO were then calculated separately from Equations 2 and 3, where the hat indicates the OLS estimators for the regression coefficients:

$$\eta_{\mathrm{ENSO}}(t) = \hat{\beta}_{\mathrm{ENSO}}\mathrm{ENSO}(t) \qquad \text{(Equation 2)}$$

$$\eta_{\mathrm{MJO}}(t) = \hat{\beta}_{\mathrm{RMM1}}\mathrm{RMM1}(t) + \hat{\beta}_{\mathrm{RMM2}}\mathrm{RMM2}(t) \qquad \text{(Equation 3)}$$

### *Inverse barometer effect (IBE)*

The inverse barometer effect is simply the force exerted on the ocean surface through variations in sea level pressure. This contribution was considered after noting that Oct 2015 and Jan 2016 exhibited very high sea level pressure anomalies (highest since 1997/98; not shown but data available). A rise (drop) of 1 hPa of pressure leads to a drop (rise) in sea level of 1 cm:

$$\eta_{\mathrm{IBE}}(t) = -0.01p(t) \qquad \text{(Equation 4)}$$

where $p(t)$ are the daily air pressure anomalies from Groote Eylandt (in hPa). The effects of the MJO and ENSO were removed from $p(t)$ using a regression model as above, leaving the ENSO- and MJO-independent IBE contribution to sea-level variations.

### Wind-driven setup (SETUP)

In a steady state with constant density and depth, the linearised momentum equations for the ocean response to wind forcing in the vicinity of a coastal boundary leads to a balance of surface wind stress and the pressure gradient force (Csanady 1981). Assuming sea level changes far from the coastal boundary are zero, this leads to the following expression for sea levels at the coast:

$$\eta_{\mathrm{SETUP}}(t) = \frac{L\tau(t)}{\rho g h} \qquad \text{(Equation 4)}$$

where (now considering the Gulf of Carpentaria specifically) $L$ is the length of the Gulf of Carpentaria, $\tau(t)$ is wind stress in the on-shore direction, $\rho$ is seawater density (1024 kg $\mathrm{m}^{-3}$), $g$ is acceleration due to gravity (9.8 m $\mathrm{s}^{-2}$) and $h$ is the Gulf of Carpentaria water depth.

A model of this form was used by Oliver and Thompson (2010) to estimate intraseasonal variations in Gulf of Carpentaria sea levels; following that work we chose $L$ = 1000 km and $h$ = 36 m. Wind stress was calculated from daily ERA-Interim 10 m winds, averaged over the domain 8.75°S–16.25°S and 136.25°E–141.5°E (Oliver and Thompson 2010), and the onshore direction was chosen to be north-northwesterly following the idealised model results of Oliver and Thompson (2011). As above, the effects of MJO and ENSO were removed from $\tau(t)$ using a regression model, leaving the ENSO- and MJO-independent SETUP contribution to sea-level variations.

### Results

The full model, obtained by combining all four estimated sea level components, provided a correlation of 0.71 against monthly sea level anomalies. This high correlation was primarily driven by the ENSO component (correlation of 0.62 for this component alone) although the addition of each component further increased the correlation and reduced the root mean squared error (RMSE; Table 1).

Table 1: Correlations and RMSEs against monthly sea-level anomalies obtained by successively combining the four estimated sea-level contributions

| Model | Correlation | RMSE (cm) |
|---|---|---|
| $\eta_{\mathrm{ENSO}}$ | 0.62 | 7.95 |
| $+\eta_{\mathrm{MJO}}$ | 0.66 | 7.63 |
| $+\eta_{\mathrm{IBE}}$ | 0.69 | 7.29 |
| $+\eta_{\mathrm{SETUP}}$ | 0.71 | 7.19 |

Most of the months in 2015/16 with low sea-level anomalies could be explained by the ENSO component (Figure 5, lower panel, dark and light blue bars). However, the particularly low levels in October 2015 and January 2016 required additional contributions from all three of the other components (green, orange, and red bars).

October 2015 sea-level anomalies were 19.7 cm lower than the seasonal average. ENSO contributed about half of this (–10.5 cm), the MJO another –1.1 cm, the independent IBE adds –2.6 cm, and the independent SETUP a further –2.3 cm. The full model explains 84% (–16.5 cm) of the low levels in Oct 2015. A similar situation also occurred in January 2016. It is not clear how this might have contributed to the stressful situation for the mangroves, but, alongside the warm temperatures normally experienced during the wet season, it may have further stressed any mangroves still living after the initial stages of the major dieback event.

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