Indian Ocean Climate Initiative Stage 3: Summary for Policymakers

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N. B.: The order of authors presented here corresponds to the sequence of presentation in the report body, and is not intended to reflect the level of contribution of individual authors.

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Important disclaimer

1 Introduction

The climate of Western Australia is varied and at times extreme, punctuated by droughts, fires, cyclones and flooding rains. Climate change will be superimposed on these fluctuations and extremes, creating new challenges and opportunities for those who must guide adaptation. The Indian Ocean Climate Initiative (IOCI) aimed to empower these decision makers by delivering a strategic program of climate research, providing the best available scientific knowledge in a policy-ready and application-ready form.

1.1 About the Indian Ocean Climate Initiative

A partnership between the Government of Western Australia, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Australian Bureau of Meteorology (BoM), IOCI began in 1998. Catalysed by the need to investigate south-west Western Australia's (SWWA's) winter rainfall decline, the first stage of IOCI also sought to understand how this region's climate varied across the years and decades. Stage 2 of IOCI (2003 to 2006) investigated the causes for the climatic changes detected during Stage 1. IOCI's independent and objective research has influenced public policy by providing high-quality, respected science information, including dozens of peer-reviewed and highly-cited publications.

1.2 About IOCI3

Commencing in January 2008 and completed in June 2012, IOCI Stage 3 (IOCI3) built on the foundation of climate knowledge from the Initiative's previous stages. An important and fundamental achievement of IOCI3 was the delivery of high-quality climate reference datasets, and the extension of their spatial coverage (Box 1). And while SWWA remained an important research focus, Stage 3 extended the Initiative's inquiry to the climate and weather systems of north-west Western Australia (NWWA).[1]

IOCI3 research on SWWA's changing climate further improved our understanding of the causes of rainfall trends, including the regional weather systems and hemisphere-scale atmospheric effects driving these changes. IOCI3 also sought to determine whether there is a human fingerprint on these climatic changes, and if the current drying trend is likely to continue in the long-term future under scenarios of increasing greenhouse gas concentrations. Advances in modelling techniques under IOCI3 yielded station-scale projections of future rainfall and temperature change in SWWA, as well as projections of possible future changes to intense rainfall events and hot spells.

IOCI3 advanced our understanding of NWWA's climate systems by providing station-scale projections of future rainfall and temperature for the Kimberley and Pilbara regions. IOCI3 also produced projections of rainfall and temperature extremes for NWWA and, because this region is affected by tropical cyclones, sought to improve our understanding of how the characteristics of these storms might change through to the end of this century. Furthermore, IOCI3 advanced the scientific understanding of how tropical cyclones could interact with the climate in response to rising greenhouse gas concentrations. Another important area of investigation was the possible causes of the rainfall increase observed in NWWA, a trend not reflected in global climate model projections of future climate conditions.

[1] See Figure 1.1 in the Technical Report for the IOCI3 study area boundaries.

1.3 About this Summary

This Summary provides a synthesis of IOCI3 research results for policymakers and the general public. Each section also provides links to the companion Technical Report of the Indian Ocean Climate Initiative, Stage 3, where more detailed descriptions of methods, results, knowledge gaps and references may be found.

BOX 1 IMPROVING THE QUALITY, COVERAGE AND ACCESSIBILITY OF CLIMATE DATA FOR WESTERN AUSTRALIA

The quality of long records of climate can be affected by changes unrelated to climate or weather, such as relocating a weather station from a city centre to a local airport, or changing the type of thermometer shelter used. In high-quality climate datasets, these external influences in the data have been removed or reduced. As a result these datasets may provide a clearer picture of long-term climate trends. High-quality datasets are vital for planning and management because they provide information on how the climate varies across fine scales of distance and time (such as localised extreme rainfall events). These datasets also underpin the knowledge needed for climate models and projections, including those for downscaled results (Technical Report, Box 1).

An important IOCI3 goal was to extend the coverage of Western Australia's high-quality climate datasets in SWWA and NWWA, with a particular focus on regions where there is evidence of changes in rainfall. IOCI3 scientists also improved the quality, accessibility and usability of these data. They used statistical tests to identify 'break points' in data, using neighbouring stations for reference. Once identified, these break points were confirmed using background information about the weather measurements. Reference stations were then used to make any necessary adjustments to compensate for external influences. This work has yielded the following datasets:

- **High-quality rainfall dataset:** now 157 stations in Western Australia; www.bom.gov.au/climate/change/acorn-rainfall
- **High-quality temperature dataset:** now 25 stations in Western Australia): www.bom.gov.au/climate/change/acorn-sat/
- **High-quality cloud dataset:** www.bom.gov.au/climate/change/hqsites.
- **Solar data:** www.bom.gov.au/climate/data/
- **An enhanced homogenised tropical cyclone database:** www.bom.gov.au/cyclone/history/tracks/.

Further reading: Section 2.1 of Technical Report.

2 Changes Observed in Western Australia's Climate

This section describes IOCI3 work to improve our understanding of observed changes in Western Australia's climate and weather. The factors that influence observed rainfall trends in SWWA and NWWA were a major focus of this work. IOCI3 results on extreme climate events, including extreme rainfall and hot spells, are also reported here, along with advances in the scientific understanding of climate change impacts on tropical cyclone behaviour.

2.1 South-West Western Australia's Climate

The climate of SWWA is characterised by dry, hot summers. This is due to the subtropical belt of high pressure (the subtropical ridge) that extends across this region, reaching its southernmost extension in January and February. Summer rainfall in SWWA is highly sporadic, and can be associated with the breakdown of tropical cyclones. During winter, this subtropical high-pressure belt lies further to the north, almost completely outside the SWWA region. Winter weather in SWWA is characterised by moist, unstable winds. Eighty percent of rainfall occurs from April to October, most of it during the cooler winter months of June and July.

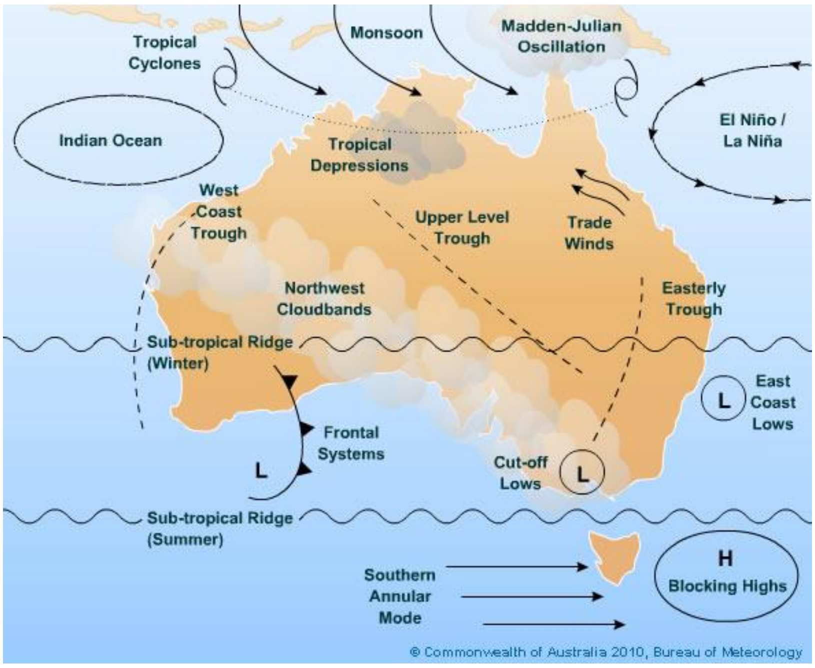

Figure S1 The main (but not all) influences upon the Australian climate. These influences vary in their level of impact in different regions and in different times of the year.

2.1.1 SWWA RAINFALL: INTENSIFIED AND EXPANDED DECLINE

Major findings

- *The May to July drying trend in SWWA intensified and expanded over a wide area in the last 10 years.*
- *Though formerly driven by a decrease in weather systems characterised by deep lows, since 2000 early winter rainfall declines have instead been driven by an increased incidence of high-pressure systems.*
- *SWWA autumn rainfall has declined 15% since 2000, mainly due to May rainfall declines, a trend also linked to the increasing prevalence of high-pressure systems.*

Annual average rainfall in SWWA has declined since the late 1960s. IOCI3 scientists found that this downward trend observed in rainfall has intensified and expanded. Since 2000, rainfall totals have continued to be low; early winter (May to July) rainfall in many locations was even lower than their 1969 to 1999 average. This drying has also expanded in geographic extent. In addition, the year-to-year fluctuation (interannual variability) in winter rainfall in the far south-west of Western Australia has also declined. IOCI3 scientists investigated these declines by examining SWWA rainfall trends across all seasons. The rainfall decline has been greatest in May, June and July.

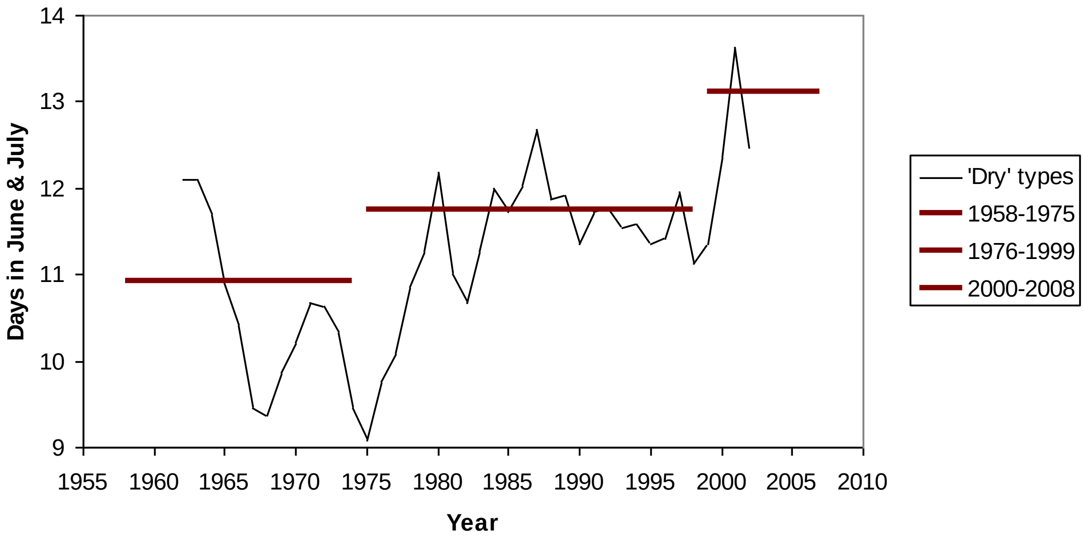

Figure S2 Increase in the number of June and July days with synoptic types associated with dry conditions. Since the 1970s extensive high-pressure synoptic types have steadily increased in occurrence. Horizontal red lines indicate the average incidence of dry types over the periods stated in the key.

Early winter rainfall: Early winter rainfall has undergone the most marked reductions of any season. To investigate this change, IOCI3 scientists studied synoptic patterns (the large-scale patterns of high and low pressure in the lower atmosphere) that influence SWWA weather in June and July. The focus was particularly on the months when the subtropical ridge (Figure S1) is at its most northerly extent. This work revealed a key group of weather systems characterised by deep lows across the region and associated with widespread rainfall across SWWA.

The occurrence (number of days) of these systems with deep lows declined 20% between the two periods 1958 to 1975 and 1976 to 1999. And whereas the incidence of some types of deep low has actually increased since 2000, the occurrence of types of deep low associated with inland rainfall has fallen to very low levels. However, the main weather system shift driving the continuing rainfall reductions since 2000 has been a 15% increase (compared to the 1958 to 1999 mean) in the number of days with high-pressure systems. Thus recent rainfall reductions have more to do with the persistence of high-pressure systems over the region, and less to do with further decreases in the number of low-pressure systems (Figure S2).

This is important to recognise because high-pressure systems influence a wider region than do low-pressure systems, and their increased prevalence would be expected to cause the area experiencing rainfall declines to expand. This is indeed the case. Regions that were already drying show a strengthened signal of rainfall decrease (the far south-west of Western Australia and wheatbelt), and those that did not formerly undergo May to July rainfall declines (the south coast and inland areas) are now experiencing early winter rainfall declines (Table S1).

Table S1 Representative SWWA stations indicate expanded and intensifying drying trend. The percentage change in May to July rainfall for recent periods, compared to the 1910 to 1968 average. Note: the data used here end with the year 2009; Inclusion of later years would show still stronger declines.

REGION	REPRESENTATIVE STATION	1969-1999	2000-2009
Far south-west	Wilgarrup (Manjimup)	-25%	-39%
Wheatbelt	Nyerilup	-14%	-33%
South coast	Peppermint Grove	+7%	-13%
Inland	Bulong (near Kalgoorlie)	+22%	-35%

Spring rainfall: Rainfall trends for the latter half of the cool season (August, September and October) are weak. October rainfall decreased but August and September rainfall increased over the period 1950 to 2007.

Summer rainfall: Rainfall during the summer half-year (November to April) has seen minimal trend since 1950. Exceptions include inland areas (increases of 14 millimetres per decade at Bulong) and along the south coast of SWWA (increases by 6.8 millimetres per decade at Peppermint Grove). Summer rainfall in SWWA is dominated by precipitation from extreme events, and increases in extreme rainfall have contributed to this increase in summer rainfall totals.

Autumn rainfall: Since the year 2000 autumn rainfall has declined by 15%, largely due to a 25% decrease in May rainfall.[2] May rainfall made up 58% of the total autumn (March to May) rainfall over the period 1900 to 2010. IOCI3 research showed that the May rainfall decline is largely being driven by an increase in high-pressure systems, as described above for winter rainfall. In contrast to the May trend, April rainfall has increased. As a proportion of total autumn rainfall, April rainfall grew by 8% over the period 2000 to 2010 compared to the long-term 1900 to 2010 mean. As amounts in May, June and July decrease, rainfall in months outside of this key high rainfall period may become more important to this region.

Further reading: Section 4.1.1 of Technical Report

[2] Comparing the 2000 to 2010 average to the 1900 to 2010 long-term mean.

2.1.1.1 Large-scale changes are driving SWWA's drying trend

Major findings

- *Rainfall reductions in SWWA can be explained by major changes in global atmospheric circulation and temperature.*
- *The strength of the subtropical jetstream decreased by 17% between the periods 1949 to 1968 and 1975 to 1994.*
- *Significant warming south of 30° S over these periods has reduced the temperature gradient between the equator and South Pole, particularly over the Indian Ocean.*
- *As a result, the stability of the atmosphere increased in winter and in other seasons over the period 1950 to 1999 in regions important for the formation of storms affecting SWWA. The net result has been fewer storms impacting on SWWA, and a downward trend in rainfall in the region.*

Changes to the subtropical jetstream and storm tracks

As discussed above, autumn and winter rainfall over SWWA has declined. Total decline in these seasons over the past 60 years is approximately 20%, with some of the largest rainfall decreases in the month of July. An important IOCI3 finding was that rainfall reductions in SWWA can be explained by major changes in global atmospheric circulation and temperatures. The strength of the subtropical jetstream decreased by 17% (or 9.4 metres per second) between the periods 1949 to 1968 and 1975 to 1994. This reduction occurred in the region over the southern Indian Ocean where the jetstream reaches maximum strength, at an altitude[3] of approximately 12 kilometres and a latitude of about 30° S, west (upstream) of Australia. The thermal structure of the atmosphere also changed. Significant warming south of 30° S between the aforementioned periods has reduced the temperature gradient between the equator and South Pole, particularly over the Indian Ocean.

BOX 2 SOME ATMOSPHERIC FEATURES THAT CONTRIBUTE TO STORM FORMATION

One of the most important circulation features associated with winter storm formation is the strength of the subtropical jetstream, which peaks approximately 12 kilometres above the Earth. The subtropical jetstream is a source of potential energy in the atmosphere; conversion of this potential energy into kinetic energy drives the formation of storms, which influence weather development in Australia.

An unstable atmosphere is an important factor in the likelihood of storm development. Wind shear conditions (strong winds up high, lighter winds down below) create the instability necessary for weather systems to 'grow', with storms developing when the vertical wind shear exceeds a critical value. The temperature gradient between subtropical and higher latitudes is an important factor contributing to this vertical wind shear instability. If the temperature gradient is reduced, the strength of the subtropical jetstream is also reduced, and the atmosphere becomes more stable.

These changes would be expected to have a major impact on the stability of the atmosphere and likelihood that weather systems which affect SWWA will form (Box 2). Winter weather systems are associated with Southern Hemisphere storm tracks, which owe their formation to an unstable atmosphere created by vertical wind shear. However, the reduced temperature gradient between subtropical and higher latitudes just noted tends to reduce the vertical wind shear. This stabilises the atmosphere and decreases the likelihood that storms will form.

[3] More accurately, at an altitude corresponding to the 200 hectopascal pressure level.

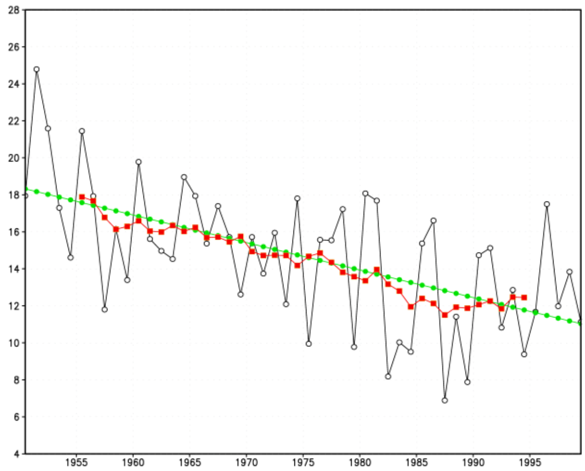

Figure S3 Reduction in the instability of the atmosphere at 87° E, 30° S. This is the region where storms affecting SWWA are generated. The figure shows the downward trend in the Phillips Criterion, in metres per second per year, over the period 1950 to 2000. The Phillips Criterion is a measure of wind shear, and provides an indication of the instability of the atmosphere. The black line illustrates year-to-year variation, the red line shows decadal variation, and the green line illustrates the long-term trend.

The stability of the atmosphere increased in winter and in other seasons over the period 1950 to 1999 (Figure S3). Atmospheric instability decreased in all months in regions associated with storm formation roughly west (upstream) of Australia. These trends of decrease are highly statistically significant. The likelihood of storm development has reduced at the mid-latitudes, but increased at higher latitudes (where positive trends in atmospheric instability have been observed), resulting in a southward shift in storm tracks. The net result is fewer storms impacting on SWWA, and thus a downward trend in rainfall.

These changes in large-scale circulation are consistent with those seen in the frequency of low and high-pressure weather systems described above. The subtropical jetstream steers cyclonic, mid-latitude storm systems and thunderstorms at lower levels in the atmosphere. A vigorous jetstream brings low- and high-pressure systems through in quick succession. A weakening of the jetstream leads to a stagnation of atmospheric patterns, and weaker surface low-pressure systems and cold fronts.

Further reading: Section 3.1 of Technical Report.

2.1.1.2 What are the ultimate causes of these large-scale atmospheric changes?

Major findings

- *The observed patterns of large-scale atmospheric change associated with SWWA rainfall reductions are consistent with what would be expected in an atmosphere influenced by increasing greenhouse gas concentrations.*

Determining the ultimate causes (attribution) of the observed SWWA rainfall reductions and likely drivers of further change during the 21st century was given priority in this research Initiative. IOCI3 scientists developed new modelling methods to establish the drivers of the large-scale atmospheric circulation and temperature changes described above. They showed that these observed patterns of change are consistent with what would be expected in a climate influenced by increasing greenhouse gases concentrations.

Limitations and knowledge gaps

Existing methods to detect and attribute climate change need to be built upon and expanded. They should be used not just to investigate SWWA drying, but also to study the rainfall trends observed in central and northern Western Australia. There is also a need to provide greater confidence in our understanding of causes of observed changes, and in projections (section 3.1.1). However, the signal of rainfall decline in

SWWA is one for which the projections are exceedingly robust, in that models agree on the direction of change (that is, they project further rainfall reductions).

2.1.2 SWWA TEMPERATURE: OBSERVED CHANGES

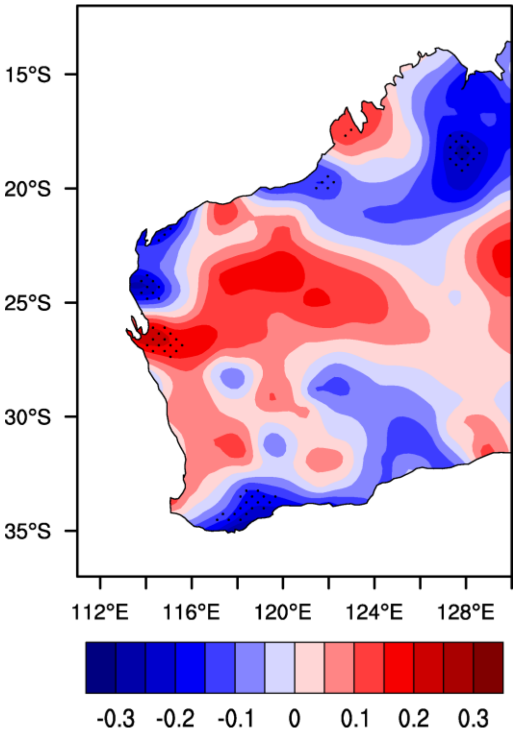

Figure S4 Trends in December-to-February maximum temperature for Western Australia. Note the cooling trend in the south-east of SWWA. Stippling indicates regions where trends are statistically significant.[4] Australian Water Availability Project gridded data in degrees Celsius per decade over the period 1961 to 2011.

Western Australia's annual mean temperatures have warmed over the last 50 years (see Technical Report, Figure 4.7). However, in the some north parts of the state, the south coast, and the east of SWWA *maximum* temperatures have cooled (Figure S4). The cooling in the south of SWWA has had impacts, such as a trend towards later ripening of wine grapes. IOCI3 scientists explored the possible causes and likely future progression of the cooling trend in the south-east of SWWA.

They examined the range of circulation patterns that influenced SWWA in summer (December, January and February) over the period 1958 to 2011. They observed that this cooling trend in the south-east is likely due to the increasing occurrence of particular weather patterns, which they named synoptic types A3 and A4, which enhance cooler conditions across the south-east of SWWA. Synoptic types A3 and A4 have the highest sea level pressure in the Indian Ocean of those examined.

IOCI3 scientists surmised that the cooling of maximum temperatures in south-east SWWA is likely due to the increasing trend in the number of these weather patterns, and to the slight decrease in weather patterns typically associated with warmer- than-average temperatures. These weather system trends are linked to the intensifying high pressure in the southern Indian Ocean and across southern Australian latitudes; that is, an intensifying Indian Ocean high and rising Southern Annular Mode (SAM) index. (The SAM is a mode of climate variability that can affect rainfall in southern Australia. It refers to the north/south movement of a belt of strong westerly winds associated with storm systems. Rising positive values of the SAM index indicate the contraction of this belt toward the South Pole.)

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[4] At the 5% level of significance.

In contrast to the south-east part of SWWA, maximum summer temperatures on the west coast of this region have warmed. The response of winds to the intensifying high-pressure band across southern Australia (and a rising SAM index) may have exacerbated this warming. These trends would result in weaker than normal westerly winds, and a reduction of their associated cooling effect.

What is driving these changes? The answers are not yet clear, but a plausible hypothesis is that the rising SAM index is due in part to the depletion of stratospheric ozone. If the ozone hole shrinks in coming decades, as expected, then its influence over SAM may diminish too. However, increasing concentrations of greenhouse gases in the atmosphere are expected to have the opposite effect, that is, to continue to push the SAM index higher.

Climate modelling[5] indicates that these competing influences will cause the SAM index to remain at approximately its current level at mid-century, but to be pushed to a higher value by the end of the century, leading to higher pressures in the belt south of Australia during summer. In this scenario, synoptic type A4 would be expected to occur approximately 35% more often, and types with the opposite patterns 35% less often. This suggests that current trends discussed above could persist to the end of this century, that is, the enhanced warming in the west and cooling in the east of SWWA would continue.

Further reading: Section 4.2.1 of Technical Report.

2.1.3 SWWA EXTREME EVENTS: OBSERVED CHANGES

Changes in climate extremes, rather than changes in mean climate, are expected to have a greater negative impact on natural ecosystems, society, and infrastructure. IOCI3 results on observed rainfall and temperature extremes specific to the SWWA region are presented here. (See Section 3.2.3 for projections of future climate extremes.)

2.1.3.1 SWWA extreme rainfall: observed changes

Research under the current and previous stages of IOCI showed that extreme rainfall intensity has decreased, a trend that has contributed to SWWA's total rainfall decline. It is important to understand these declines, which have already negatively affected hydrological systems including rivers, wetlands, and shallow groundwater. Knowledge of extreme rainfall is also important for the engineering design of culverts, roads and dams.

IOCI3 scientists found that trends in the total seasonal rainfall from intense daily rainfall events[6] (those events greater than the 95th percentile, that is, the top 5% in terms of intensity) across SWWA generally followed the trend in mean rainfall over the period 1950 to 2007. However, this was not true for intense rainfall during early winter (May, June and July) at stations in the far south-west of Western Australia in more recent years (1970 to 2007). The total rainfall from intense events in this area *increased* by two millimetres per decade over this period, even as mean rainfall declined by 21 millimetres per decade. Extreme rainfall events are still occurring in this area, but interspersed by ever-longer periods of dry conditions.

What is driving these and the wider changes to extreme rainfall in SWWA? This is a challenging research question. IOCI3 scientists found that seven measures describing different aspects of the climate system – the Indian Ocean Dipole, ocean heat content (for the southern, northern and total Indian Ocean), Southern Oscillation Index, SAM and Southwest Western Australia Circulation index – are not useful for seasonal forecasting of extreme rainfall.

Further reading: Section 4.3.1.1 of Technical Report.

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[5] Under a high (SRES A2) greenhouse gas emissions scenario.

[6] Based on data from high-quality stations across SWWA.

2.1.3.2 Extreme temperatures in the South West: observed changes to hot spells

Major findings

- *At Perth Airport the mean hot spell frequency increased from approximately six events in 1958 to eight events in 2011. However, over the same period the mean duration of hot spells declined, from approximately two days to 1.5 days.*
- *The intensity of hot spells increased over inland south Western Australia, but decreased over south-west and north-west parts of this region over the period 1958 to 2010.*
- *The frequency of hot spells increased over much of south Western Australia, but decreased in the north-east and south-west of this region (1958 to 2010).*
- *Over the same period the duration of hot spells decreased over the south, but increased over the central to north parts of south Western Australia.*

Rare and severe events such as heat waves are an important cause of weather-related fatalities. However, they are under-investigated compared to other natural disasters including tropical cyclones, floods and earthquakes. Under climate change, heat wave events may change in their intensity, frequency or duration (see Box 3 for definitions that reflect the use of these terms in this report).

BOX 3 HOT SPELL DEFINITIONS USED IN THIS REPORT

There is no universally accepted definition of a heat wave or hot spell. However, heat waves are typically regarded as prolonged hot spells. In this IOCI3 research, a hot spell is defined as one or more (consecutive) days with daily maximum temperature exceeding a particular threshold of high temperature.

Hot spell threshold: IOCI3 scientists used a statistical model to identify hot spell thresholds. The threshold was selected in such a way as to satisfy the assumptions made in fitting the statistical model for hot spell occurrence. Thresholds obtained in this manner may not coincide with temperature thresholds important to all stakeholders, but they are nevertheless realistic enough for the estimated trends in intensity, frequency, and duration to be broadly meaningful.

Hot spell intensity: the maximum daily temperature within a hot spell (in degrees Celsius).

Hot spell frequency: the number of hot spells per summer (number of events).

Hot spell duration: the length of a hot spell (in days).

At Perth Airport the mean hot spell frequency of hot spells (defined at this location as one or more consecutive days of maximum temperature exceeding 37 °C) increased from approximately six events in 1958 to eight events in 2011. However, over the same period the mean duration of hot spells declined, from approximately two days to 1.5 days (Figure S5). There was no trend in hot spell intensity.

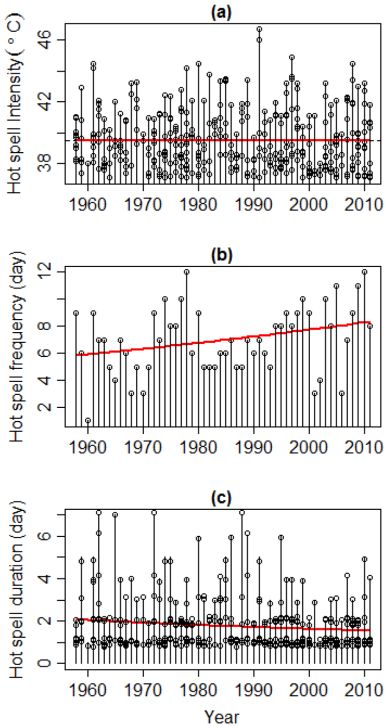

Figure S5 Trends in summer hot spell characteristics at Perth Airport over the period 1958 to 2011. The results indicate a trend of increase in hot spell frequency and decrease in hot spell duration. No trend in hot spell intensity was observed at Perth Airport over this period. (a) Observed hot spell intensity ('o' points) and estimated trends (red curve); (b) observed hot spell frequency ('o' points) and estimated trends (red curve); (c) observed hot spell duration ('o' points) and estimated trend (red curve).

The quantity of high-quality data on maximum temperature is limited, so IOCI3 scientists used other data sources to overcome this challenge.[7] They also developed statistical methods to analyse how hot spell characteristics including thresholds, intensity, frequency and duration vary across the different areas of south Western Australia, and to identify trends in these characteristics over the period 1958 to 2010. In this analysis, 'south Western Australia' refers to the area below the black horizontal line in Figure S6 (that is, south of 25° S).

Hot spell thresholds (not shown) are highest in central and interior areas of south Western Australia, where they range from 40 to 45 °C. South and coastal areas of have lower thresholds of approximately 30 °C. The intensity of hot spells (Figure S6a) over south-west and coastal parts of south Western Australia is generally lower, around 30 °C. In Perth and over the north part of this region, hot spell intensity is generally high, about 40 to 42 °C. As for trends over the period 1958 to 2010, whereas hot spell intensity decreased over south-west and north-west parts of this region, it increased over inland south Western Australia (Figure S6d).

[7] They used daily maximum temperature data from the Australian Water Availability Project (AWAP) for the period 1958 to 2010 as well as station data; see Technical Report Section 4.3.2 for more information.

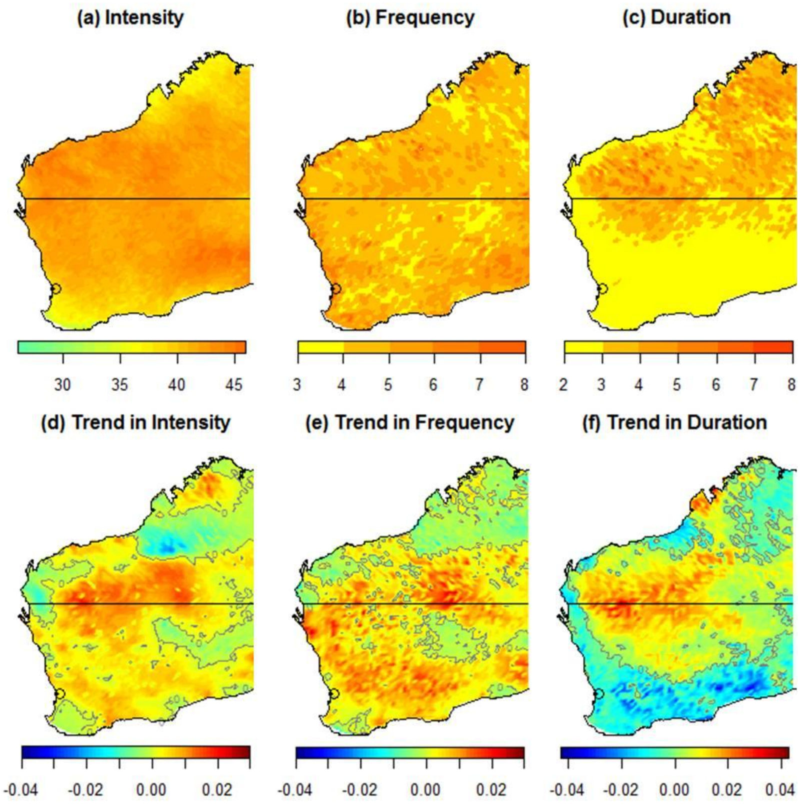

Figure S6 Spatial patterns of hot spell characteristics in south and north Western Australia and their trends. Upper panels: spatial distribution of hot spell (a) intensity (b) frequency and (c) duration. Lower panels: spatial distribution of trends in (d) hot spell intensity (e); frequency and (f) duration. Estimated by the hot spell model, and based on data from 11 high-quality stations and Australian Water Availability Project daily maximum temperatures (1958 to 2010). 'South Western Australia' refers to the area below the black horizontal line (that is, south of 25°S); 'north Western Australia' to the area above the black line.

Hot spell frequency in south Western Australia varies from three to eight events per summer, depending on the location (Figure S6b). Most of central-south Western Australia experiences an estimated three to five events per summer, but numbers are higher in the area north of Perth and inland areas in the south-east of this region. Over the period 1958 to 2010 hot spells became more frequent in central and north-west parts of this region, but less frequent in the north-east and south-west (Figure S6e).

The duration of hot spells is fairly uniform across south Western Australia, typically two or three days (Figure S6c). However, some areas in the north of this region have longer hot spells of five or six days. As for trends in duration, over the period 1958 to 2010 hot spells became shorter in the south-west part of the region (including Perth), but longer over central to north areas of south Western Australia (Figure S6f).

Further reading: Section 4.3.2 of Technical Report.

2.2 Observed Changes to North-West Western Australia's Climate

An important goal of IOCI3 was to further our understanding of climate systems in NWWA, an economically important and fast-developing region of the state. IOCI3 scientists investigated possible drivers of rainfall trends. Improved understanding of drivers of past and future rainfall trends could inform policy related to water management and water supply for settlements and catchments in NWWA. Better knowledge of rainfall trends and variability can also inform infrastructure planning, including transport infrastructure for the mining sector. IOCI3 scientists also studied extreme climate events that affect NWWA, including extreme rainfall, hot spells and tropical cyclones.

2.2.1 NWWA RAINFALL: OBSERVED CHANGES

North-west Western Australia receives most of its rainfall during the summer monsoon season (late December to March), which overlaps with the tropical cyclone season (November to April). Thus rainfall in the north is strongly influenced by the intensity of the wet season and monsoon, and by tropical cyclones.

Total annual rainfall in NWWA has increased since 1950. IOCI3 scientists studied this region's weather patterns and investigated whether tropical cyclones and other closed low weather systems ('closed lows') may have contributed to observed rainfall changes. They also examined the possible influence of aerosols on the rainfall trends of this region. (Aerosols are a collection of airborne solid or liquid particles with a typical size between 0.01 and 10 micrometer that reside in the atmosphere for a least several hours.)

2.2.1.1 NWWA rainfall increases and regional weather pattern changes

Major findings

- *In the Kimberley region, weather patterns associated with very wet conditions became more common, and those with very dry conditions less common, during the summer wet season since 1960.*
- *In the Pilbara, weather patterns associated with summer dry conditions have also decreased since 1980, and some associated with summer wet conditions have increased since 1960.*

Rainfall in the Kimberley is highly seasonal, and a large proportion of the annual total falls from December to March. Both the Kimberley and the Pilbara have a dry season, although the Pilbara's is less distinct. IOCI3 scientists examined summer weather patterns to determine how they might be associated with the observed trend of increasing annual rainfall totals in these regions. They found that weather patterns associated with very wet conditions throughout the Kimberley during the summer half-year have become more common, whilst those associated with very dry conditions decreased in occurrence since 1960. Similar weather system shifts also occurred in the Pilbara during summer. Since 1980 the frequency of weather patterns associated with dry conditions in the Pilbara has decreased. And since 1960, the frequency of a weather pattern associated with wet conditions across the Pilbara, and another with wet conditions in the north-east Pilbara, have both increased. These changes could indicate longer tropical wet seasons for the Kimberley and eastern Pilbara.

Further reading: Section 5.1.1 of Technical Report

2.2.1.2 Tropical cyclone and other closed low contributions to rainfall totals and trends

Major findings

- *In north-west Australia tropical cyclones contribute up to 30% of the total annual rainfall amount.*
- *This contribution may reach 40% in coastal regions during the peak tropical cyclone season (January to March).*
- *For extreme rainfall only, tropical cyclones and other forms of closed low systems contributed more than 60% of the annual total in the north and west Australia over the period 1989 to 2009.*
- *The amount of precipitation associated with closed lows (excluding tropical cyclones) increased over north-west Australia during the period 1989 to 2009.*

How much do tropical cyclones contribute to rainfall totals?

Landfalling tropical cyclones can bring torrential rainfall, causing flooding and contributing to landslides. However, their rainfall may also significantly contribute to fresh water supplies for settlements, agriculture and ecosystem health. IOCI3 projections suggest that tropical cyclones may become less frequent in the future (Section 3.2.3.3). Thus it is important to understand the extent to which cyclones contribute to NWWA's rainfall totals and trends.

Tropical cyclones influence the continent's north and north-west, and the largest annual totals of tropical cyclone rainfall occur over north-west Australia. IOCI3 scientists found that days with tropical cyclone rainfall provide 20 to 30% of the total annual rainfall to parts of the north-west Australian coastline around Port Hedland. Further north, beyond Broome, the majority of annual rainfall is provided by the monsoon and the tropical cyclone contribution decreases to around 10%: the contribution of other closed lows (this includes monsoonal depressions) is discussed below. As for extreme rainfall, tropical cyclones are the source of more than 35% of rainfall events greater than the 99th percentile (the top 1% in terms of rainfall intensity) over north-west Australia.

When IOCI3 scientists considered only the November-April tropical cyclone season totals, they found that tropical cyclone rainfall makes up a substantial proportion of mean rainfall in areas affected by these storms. For the west-central Pilbara, Gascoyne and Mid-West regions of Western Australia (areas west of 125° E), tropical cyclones supplied 20 to 40% of rainfall within 150 kilometres of the coast, and approximately 20% further inland. This proportion is much higher during December, prior to the wet season, when tropical cyclones supply approximately 60 to 70% of rainfall totals for coastal regions of the Pilbara and Gascoyne (i.e. the region west of 115° E).

Tropical cyclone rainfall amounts generally decrease with distance inland from the coast. However, the western region experiences the greatest inland penetration of tropical cyclone tracks in Australia – up to 500 kilometres inland. This is associated with a greater inland penetration of tropical cyclone rainfall in this region. In particular, in the Pilbara the rainfall percentage due to tropical cyclones makes up a fairly large proportion of the relatively low rainfall total.

However, IOCI3 also demonstrated that the valuable contribution of tropical cyclones to rainfall in the Western Australian region varies greatly from one tropical cyclone season to the next. Only a small number of tropical cyclones affect a given coastal area each season, and some longitude bands receive no tropical cyclone rain at all during some seasons. For example, the tropical cyclone contribution to rainfall totals in the Gascoyne varies from 0 to 86%, depending on the year. This high interannual variation also strongly affects the reliability of tropical cyclone rainfall as a water supply source in NWWA. The storage level at Harding Dam (a source of potable water for 20,000 people) fell to 20% in 2010 before being recharged by tropical cyclone rainfall.

Contribution of closed low weather systems to NWWA's rainfall trends

Closed lows (including tropical cyclones and monsoonal depressions) accounted for approximately 40 to 60% of the annual rainfall over north-west Australia during the period 1989 to 2009. Considering extreme precipitation events alone, this closed low contribution was more than 60%. Have trends in rainfall from closed low systems – excluding those associated with tropical cyclones – contributed to this region's trend of rainfall increase? IOCI3 scientists found that these long-lived closed lows explained a very high proportion (50%) of this rainfall trend over north-west Australia during the period 1989 to 2009. Yet this has taken place with only a slight increase in the occurrence of these closed lows. Rather, the contribution of closed lows to the rainfall trend was found to be due to an increase in the amount of rainfall per closed low day, that is, an increase in the 'precipitation efficiency' of closed lows over this period. Section 2.2.3.1 reports on tropical cyclone rainfall and extreme rainfall contributions to NWWA rainfall trends.

Further reading: Sections 5.1.3 and 5.3.1.1 of Technical Report.

2.2.1.3 Large-scale weather system influence on rainfall trends in NWWA and other regions

Major findings

- *Winter (July) rainfall has increased in central north-west Western Australia and central Western Australia.*
- *The increased formation of north-west cloud bands and intraseasonal oscillations over approximately the past 60 years is consistent with rainfall increases observed in parts of Western Australia.*

Winter (July) rainfall has increased over central north-west and central Western Australia. IOCI3 research links this increase to changes in two types of weather systems commonly seen in these regions: north-west cloud bands and intraseasonal oscillations. The influence of aerosols generated by human activity, another possible factor in the NWWA rainfall increase, but in summer, is covered below.

North-west cloud bands originate in the Indian Ocean off north-west Australia and then travel eastward (Figure S1). Associated with an extensive layer of rain-bearing cloud, these weather systems provide rainfall across much of Australia. Their growth rates increased by approximately 25% or more over about the past 60 years (comparing the 1997-2006 average to the 1949-1968 average). This increase would be expected to increase rainfall over the regions mentioned in the preceding paragraph, as has been observed.

Intraseasonal oscillations cause weather disturbances that extend from the central Indian Ocean across to central and north Western Australia. The growth rate of these weather systems has increased by about 30% over approximately the past 60 years (again comparing the 1997 to 2006 average with the 1949 to 1968 average). Increased formation of these weather systems is consistent with increases in rainfall over central NWWA in July.

Further reading: Section 3.2 of Technical Report.

2.2.1.4 NWWA rainfall increase and the possible role of aerosols

Major findings

- *IOCI3 modelling studies suggest that aerosols have contributed to NWWA's observed rainfall increase, offsetting a possible drying influence of increasing greenhouse gas concentrations. However, some of this rainfall trend is also likely due to natural variation in the region's climate.*
- *Antarctic ozone depletion may have had a lesser but similar effect to aerosols, also contributing to an increase in mean rainfall.*
- *A future decrease in aerosol levels could 'unmask' the effects of greenhouse gas emissions. If future trends are driven to a greater extent by increasing greenhouse gas concentrations, this region may be expected to undergo a drying trend.*

A number of modelling studies suggest that enhanced greenhouse gas concentrations cannot explain the summer rainfall increase in NWWA. IOCI3 scientists examined whether the Asian aerosol haze, fine particles generated by human activity that are suspended in air pollution, could play a role. Although Australia has relatively low levels of aerosols, it is just across the equator from the planet's highest concentration of aerosols from human activity. Furthermore, the strongest cooling effects of aerosols occur in the South-East Asian Region (Figure S7). Establishing the possible role of aerosols in the observed rainfall increase has policy implications. If efforts to reduce Asian aerosols (due to concern about their adverse effects on human health) are successful, this wetting trend could reverse in future.

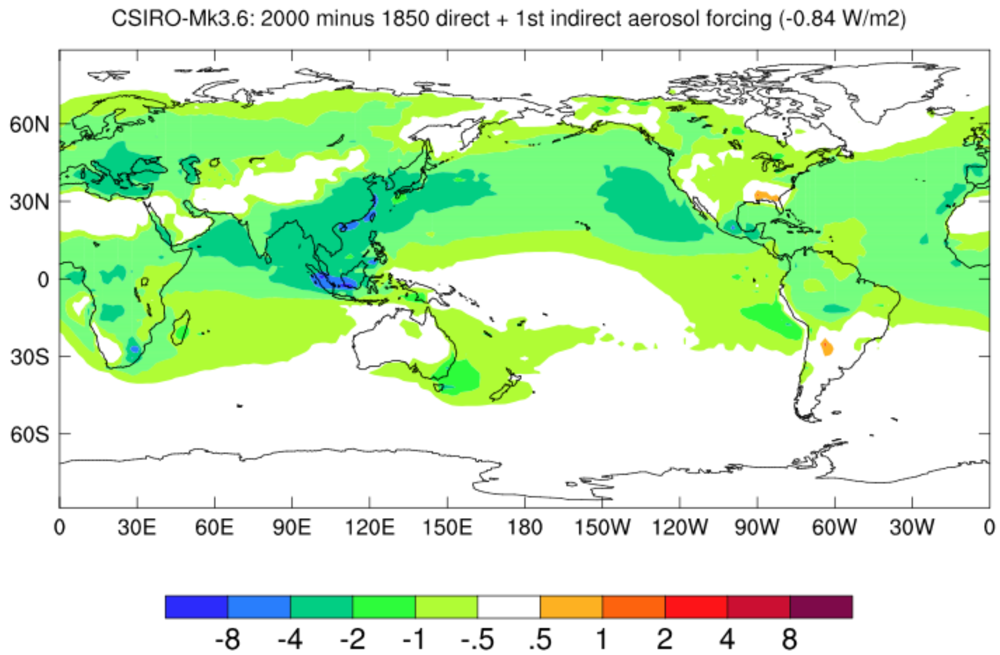

Figure S7 The cooling influence of aerosols. Note that this cooling influence (shown as green through blue areas) on solar radiation intensities (in Watts per square metre) at the top of the atmosphere is most pronounced in the South-East Asian Region, just across the equator from Australia. These estimates were calculated using the CSIRO Mk3.6 global climate model.

IOCI3 scientists collaborated with the Queensland Climate Change Centre of Excellence to examine the role of aerosols and other possible drivers of the region's rainfall increase, including Antarctic ozone depletion. They used modelling techniques that separated out the possible effects of aerosols, enhanced greenhouse gas concentrations, ozone and other such 'forcing' agents.

Their analysis suggests that human-generated aerosols have contributed to the observed rainfall increase, substantially masking the effects of greenhouse gases, which on their own were simulated to cause drying over north-west Australia. Ozone depletion, the modelling suggests, may have had a lesser but similar masking effect to aerosols, also contributing to an increase in mean rainfall. However, this modelling work also suggests that some of this observed trend is associated with natural climate variability.

Future mean rainfall changes could differ greatly from those recently observed in this region. Modelling suggests that if aerosol levels decrease, and if future changes are driven by increasing concentrations of long-lived greenhouse gases, drying would take place over much of Australia. This rainfall decrease would be most pronounced in the North, including NWWA.

Limitations and knowledge gaps

Results such as these, based on one climate model,[8] should be treated as hypotheses. To better establish the aerosol–rainfall link, scientists must compare results from a range of global climate models. They must also explain the physical mechanism by which aerosols influence the region's rainfall. One possibility is that aerosols may strengthen the cyclonic (clockwise) circulation off Australia's north coast, thereby bolstering monsoonal winds and bringing more moisture towards NWWA from the Indian Ocean.

Further reading: Section 5.1.4 of Technical Report.

[8] The CSIRO Mk3.6 global climate model.

2.2.2 EXTREME EVENTS IN NWWA: OBSERVED CHANGES

As already noted, extremes of weather and climate can have significant socio-economic and environmental consequences. IOCI3 sought to improve our understanding of extreme events in NWWA for both present-day and possible future (Sections 3.2.3) climate conditions. This section reports IOCI3 results on extreme rainfall and hot spells. It also covers IOCI3 findings on tropical cyclones, Western Australia's most regular major natural meteorological disaster.

2.2.3.1 Tropical cyclone contributions to rainfall and extreme rainfall trends in NWWA

Major findings

- *The amount of precipitation associated with each tropical cyclone increased over the past 40 years in the north and west of Australia, most markedly over the period 1989 to 2009.*

Is the increase observed in NWWA's annual rainfall linked to changes in the characteristics of tropical cyclones? The number of tropical cyclone days remained constant over central-north and north-west Australia over period 1970 to 2009. Over much of north-west Australia, between Broome and Carnarvon, the percentage contribution of tropical cyclones to annual rainfall has decreased (but not significantly). However, further north close to Darwin, where tropical cyclones contribute a much smaller percentage of annual rainfall, their associated rainfall has increased significantly. If this analysis is restricted to the percentage of extreme precipitation (greater than the 99th percentile) influenced by tropical cyclones, these results are even more pronounced, except in the very north of the region (Figure S8). However, the average over Australia's entire north-west indicates no overall change in the percentage of tropical cyclone rainfall. This suggests that rainfall increases over this region are the result of weather systems other than tropical cyclones (Section 2.2.1.2).

Nonetheless, the amount of rainfall associated with each tropical cyclone (precipitation efficiency) has increased, as is the case with other forms of closed low systems (Section 2.2.1.2). IOCI3 scientists examined changes in rainfall amounts associated with Australian-region tropical cyclones over the past 21 (1989 to 2009) and 40 (1970 to 2009) years. The precipitation efficiency (measured as rainfall per tropical cyclone day) increased over the 21-year period in the north and west of Australia; if the full 40-year period is taken, a smaller increase is apparent (Figure S8e-f). This indicates that the greater share of this increase in tropical cyclone precipitation efficiency occurred during the more recent period.

Further reading: Section 5.1.3.1 of Technical Report.

2.3.3.2 Extreme temperatures in the North West: hot spell spatial patterns and trends

Major findings

- *IOCI3 research on observed hot spell trends indicates that their intensity, frequency and duration increased in most inland areas of north Western Australia over the period 1958 to 2010, some exceptions to this general trend notwithstanding.*

IOCI3 scientists developed new statistical methods to estimate hot spell characteristics and applied these methods to temperature data for north Western Australia.[9] For this analysis, 'north Western Australia' refers to the area above the black horizontal line in Figure S6 (that is, north of 25° S). They found that hot spell thresholds in most parts of north Western Australia exceed 40 °C, according to data for the period

[9] Due to the limited quantity of high-quality station data on temperature extremes, IOCI3 scientists used both station data and data from the Australian Water Availability Project (1958 to 2010) for this analysis. See Technical Report Sections 4.3.2 and 5.3.2 for more information about data and methods used.

1958 to 2010. Most inland areas have high thresholds, approaching 45 °C. On the Pilbara coast, thresholds range from 33 °C to 46 °C. Thresholds are considerably lower along the Kimberley coast, where they range from the low to mid-30s (°C).

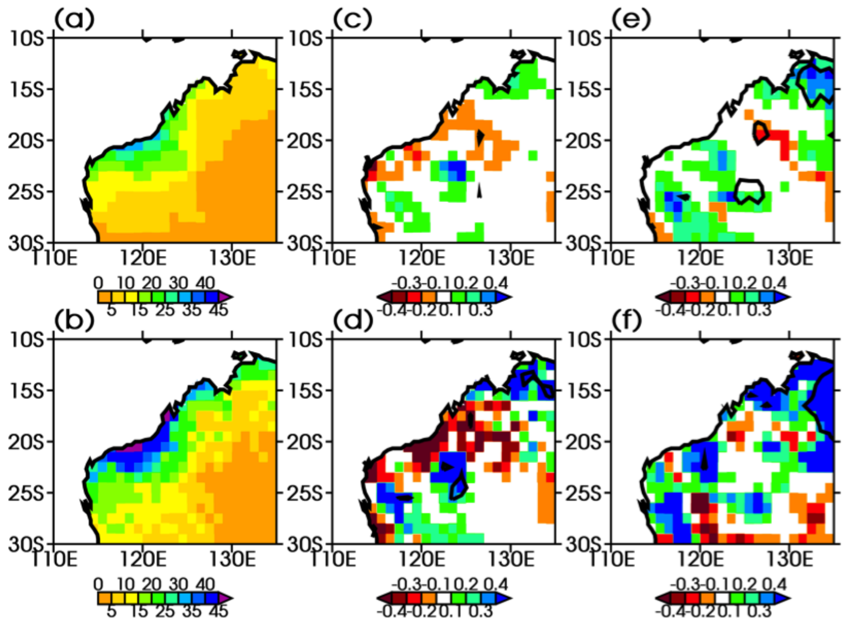

Figure S8 Climatologies over the period 1970 to 2009 of the percentage of (a) annual precipitation; and (b) extreme precipitation influenced by tropical cyclones. Tropical cyclones provide 20 to 30% of the annual rainfall to the area around Port Hedland, and about 35% of the total *extreme* rainfall to a considerable portion of north-west Australia. Also shown are trends in the percentage of: (c) annual precipitation; and (d) extreme precipitation influenced by tropical cyclones over the period 1970 to 2009. Panels (e) and (f) show the trend in the amount of precipitation (in millimetres) per tropical cyclone day per year over the periods (e) 1970 to 2009 and (f) 1989 to 2009. Black lines in panels (c) to (f) highlight values significant at the 90% level.

The spatial pattern of hot spell intensity resembles that of thresholds (Figure S6a). For most of north Western Australia, hot spell intensities range from 40 to 45 °C, however, along the Kimberley coast lower intensities from the mid- to high 30s are seen. As for trends over the period 1958 to 2010, hot spell intensity generally increased over most inland (particularly south inland) areas of north Western Australia, but decreased in coastal areas and the south Kimberley (Figure S6d)

Hot spell frequency in coastal areas of north Western Australia typically ranged from four to seven events per summer over the period 1958 to 2010 (Figure S6b). South-west parts of the Kimberley experienced lower frequencies of three or four events per summer. In some areas of inland north Western Australia, frequencies were higher: three to eight events per summer. As for trends (Figure S6e), hot spell frequency increased in most inland areas over the period 1958 to 2010. In Meekatharra hot spell frequency increased significantly, from three to six events over the period 1958 to 2011.[10] However, hot spell frequency tended to decrease in the southern and northern parts of the Kimberley, and in the south-west corner of north Western Australia.

[10] This increase is statistically significant at the 0.001 level. Here the period 1958 to 2011 is referred to because this result is based on station data available for this period.

As for hot spell duration, coastal areas generally experienced shorter events than inland areas (Figure S6c). From the Pilbara coast and along south-west parts of north Western Australia hot spells have generally lasted two or three days, somewhat shorter than the three to seven day events typically experienced in the region's southern inland areas. As for trends, hot spell duration has increased in most inland areas of the region (Figure S6f). However the duration of these events decreased in the south-west and eastern parts of the Kimberley, and in the south-west corner of north Western Australia, over the 1958 to 2010 period.

Further reading: Section 5.3.2 of Technical Report.

2.3.3.3 Tropical cyclones: observations

Major findings

- *Tropical cyclones occurring in the first half of the cyclone season disrupt the seasonal warming trend, which does not resume until 20 to 30 days after cyclone passage. Conversely, cyclones in the later half of the season bring about an approximately 0.5 °C temperature drop from which the ocean does not recover due to the seasonal cooling cycle. This is a large impact and its effect is currently not incorporated in climate models.*
- *The first-ever documentation of the sea surface temperature threshold for tropical cyclone formation for all individual cyclone cases confirmed that a threshold of 26.5 °C exists for 98% of cyclone cases worldwide, but that cyclones can exist at cooler temperatures later in their lifecycle.*
- *Study of the response of the sea surface temperature threshold to global warming found that a 0.2 °C shift has occurred in the mean temperature of tropical cyclone formation. No shift can be detected in the threshold temperature towards a higher value.*
- *The quality of the historical tropical cyclone datasets was documented in detail. Statistical techniques were developed to determine whether any trends are statistically significant. Despite firm model predictions for future changes in tropical cyclone behaviour, currently there are no statistically significant trends in historical Western Australian tropical cyclone frequencies or intensities.*
- *A study on the economic impact of tropical cyclones in Western Australia suggests that the major impact is not direct damage to private housing and public infrastructure. Rather it suggests the major impact is on the minerals and energy sector. However, because the ongoing costs to this sector are not reflected in insurance payouts, they are largely undocumented.*

Tropical cyclones produce fierce winds, extreme rainfall, storm surge, lightning and shoreline erosion, and along with floods they can threaten life, property, businesses, and the environment.

IOCI3 scientists participated in a major international collaboration to summarise what is known – and what is not yet understood – about tropical cyclones and climate change. They also improved the fundamental understanding of the role tropical cyclones play in climate and examined historical data for trends in the activity of tropical cyclones that affect Western Australia (Table S2). In addition, they performed modelling studies on possible future changes in the characteristics of tropical cyclones (Section 3.2.3.3).

Correlations with ocean temperature

IOCI3 advanced the understanding of the complex relationship between tropical cyclones and ocean temperatures. At the beginning of the tropical cyclone season (October through December), the presence of warmer sea surface temperatures corresponds to higher numbers of tropical cyclones. However, in mid-season (January through March), warmer sea surface temperatures actually correspond to fewer tropical cyclones. It appears that tropical cyclones' response to ocean temperature is not simply a local one. Instead it must be interpreted in terms of the larger circulation system that fosters tropical cyclones.

Table S2 Observations on tropical cyclones in north-west Western Australia.

OBSERVATIONS ON TROPICAL CYCLONES IN THE NORTH WEST	
Number per year	7-8
Number of severe cyclones (categories 4 and 5) per year	2-3
Trend in cyclone numbers	No
Statistically significant trend in percentage of severe cyclones?	No

Sea surface temperature threshold for tropical cyclone formation

It has generally been accepted that tropical cyclones form only over tropical oceans with sea surface temperatures of at least (approximately) 26.5 °C. This because the energy source for a tropical cyclone is the heat stored in the ocean. Because ocean temperatures have warmed and are likely to continue to do so, the extent of ocean area providing the threshold temperature for tropical cyclone formation may increase. Determining the robustness of this 26.5 °C formation threshold is therefore important.

IOCI3 scientists examined the sea surface temperatures at which tropical cyclones formed using a local database and information within an international database on tropical cyclones and tropical cyclone tracks for the years 1981 to 2003. This revealed that, although 26.5 °C is not an absolute threshold, more than 98% of tropical cyclones form above this sea surface temperature. This threshold is most apparent during the 48 hours preceding the development of a tropical cyclone.

They also examined the response of the sea surface temperature threshold to global warming. They observed that, globally, tropical cyclones are forming at sea surface temperatures warmer than 26.5 °C, that is, a 0.2 °C shift has occurred in the mean temperature of tropical cyclone formation. However, no shift can be detected in the threshold temperature towards a higher value. Therefore as the oceans warm, it cannot be assumed that the region of tropical cyclone formation will expand. Sea surface temperatures are just one of a number of pre-conditions for tropical cyclone formation.[11] Thus ocean warming does not automatically imply a larger area off Western Australia's coast conducive to their formation.

Tropical cyclones influence ocean temperature

IOCI3 scientists also confirmed that the relationship between tropical cyclones and sea surface temperatures is complex. Not only do sea surface temperatures influence tropical cyclone development and final intensity, but tropical cyclones also greatly influence the heat balance of the underlying ocean. Tropical cyclones can have a large impact on the seasonal cycle of ocean surface temperature, as follows. When tropical cyclones occur in the first half of the cyclone season, they disrupt the seasonal warming trend, which does not resume until 20 to 30 days after cyclone passage. Tropical cyclones that occur in the late half of the season bring a decrease of approximately 0.5 °C from which the ocean temperature does not recover, due to seasonal cooling.

Tropical cyclone intensity and frequency: no significant trends thus far

Whether the characteristics of tropical cyclones have changed or will change in a warming climate – and if so, how – has been the subject of considerable investigation, often with conflicting results. Large year-to-year fluctuations in the frequency and intensity of tropical cyclones greatly complicate efforts to both detect long-term trends and to determine whether any changes are driven by rising levels of atmospheric greenhouse gases. The availability and quality of global historical records of tropical cyclones is quite

[11] Additional pre-conditions include a potentially unstable atmosphere; a moist mid-troposphere; a pre-existing near surface disturbance with established spin and convergence; and a small amount of vertical wind shear (that is, little difference in the wind speed of the upper and lower atmosphere).

limited, and this further impedes efforts to detect trends in tropical cyclone characteristics. As a result, it is not yet possible to ascertain whether past changes in tropical cyclone activity have exceeded the variability expected from natural causes.

IOCI3 scientists collaborated with the BoM National Climate Centre to investigate and document the history of the methods used for reporting in the west Australian (that is, South Indian Ocean) tropical cyclone dataset. Using this homogenised dataset, they determined that there are no significant trends in the frequency or intensity of tropical cyclones for the South Indian Ocean over the last 30 years, the period for available records that can be considered consistent.

Limitations and knowledge gaps

The impact of tropical cyclones on climate is still not well understood. Under IOCI3, important first steps were made to document the impact of cyclones on sea surface temperature. Further work should incorporate sub-surface temperature data and should involve case studies of individual cyclone and cyclone seasons.

The study on the sea surface temperature at which cyclones form should be extended to study cyclone intensification and particularly rapid intensification. The lack of a discernible trend in the threshold temperature for tropical cyclone formation in this region is at odds with reports in the international literature of changes in the threshold for large-scale organized convection. These differences need to be resolved.

Changes in satellite detection methods and limitations in the historical data have made it difficult to detect trends in cyclone behaviour. More analysis of tropical cyclone records is required to understand the conditions that lead to some years having more intense cyclones and cyclones making landfall further southwards. Additional work is also needed on historical tropical cyclone data, including landfall observations, to obtain a longer, consistent cyclone record suitable for trend detection.

IOCI3 also showed that the ongoing economic impact of tropical cyclones on the mining sector is not publicly documented (see Technical Report, Section 5.3.3.3). These costs are associated with operating in a region subject to flooding of mines, road and port closures, evacuation of personnel and cyclone-dominated design criteria for offshore platforms. Industry costs and outputs should be recorded such that cyclone impacts can be quantified. The IOCI3 economic study concluded that climate change-related impacts on tropical cyclone activity will probably not be detectable in economic data due to the compounding influences of increases in coastal population, coastal infrastructure and increasing constructions costs. However, an exception may be future cost amplification from storm-surge inundation, due to these surges occurring against a background of higher sea levels. To date no studies have incorporated this effect into economic modelling of future cyclone costs.

Further reading: Section 5.3.3 of Technical Report

See also the tropical cyclone database at: www.bom.gov.au/cyclone/history/tracks/

3 Anticipated Future Changes in Western Australia's Climate

Climate change will be superimposed on present-day climate fluctuations and extremes, creating new challenges and opportunities. Improved understanding of possible future changes could inform those who must plan for future action based on assumptions about the climate. IOCI3 scientists provided projections of possible changes to mean rainfall and temperature under future climate scenarios. They also provided high-resolution projections of extreme rainfall and hot spells, and projections of tropical cyclone characteristics, including their frequency, intensity and associated rainfall. IOCI3 advances on the forecasting of rainfall, temperature and tropical cyclones in Western Australia are reported in Section 3.3.

BOX 4 PROJECTION OR FORECAST?

Climate projections and forecasts both make statements about future climate conditions, but they differ in important ways.

Climate forecasts (or climate predictions) attempt to estimate the actual evolution of the climate in seasons or years ahead, or over still longer-term future periods.

However, in climate projections the response of the climate system to emissions[12] scenarios of greenhouse gases or aerosols is calculated, often based on simulations by climate models. Thus climate projections differ from climate forecasts in that they critically depend on these scenarios, and the highly uncertain assumptions of future socio-economic and technological development that underpin them. Information on the scenarios used in IOCI3 analyses is given in Box 3 of the Technical Report.

3.1 SWWA Climate Projections

This section summarises the results of multiple approaches used under IOCI3 to provide projections of possible changes to SWWA's climate through to the end of the century.

3.1.1 SWWA RAINFALL PROJECTIONS

Major findings

- *Climate modelling of large-scale changes to the atmosphere indicates that as greenhouse gas concentrations continue to increase, further rainfall reductions may be expected in SWWA in all months from May to October.*
- *High-pressure weather systems could become more prevalent, such that their incidence could increase by 70% by the period 2081 to 2100 (compared to the 1961 to 2000 baseline). The incidence of low-pressure systems is expected to decrease by almost as much.*
- *Station-scale (statistically downscaled) climate projections also suggest that the SWWA drying trend will continue to intensify through to the middle and end of this century.*

[12] Scenarios of concentrations of greenhouse gases or aerosols ('concentration scenarios'), or forcings ('forcing scenarios') may also be used.

Will SWWA's drying trend continue to intensify and expand? This important question has relevance for policymakers who must manage water resources for urban supply, agricultural use or ecosystems. IOCI3 scientists provided projections of future SWWA rainfall using three different approaches. They provided projections of future changes to: large-scale characteristics of the atmosphere in the Southern Hemisphere; regional low and high-pressure weather systems that influence SWWA rainfall; and rainfall at the scale of individual weather stations.

3.1.1.1 SWWA rainfall projections: large-scale climate systems

IOCI3 modelling work indicates that as greenhouse gas concentrations continue to increase,[13] the large-scale changes to the atmosphere observed during the second half of the 20th century (described in Section 2.1.1.1) could continue during the 21st century. This includes further large reductions in wind shear instability and storm formation, and continued rainfall decline around the Southern Hemisphere north of 40° S. Decreases in rainfall are projected for SWWA in all months of the May to October half-year. In some months these reductions could exceed 20 millimetres. These reductions may be as large as, or larger than, those experienced at the end of the 20th century.

Further reading: Section 3.3 of Technical Report.

3.1.1.2 Weather system projections and SWWA rainfall

Like the projections of large-scale atmospheric changes described above, IOCI3 projections of changes to regional weather systems indicate future drying. Taking the weather systems discussed in Section 2.1.1, IOCI3 scientists compared the present (1961 to 2000) period with projections for the end of the century (2081 to 2100) under a high (Special Report on Emissions Scenarios [SRES] A2) greenhouse gas emissions scenario. The results suggest a future increase in the incidence of synoptic types associated with high-pressure systems affecting SWWA, and a decrease in those associated with low-pressure systems. Some climate models project an increase of up to 70% in the daily occurrence of synoptic types associated with extensive high-pressure systems, and almost as much decline in those with deep lows.

Further reading: Section 4.1.2.2 of Technical Report.

BOX 5 STATION-SCALE CLIMATE PROJECTIONS FOR SWWA AND NWWA

Downscaled projections[14] have greater spatial resolution than global and regional climate models. IOCI3 downscaling methods used the 100 to 200-kilometre gridded outputs of climate models to infer changes at the resolution of individual weather stations. This work yielded downscaled projections of daily mean rainfall and daily minimum and maximum temperature for 29 selected BoM stations in SWWA, nine stations in the Kimberley, and ten stations in the Pilbara (see Sections 3.1.1.3, 3.1.2, 3.2.1 and 3.2.2). These stations were selected for the relatively high quality of their historical data, and those in SWWA were also chosen for their relevance to the water and agriculture sectors.

Results from the application of this downscaling method can inform climate adaptation and planning: they are suitable for making impact, vulnerability and risk assessments. However, users should carefully note the associated caveats and limitations discussed in the sections referred to above. Whilst suitable for scenario planning, projections are not the same as predictions or weather forecasts, given uncertainties in the driving emissions scenarios (Box 4).

The complete results for these downscaled climate projections are available at: http://data.csiro.au/dap/

Further reading: Technical Report sections 2.2, 4.1.2.2, 4.2.2, 5.1.2 and 5.2; Appendix A and C for supplementary information on methods; Appendix B & D for tables of results.

[13] These projections were made using low (B1), intermediate (A1B) and high (A2) SRES greenhouse gas emissions scenarios. See Technical Report Box 3 for an explanation of SRES greenhouse gas emissions scenarios.

[14] See Box 1 and Section 2.2 of the Technical Report for an explanation of downscaling methods.

3.1.1.3 Station-scale projections of SWWA rainfall

In addition to the broad-scale projections described above, IOCI3 scientists produced station-scale projections of rainfall changes for 29 stations across SWWA. Statistical downscaling was applied to simulations from five different global climate models for the low (B1), intermediate (A1B) and high (A2) SRES greenhouse gas emissions scenarios for the middle (2047 to 2064) and end of this century (2082 to 2099). Box 5 provides further information on these projections as well as links to the complete results. For illustrative purposes the results for a subset of six of the 29 selected stations are given in Table S3.

Table S3 Range, from downscaling five global climate models, of present-day (1962 to 1999) and projected annual mean rainfall (in millimetres) for selected stations across SWWA. Projections are given for mid-century (2047 to 2064) and end-of-century (2082 to 2099) periods under low (B1), intermediate (A1B) and high (A2) SRES emissions scenarios. For present day and for each emissions scenario and period, downscaling from each of the five global climate models produces a different result. The range across these different results is one source of uncertainty in the downscaled results, as shown by the range in each cell.

STATION	PRESENT DAY	MID-CENTURY B1 (LOW)	MID-CENTURY A1B (MID-RANGE)	MID-CENTURY A2 (HIGH)	END OF CENTURY B1 (LOW)	END OF CENTURY A1B (MID-RANGE)	END OF CENTURY A2 (HIGH)
Dalwallinu	390–410	330–360	270–360	290–340	290–350	220–320	230–310
Perth Airport	770–800	610–690	510–720	550–680	560–730	400–630	420–610
Cape Leeuwin	990–1020	840–920	760–950	780–920	800–960	650–880	660–860
Pemberton Forestry	1160–1190	970–1060	850–1100	890–1050	910–1110	710–1000	720–970
Lake Grace	360–380	300–330	250–340	270–320	270–320	200–290	210–280
Wandering	570–600	460–510	380–520	410–500	410–530	300–460	310–440

The range in results from the different global climate models used produces considerable uncertainty (Table S3). Nevertheless projections from all 29 stations indicate a drier future for SWWA compared to the 'present day' baseline (1962 to 1999). The high emissions scenario produces the greatest projected rainfall reductions in most (four out of five) models. The scale of potential rainfall decline is evident from the average taken across all stations and simulations years: by mid-century mean annual rainfall is projected to decrease by 10 to 21%[15] under the low emissions scenario; 8 to 33% under the intermediate scenario; and 11 to 28% under the high scenario. By the end of the century the corresponding ranges are decreases of 6 to 28% (low scenario); 17 to 46% (intermediate); and 20 to 43% (high).

Limitations and knowledge gaps

The signal of rainfall decline in SWWA is very robust: modelling results including those reported by the Intergovernmental Panel on Climate Change agree that SWWA's rainfall decline will continue to the end of this century (2080 to 2099). However, as noted in Section 2.1.1, further work is required on the methods used to detect and attribute climate change, and to provide greater confidence in climate projections.

Regarding the downscaled results in this section, although they are suitable for scenario planning they are not predictions. That is, they are plausible future climate scenarios, not weather forecasts (Box 4). Confidence in statistical downscaling projections also depends on the performance of the global climate models. Much of the range in these projections is due to the differences between the five global climate models used, and the use of more global climate models would undoubtedly produce a larger range – demonstrating that the range of uncertainty is larger than that presented here. Furthermore, statistical

[15] The indicated range reflects the different global climate models used.

downscaling does not necessarily reduce projection uncertainty compared to outputs at the scale of global climate models. Confidence in statistical downscaling also assumes that present-day relationships between station-scale climate variables and large-scale global climate model variables will still hold in the future. In addition, this method is currently not designed to model changes in daily rainfall extremes; see Section 3.1.3.1 for projections using extremes-based methods.

Further reading: Section 4.1.2.2 of Technical Report; Appendix B for a full list of results.

Full statistical downscaling results available at: http://data.csiro.au/dap/

3.1.1.4 Station-scale projections of SWWA temperature

Major findings

- *Station-scale (statistically downscaled) climate projections for SWWA indicate that both maximum and minimum temperatures will warm by mid-century through to the end of the century under a high greenhouse gas emissions scenario.*

IOCI3 provided downscaled projections for daily maximum and minimum temperature under a high (SRES A2) greenhouse gas emissions scenario. Five global climate models were dynamically downscaled with the CSIRO Conformal-Cubic Atmospheric Model (CCAM) to provide changes for a stochastic weather generator.[16] Averaged across all of the 29 selected SWWA stations,[17] daily minimum temperatures are projected to increase by 1.6 to 2.2 °C by mid-century, and by a total of 3.0 to 4.1 °C by the end of the century. Maximum daily temperatures are projected to increase by 1.5 to 2.4 °C by mid-century and by a total of 2.6 to 3.5 °C by the end of the century. Most (four out of five) models suggest that maximum temperatures could warm more than minimum temperatures at both the middle and end-of-century time periods. For illustrative purposes the results for a subset of six of the 29 selected stations are given in Table S4.

Limitations and knowledge gaps

Although these results are suitable for scenario planning, they are subject to the same caveats and limitations as the downscaled rainfall results described in Section 3.1.1.3 above.

Further reading: Section 4.1.2 of Technical Report; Appendix B for a full list of results.

Full statistical downscaling results available at: http://data.csiro.au/dap/

3.1.2 SWWA EXTREME EVENTS: PROJECTIONS

IOCI3 scientists provided projections to indicate how extreme rainfall and hot spells in SWWA may be expected to change under future climate conditions.

[16] A method for producing synthetic time series of weather data with the statistical characteristics of observed or projected weather.

[17] The same selected stations as noted in Section 3.1.1.3 above; see Technical Report, Appendix A for a complete list of stations.

Table S4 Downscaled projected mean annual maximum and minimum temperatures in degrees Celsius for mid-century (2047 to 2064) and end-of-century (2082-2099) periods for six stations across SWWA. A list of these results for all 29 selected SWWA stations is available in Appendix B of the Technical Report. For 'present day' the method reproduces the observed 1962 to 1999 means. Downscaling from each of the five global climate models for each emission scenario and period produces a different result. The range across these different results is one source of uncertainty in the downscaled results, as shown by the range in the cells.

	MINIMUM TEMPERATURE			MAXIMUM TEMPERATURE		
STATION	PRESENT DAY	MID-CENTURY A2 (HIGH)	END OF CENTURY A2 (HIGH)	PRESENT DAY	MID-CENTURY A2 (HIGH)	END OF CENTURY A2 (HIGH)
Dalwallinu	12.2	14.0–14.8	15.7–16.8	26.0	27.5–28.8	28.6–30.8
Perth Airport	12.6	14.1–14.7	15.5–16.5	24.5	26.0–26.8	27.3–28.6
Cape Leeuwin	14.1	15.3–15.8	16.5–17.1	20.1	21.3–21.7	22.5–22.9
Pemberton Forestry	10.3	11.6–12.1	12.8–13.6	20.5	22.0–22.4	23.3–23.9
Lake Grace	10.4	12.0–12.7	13.5–14.6	23.1	24.4–25.7	25.4–27.5
Wandering	9.1	10.8–11.4	12.3–13.4	23.3	24.8–25.8	26.0–27.8

BOX 6 HIGH-RESOLUTION PROJECTIONS OF EXTREME RAINFALL AND TEMPERATURE FOR SWWA AND NWWA

Projecting future changes in the characteristics of extreme events is an emerging area of climate science. Thus IOCI3 work in this area focussed on developing new methods and techniques. IOCI3 scientists used model output, and a statistical approach that integrates climate model output with data. This work yielded the following projections of future extreme rainfall and temperature:

- Extreme rainfall projections in the form of maps of 100-year return levels[18] for 24-hour extreme rainfall centred on 1990, 2030 and 2070 for both SWWA and NWWA. Intensity-frequency-duration curves[19] are also available for Millstream, Port Hedland, Derby and Broome for these time periods.
- Additional extreme rainfall projections are also available for 12 locations in NWWA. These are projections of changes in the intensity of two-hour, 24-hour and 72-hour rainfall events at return levels of five and 100 years, at 2030 and 2070.
- Estimates of current and projected extreme rainfall associated with tropical cyclones over NWWA are also available. These results based on observations are provided in the form of maps showing the tropical cyclone contribution to average annual and extreme rainfall in the region. In addition, fine-scale (five-kilometre-resolution) projected changes in rainfall associated with tropical cyclones (average one-hour, 12-hour and storm-lifetime tropical cyclone rainfall) are provided in the form of a table of percentages.
- Also provided are maps of mean hot spell intensity, frequency and duration for the period 1958 to 2010, and of trends in hot spell intensity, frequency and duration over this period. In addition IOCI3 provided maps of mean hot spell thresholds, intensity, frequency and duration for the period 1981 to 2010, projections for the period 2070 to 2099, and of the difference between these two periods.[20]

Readers should carefully note the associated caveats and limitations discussed in this volume and in the Technical Report sections referred to below. The complete results for these projections are available at: http://data.csiro.au/dap/

Further reading: Sections 4.3 and 5.3 of Technical Report, and Appendices E-G for supplementary information on methods.

[18] See Box 5 of Technical Report for an explanation of return levels.

[19] See Box 6 of Technical Report for an explanation of intensity-frequency-duration curves.

[20] See Technical Report Section 4.3.2 for an explanation of the modelling methods used for these hot spell estimates.

3.1.2.1 SWWA extreme rainfall projections

Major findings

- *Projections suggest that changes in extreme rainfall will not be consistent across SWWA.*
- *Whereas decreases in the intensity of 1-in-100 year events are projected for the far south-west of Western Australia near Pemberton, increases are projected to the north near Dalwallinu and in the region east of Lake Grace.*

IOCI3 scientists produced very high-resolution climate change projections to indicate how the characteristics of extreme rainfall events, that is, their intensity, frequency and duration, might shift under climate change. Figure S9 shows projected spatial return levels[21] of annual maximum 24-hour rainfall events with a 100-year return period at a four-kilometre spatial resolution. Projections are for the 2030 and 2070 time periods under a high (SRES A2) emissions scenario.[22] A triangle bounded by Dalwallinu, Lake Grace and Pemberton defines the study region for this IOCI3 research on extreme rainfall projections.

The figure clearly illustrates how the projected change in extreme rainfall is not uniform across the study region under this high greenhouse gas emissions scenario. The results suggest a decrease in the amount of rainfall associated with a 1-in-100 year rainfall event in the far south-west of Western Australia near Pemberton, but a slight increase to the north near Dalwallinu and in the region east of Lake Grace. For example, the 100-year return level of 24-hour rainfall at Pemberton changes from 115 millimetres of rainfall under present-day conditions to 99 millimetres in 2070.

Limitations and knowledge gaps

These projections of extreme rainfall should be seen as initial estimates only, and should not be used for making impact, vulnerability and risk assessments. They were made using only one climate model; more work using an ensemble of global and regional climate model results is required to provide more robust projections of climate extremes for SWWA and NWWA. Use of higher-resolution models may also improve projections. Further work is also needed to refine the model that links the outputs from the regional climate model and the spatial model.

Projections of extremes also present additional challenges. Because these events are rare, their analysis relies on small datasets. Furthermore, scientists may seek to estimate extremes beyond relatively small observed records, for example, to estimate a 1-in-200 year event when there is only 50 years of historical data. As a consequence the uncertainty associated with these projections is large.

Further reading: Section 4.3.1.3 of Technical Report.

Full statistical downscaling results available at: http://data.csiro.au/dap/

[21] See Box 5 of Technical Report for an explanation of return levels and return periods.

[22] Projections were made using CCAM (a dynamical downscaling model; see glossary and Technical Report, Box 1) driven by the CSIRO Mk3.0 global climate model.

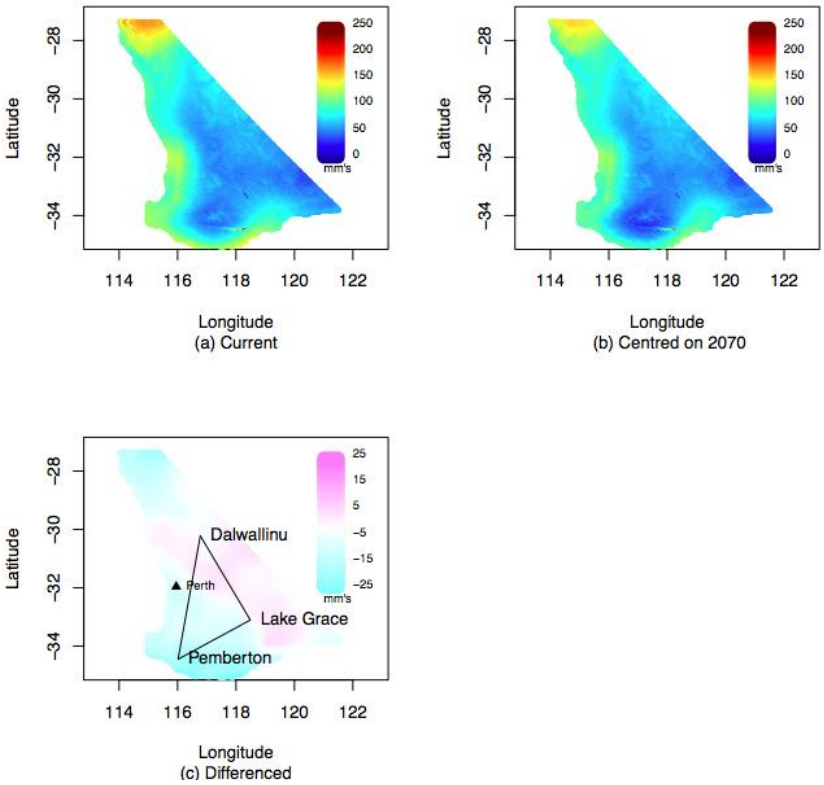

Figure S9 Extreme rainfall for a 100-year average recurrence interval for (a) the current climate, and (b) projected climate centred on the year 2070 under a high (SRES A2) emissions scenario. The bottom figure (c) shows the differences between these two periods: pale blue areas indicate regions of decrease in 100-year extreme rainfall return levels, magenta areas represent an increase. The triangular area shown in (c) is the IOCI3 study region for this project, bounded by Dalwallinu, Lake Grace and Pemberton.

3.1.2.2 Extreme temperature projections: hot spells in the South West

Major findings

- *IOCI3 projections suggest that hot spells will become more intense over all of south Western Australia by the end of the century (2070 to 2099), and that the greatest intensity increases will occur in west inland and north parts of this region.*
- *The frequency of hot spells is projected to decrease in the north-west but increase in south-west parts of south Western Australia.*
- *The duration of hot spells in central-south Western Australia is projected to increase markedly.*

IOCI3 scientists also provided projections of future hot spell characteristics under a high (SRES A2) emissions scenario. They used climate modelling[23] techniques to simulate these characteristics for the baseline (1981 to 2010) period and to produce projections for the end of the century (2070 to 2099). For this analysis, 'south Western Australia' refers to the area below the black horizontal line in Figure S6 (that is, south of 25° S).

These projections suggest that the intensity of hot spells will increase over all of SWWA by the end of the century. The greatest future intensity increases are projected for west inland and north parts of this region, with less intense increases indicated for coastal and central parts of south Western Australia. As for hot

[23] CCAM was driven by atmospheric fields from a CSIRO Mk3.0 host global climate model; see Technical Report Section 4.3.2 for details of the method used.

spell frequency, projections suggest that the number of these events could decrease in central areas of south Western Australia, but increase over south-west parts of the region by end of century. Regarding hot spell duration, projections suggest that the longer hot spells experienced in north parts of this region may occur further south in future, with marked increases in hot spell duration projected for central-south Western Australia by the end of the century.

Limitations and knowledge gaps:

As is the case with the projections of extreme rainfall in Section 3.1.2.1 above, these projections of hot spells should be seen as initial estimates only, and should not be used for making impact, vulnerability and risk assessments. Many of the same caveats and limitations apply: the use of a single climate model and the need to extrapolate beyond relatively small observed records. The methods used by this study to overcome data shortages[24] may also result in the underestimation of extremes in some cases. Additional sources of uncertainty are those inherent in climate scenarios as well as those related to the use of climate models.

Further reading: Section 4.3.2 of Technical Report; Appendix E.

Full results of projections available at: http://data.csiro.au/dap/

3.2 NWWA Climate Projections

IOCI3 provided station-scale projections of possible changes to rainfall and temperature under future climate scenarios. Results from research on high-resolution projections of changes in extreme rainfall, hot spells and tropical cyclones are also reported here.

3.2.1 STATION-SCALE PROJECTIONS OF NWWA RAINFALL

Major findings

- *Station-scale climate modelling suggests that the Kimberley and Pilbara regions will undergo a drying trend by the mid-century, continuing through to the end of this century.*
- *Projections for this drying trend are highly (but not completely) consistent across the different climate models and emissions scenarios used in this IOCI3 modelling study.*

IOCI3 scientists applied the downscaling techniques described in Section 3.1.1.3 for the first time to regions influenced by tropical climate. They downscaled from five global climate models to produce projections for daily rainfall at nine stations in the Kimberley and ten stations in the Pilbara under the low (B1), intermediate (A1B) and high (A2) SRES emissions scenarios for the middle (2047 to 2064) and the end of this century (2082 to 2099). Stations[25] were selected for the relatively high quality of their weather records.

The Kimberley: Averaged across all nine Kimberley stations, the results generally indicate a drying trend for this region by mid-century. All five global climate models agree on this future drying trend under the low and intermediate scenarios at mid-century. However, under the high emissions scenario there is less agreement; whereas some models indicate drying or little change, others indicate a slight wetting trend at mid-century.

By the end of the century this projected drying is more clear-cut. For the period 2082 to 2099, all models suggest drying across the Kimberley regardless of the emissions scenario. Nevertheless, the range of projections produced by the five different global climate models leads to considerable uncertainty in the downscaled results, so that the range of possible rainfall reductions is wide (see Table S5 results for a

[24] Due to use of data from the Australian Water Availability Project, which interpolates raw data.

[25] Detailed information on the 19 selected NWWA stations, including maps, is provided in Technical Report Appendix C.

subset of stations). For example, under the intermediate scenario, averaged across the nine Kimberley stations, mean annual rainfall reductions range from 2 to 24% by mid-century, and 6 to 29% at the end of the century.

Table S5 Range, downscaled from five global climate models, of present-day and projected annual mean rainfall (in millimetres) for three stations in the Kimberley. Values are given for mid-century (2047 to 2064) and end-of-century (2082 to 2099) time periods under low, intermediate and high emissions scenarios. Downscaling from each of the five global climate models produces a different result for each emissions scenario and period, including the present-day period. The range across these different results is one source of uncertainty in the downscaled results, as shown by the range in each cell. The results for all nine selected Kimberley stations are available in Appendix D.

STATION	PRESENT DAY	MID-CENTURY B1 (LOW)	MID-CENTURY A1B (MID-RANGE)	MID-CENTURY A2 (HIGH)	END OF CENTURY B1 (LOW)	END OF CENTURY A1B (MID-RANGE)	END OF CENTURY A2 (HIGH)
Kalumburu Mission	1260–1280	1030–1250	1070–1260	1030–1320	1010–1260	1010–1240	990–1260
Margaret River Station	530–550	390–530	400–520	380–560	380–530	370–500	340–520
Broome Airport	640–660	480–630	480–630	460–680	450–630	450–600	410–620

The Pilbara: The downscaled projections for the Pilbara also indicate a trend of drying by mid-century that will continue through to the end of the century. This drying signal for the Pilbara is very consistent across the climate models and scenarios used here. However, as with the Kimberley results, the range of projections from the five different global climate models leads to uncertainty in the downscaled results (see results for a subset of stations in Table S6). Under an intermediate emissions scenario, averaged across the ten selected Pilbara stations, projected rainfall reductions range from 1 to 24% for mid-century, and 9 to 24% for the end of the century.

Table S6 Downscaled present-day and projected annual mean rainfall (in millimetres) for three stations in the Pilbara, as per the description in Table S4 above. These results for all ten selected Pilbara stations are available in Appendix D.

STATION	PRESENT DAY	MID-CENTURY B1 (LOW)	MID-CENTURY A1B (MID-RANGE)	MID-CENTURY A2 (HIGH)	END OF CENTURY B1 (LOW)	END OF CENTURY A1B (MID-RANGE)	END OF CENTURY A2 (HIGH)
Port Hedland Airport	300–360	250–340	220–340	260–380	230–340	220–300	210–310
Learmonth Airport	240–280	210–280	190–270	220–290	200–270	190–240	180–250
Mount Vernon	300–320	250–310	230–310	250–330	240–320	230–290	220–300

Limitations and knowledge gaps

These projections may be used to inform climate change adaptation measures, including impact, vulnerability and risk assessments. However, the same caveats and limitations noted in Section 3.1.1.2 apply equally to these projections for NWWA. There is an additional source of uncertainty for NWWA given that observed rainfall records indicate a current increasing rainfall trend in the Kimberley and east Pilbara whereas the majority of downscaled projections indicate future decreases. Section 2.2.1.4 discusses possible reasons for this inconsistency, including the influence of aerosols generated from human activity. Global climate models in the analysis reported here do not incorporate the observed aerosol effect, however, the statistical downscaling methods used should account for historical aerosol effects to some extent, as these effects have influenced the predictors used.

Further reading: Section 5.1.2 of Technical Report; Appendix D for complete tables of results.

Full statistical downscaling results available at: http://data.csiro.au/dap/

3.2.2 STATION-SCALE PROJECTIONS OF NWWA TEMPERATURE

Major findings

- *Both the Kimberley and Pilbara regions are expected to undergo warming by mid-century through to the end of this century under a high greenhouse gas emissions scenario.*
- *Projections for both these regions indicate that, by the end of the century, minimum temperatures could warm more than maximum temperatures.*

Although mean annual temperatures in some parts of NWWA followed the general warming trend observed over most of the Australian continent, much of this region underwent minimal warming or even slight cooling over the period 1960 to 2011. Will these observed trends continue?

IOCI3 scientists applied the downscaling techniques described in Section 3.1.1.3 to provide station-scale estimates of future temperature change for nine Kimberley and ten Pilbara stations in NWWA under a high (SRES A2) greenhouse gas emissions scenario. The results for annual minimum and maximum temperatures suggest that, under this scenario, warming will occur in the Kimberley and Pilbara regions by mid-century, and continue to the end of the century.

The Kimberley: Averages taken across all nine Kimberley stations suggest that minimum temperatures will warm as much or more than maximum temperatures by mid-century and the end of the century for all five global climate models used. Depending on the global climate model used, statistical downscaling incorporating the CCAM changes projects maximum temperature increases ranging from 1.8 to 2.5 ˚C for mid-century, rising to a total range of increase of 3.6 to 4.6 ˚C by the end of the century (averaged across all nine Kimberley stations). For minimum temperatures, the corresponding averaged increases are 2.0 to 2.7 ˚C (mid-century), and 4.2 to 4.9 ˚C (end of century). Table S7 provides results for three Kimberley stations for illustrative purposes.

Table S7 Downscaled projected mean annual maximum and minimum temperatures in degrees Celsius for selected Kimberley stations for mid-century (2047 to 2064) and end-of-century (2082 to 2099) periods under a high emissions scenario relative to the present day (196 to 1999). For the present day the method reproduces the observed means. Downscaling from each of the five global climate models produces a different result for each emission scenario and period. The range across these different results is one source of uncertainty in the downscaled results, as shown by the range in the cells.

	MINIMUM TEMPERATURE			MAXIMUM TEMPERATURE		
STATION	PRESENT DAY	MID-CENTURY A2 (HIGH)	END OF CENTURY A2 (HIGH)	PRESENT DAY	MID-CENTURY A2 (HIGH)	END OF CENTURY A2 (HIGH)
Kalumburu Mission	21.0	23.0–23.6	25.0–25.7	34.4	36.0–37.2	37.5–38.8
Margaret River Station	20.5	22.6–23.4	24.9–25.8	34.6	36.6–37.5	38.5–39.7
Broome Airport	21.2	22.8–23.2	24.5–25.2	32.3	33.6–33.9	35.2–35.8

The Pilbara: All five global climate models, when downscaled, indicate that minimum temperatures will increase more than maximum temperatures by the end of the century. However, the picture at mid-century is quite mixed. Averaged across all ten Pilbara stations, maximum temperatures are expected to increase by 2.1 to 3.2 ˚C by mid-century and by a total range of 3.8 to 4.6 ˚C by the end of the century. For minimum temperatures the corresponding averaged increases are 1.9 to 2.4 ˚C (mid-century) and 4.1 to 4.6 ˚C (end of the century). Table S8 provides results for three Pilbara stations for illustrative purposes.

Table S8 Downscaled projected mean annual maximum and minimum temperatures in degrees Celsius for selected Pilbara stations for mid-century (2047 to 2064) and end-of-century (2082 to 2099) periods under a high emissions scenario relative to the present day (1962 to 1999), as per the description in Table S7 above.

	MINIMUM TEMPERATURE			MAXIMUM TEMPERATURE		
STATION	PRESENT DAY	MID-CENTURY A2 (HIGH)	END OF CENTURY A2 (HIGH)	PRESENT DAY	MID-CENTURY A2 (HIGH)	END OF CENTURY A2 (HIGH)
Port Hedland Airport	19.7	21.7–22.5	24.3–24.8	33.3	35.2–36.2	37.3–38.4
Learmonth Airport	17.7	19.0–19.5	20.4–21.3	31.6	32.9–33.3	34.2–35.0
Mount Vernon	17.3	19.4–20.2	22.1–22.7	32.1	34.1–35.3	36.0–37.6

Further reading: Section 5.2 of Technical Report. Appendix D for complete table of results.

Full statistical downscaling results available at: http://data.csiro.au/dap/

Limitations and knowledge gaps

The same caveats noted in Section 3.1.1.3 also apply here. Whilst these IOCI3 temperature projections are suitable for impact, vulnerability and risk assessments, they should be viewed as plausible future climates, not as predictions or weather forecasts.

3.2.3 NWWA EXTREME EVENTS: PROJECTIONS

IOCI3 scientists provided projections of possible changes to extreme rainfall events in NWWA, and to the intensity, frequency and duration of hot spells. They also provided projections of possible future changes to the characteristics of tropical cyclones in the Western Australian region, including their intensity, frequency and associated rainfall.

3.2.3.1 NWWA extreme rainfall projections

Major findings

- *Projections suggest that by 2070 extreme rainfall intensity will generally decrease in the Pilbara but increase in the Kimberley region around Broome, under a high (SRES A2) greenhouse gas emissions scenario.*

IOCI3 scientists used statistical modelling techniques[26] to provide very high-resolution extreme rainfall projections for NWWA for periods centred on 2030 and 2070 under a high (SRES A2) greenhouse gas emissions scenario. The results suggest that changes to extreme rainfall will not be even across NWWA. Roughly speaking, these projections indicate that the intensity of extreme rainfall will decrease in the Pilbara but increase in the Kimberley region to the north-east of Broome.

Figure S10 illustrates the estimated magnitude of extreme 24-hour (duration) rainfall events with a 100-year average recurrence interval under the current climate, and projections for these events under the 2070 climate. The figure also indicates how rainfall intensity may increase, by showing the difference in the projected rainfall intensities between these two time periods. For example, whilst extreme rainfall is projected to decrease at Port Hedland, it is projected to increase in Derby but to undergo little change at Broome and Millstream.

Limitations and knowledge gaps

For the reasons already detailed in Section 3.1.3.1 above, these projections of extreme rainfall should be seen as initial estimates only, and should not be used for making impact, vulnerability and risk assessments.

Further reading: Section 5.3.1 of Technical Report.

Full extreme rainfall projections available at: http://data.csiro.au/dap/

[26] Using outputs from the CSIRO CCAM; see Technical Report Section 5.3.1 for detailed description of methods used.

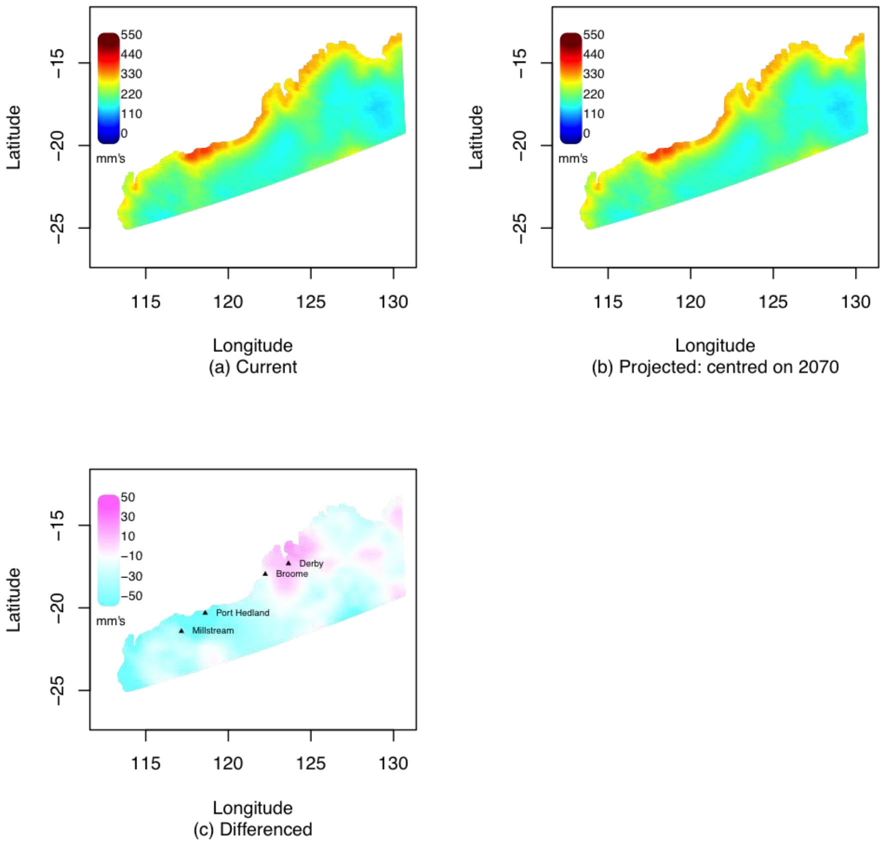

Figure S10 Extreme rainfall with a 100-year average recurrence interval under (a) the current climate, (b) projected climate at 2070 under a high (SRES A2) greenhouse gas emissions scenario, and (c) the difference between these two periods. Panels (a) and (b) show 24-hour return levels in millimetres; yellow to red areas indicate more intense extreme 24-hour rainfall, green to blue areas less intense. In (c) the magenta areas indicate areas where projected extreme 24-hour rainfall amounts are expected to increase by 2070; pale blue indicates areas of projected decrease.

3.2.3.2 Extreme temperature projections for the North West: hot spells

Major findings

- *Projections under a high (SRES A2) greenhouse gas emissions scenario suggest that hot spell intensity will generally continue to increase in north Western Australia, but that hot spell frequency will change little in most locations. These projections also suggest that in most inland areas hot spell duration will increase.*

IOCI3 scientists also provided hot spell projections for north Western Australia for the end of the century (2070 to 2099) under a high (SRES A2) emissions scenario. For this analysis, 'north Western Australia' refers to the area above the black horizontal line shown in Figure S6 (that is, north of 25° S).

The results indicate that these events could become more intense (hotter) in this region. In some Pilbara coastal areas, particularly around Karratha, large increases in hot spell intensity are projected. Somewhat lesser increases are projected for much of the Kimberley. In fact in some Kimberley areas, especially coastal locales, the intensity of hot spells is projected to decrease.

Modelling suggests that the frequency of future hot spells in north Western Australia may not change much from that of present. Most inland areas of this region are projected to undergo a small future increase in hot spell frequency by the end of the century, but decreases of roughly similar magnitude are projected along the Pilbara coast and south-east parts of north Western Australia.

The duration of hot spells is projected to decrease in some Pilbara coastal areas and the north Kimberley coast, but in Karratha and to the south of Broome hot spell duration is expected to increase. For most of inland north Western Australia, increases in hot spell duration are projected for the end of the century.

Limitation and knowledge gaps

The caveats and limitations discussed in relation to south Western Australia hot spells in Section 3.1.3.2 apply equally to these projections for north Western Australia. These projections of extremes should therefore be seen as initial estimates only and should not be used for making impact, vulnerability and risk assessments.

Further reading: Section 5.3.2 of Technical Report; Appendix F and G.

Full hot spell projections available at: http://data.csiro.au/dap/

3.2.3.3 Tropical cyclone projections

Major findings

- *Projections for the period 2051 to 2099 suggest that, compared to the present day, tropical cyclone frequency could decrease by half, and the duration of a given tropical cyclone could decrease by 0.6 days, on average, in the Indian Ocean region where they affect NWWA.*
- *These projections also suggest a 100-kilometre southward shift in the region of tropical cyclone formation and decay.*
- *They furthermore suggest that tropical cyclones could increase in size, and that the most intense tropical cyclones in this region could become still more powerful and destructive.*
- *An increase in the intensity of rainfall associated with tropical cyclones is also projected for this region.*

IOCI3 scientists sought to investigate how climate change could influence tropical cyclones in the region of the Indian Ocean where they affect Western Australia. Modelling results[27] based on a high (SRES A2) emissions scenario indicate that for the 2051 to 2099 period, relative to the 1971 to 2000 baseline, tropical cyclone numbers would decrease by approximately 50% in the NWWA region, on average. These modelling results also project a small decrease in the duration of a given tropical cyclone, by an average 0.6 days. In addition, the results suggest that there could be a 100-kilometre southward shift over this period in the regions of tropical cyclone formation and decay.

Additional studies using fine-scale modelling[28] (to a five-kilometre resolution) indicate that there could be a tendency towards larger, more intense tropical cyclones in the latter half of the 21st century (comparing 2051 to 2090 with a 1961 to 2000 baseline period).

However, wind speed alone does not fully explain a tropical cyclone's potential to cause damage, particularly via wave or storm surge. Thus IOCI3 scientists used an additional measure called integrated kinetic energy. This contains information on both strong winds and tropical cyclone size and essentially measures the amount of energy contained in the air rotating around the storm. They found that integrated kinetic energy also indicates a distinct shift toward more destructive tropical cyclones in the late 21st century. Consistent with these results, additional projections of separate measures of tropical cyclone size, such as the radius of maximum winds and radius to gale-force winds, also indicate an increase in the size of late 20th century tropical cyclones. These results suggest storm size will increase for the proportion of tropical cyclones with a maximum wind speed greater than 40 metres per second, that is, approximately Category 3–5 cyclones.

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[27] Using the CSIRO CCAM nested in global climate models, at a spatial resolution of 65 kilometres; see Technical Report Section 5.3.3.2 for modelling methods used.

[28] Performed with downscaling using the Regional Atmospheric Modelling System and based upon the SRES A2 emissions scenario.

IOCI3 scientists also provided fine-scale projections that suggest that large increases in rainfall intensity could occur in the area surrounding a given tropical cyclone. Increases of 23% are projected for average rainfall within 200 kilometres of the storm centre, and of 33% for rainfall within 300 kilometres of the storm centre, occurring during the 12 hours for which the tropical cyclones are most intense. Maximum one-hour rainfall intensity is also projected to increase (Table S9).

S9 Projected changes in tropical cyclone average and maximum rainfall intensity. Percent change for the period 2051 to 2090 relative to 1961 to 2000 baseline, under a high (SRES A2) emissions scenario

DISTANCE FROM STORM CENTRE (KM)	CHANGE IN AVERAGE RAINFALL INTENSITY (%)	CHANGE IN MAXIMUM RAINFALL INTENSITY (%)
100	-9	28
200	23	30
300	33	35
400	30	44

Limitations and knowledge gaps

These tropical cyclone projections were produced by downscaling outputs from a single climate model (CCAM). It should be cautioned that this model simulates fewer tropical cyclones than were actually recorded in observed data. To provide more robust projections, this study must be replicated using additional climate models. As noted above, this modelling study projected an increase in the intensity of the most severe tropical cyclones; this is consistent with the results of international modelling studies focusing on the North Atlantic.

Further reading: Section 5.3.3.2 of Technical Report.

Full tropical cyclone rainfall projections available at: http://data.csiro.au/dap/

3.3 Climate Forecasts for Western Australia

This section reports on IOCI3 work on the first systematic attempt to estimate the upper limits for seasonal forecasting skill for rainfall and temperature in Western Australia. It also describes work on a new statistical model to forecast tropical cyclone activity along the Australian coastline. (See Box 4 for an explanation of the difference between forecasts and projections).

3.3.1 THE LIMITS OF SEASONAL FORECASTS: HOW PREDICTABLE ARE TEMPERATURE AND RAINFALL IN WESTERN AUSTRALIA?

Major findings

- *For maximum and minimum temperature, large areas of Western Australia generally have very high potential predictability – except during autumn and early winter for maximum temperature, and late autumn for minimum temperature.*
- *For rainfall, lower potential predictability suggests more limited scope for traditional methods to predict winter rainfall across SWWA.*
  - *In SWWA, 20 to 30% potential predictability for early winter rainfall indicates some opportunity for skilful long-range seasonal prediction. However, for the rest of the year this region has very low potential predictability for rainfall.*
  - *In contrast, in north Western Australia potential predictability for rainfall is as high as 70% during winter and spring.*

Many Western Australian industries and community services are greatly affected by the climate, and predictions of climate conditions for seasons ahead could help them manage year-to-year variations. In the past, however, seasonal predictions of winter rainfall across SWWA have met with limited success. To help address this challenge, IOCI3 scientists made the first systematic attempt to estimate the upper level of skill possible for such seasonal forecasts. This work identified the regions and seasons for which skilful forecasts might be expected for maximum and minimum temperature, and for rainfall. Here the potential predictability during a given season and region is expressed as a percentage of the total year-to-year climate variability. Potential predictability values of 20 to 30% indicate that reasonably skilful prediction is likely.

Temperature: For both minimum and maximum temperature, potential predictability varies throughout the calendar year and from location to location (see Figures 6.1 and 6.2 in Technical Report). The spatial pattern for potential predictability of maximum temperature is very different from that for minimum temperature. Nonetheless, large areas of the state generally have very high potential predictability for both these temperature variables.

For maximum temperature, potential predictability is generally high (at least 50%) north of 20° S for most of the year, except spring. State-wide, potential predictability of maximum temperatures is lowest during spring and early summer. In SWWA, predictability is generally greater than 30% and can exceed 60% in all seasons except summer. Predictability for minimum temperature is also generally high in SWWA, greater than 30% in all seasons and more than 60% in some. Potential predictability is generally high north of 20° S, exceeding 70% in some regions. The lowest potential predictability tends to occur over a large area south of 25° S during late summer to early autumn and winter.

Rainfall: The picture for rainfall is quite different (see Figure S11). From late spring through to mid-autumn, potential predictability of rainfall is very low north of 20° S. South of 20° S during this period it ranges from 20 to 40% over large areas of the state, especially during summer. However, over north Western Australia levels of predictability as high as 70% are possible during early to late autumn, early winter and spring.

Potential predictability is also substantial during spring over central Western Australia including near the coast. Over SWWA, potential predictability during late autumn and early winter ranges from 20 to 30%. This indicates some potential for skilful long-range seasonal prediction during these seasons. For the rest of the year potential predictability for rainfall in SWWA is very low.

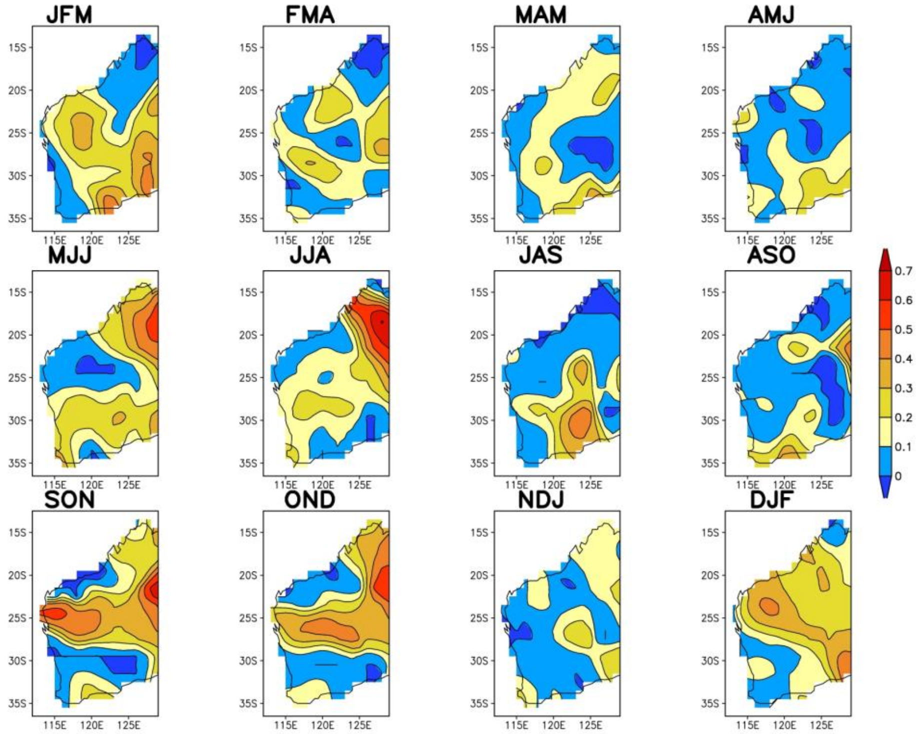

Figure S11 Potential predictability (%) of Western Australia mean seasonal rainfall. Though much less predictable than surface temperature, rainfall also exhibits a distinct annual cycle in its pattern of potential predictability.

Further reading: Section 6.1 of Technical Report.

3.3.2 TROPICAL CYCLONE FORECASTS FOR WESTERN AUSTRALIA

IOCI3 scientists collaborated with the Centre for Australian Weather and Climate Research and MeteoFrance to develop a forecast model for tropical cyclone activity along the coastline of Western Australia. This model provides an online real-time forecast system for tropical cyclone activity for one week, two weeks and three weeks ahead. The model builds on one developed previously, by adding new predictors which represent the influence of the El Niño-Southern Oscillation and Indian Ocean Dipole amongst other improvements. (The Indian Ocean Dipole is a coupled ocean-atmosphere phenomenon in the equatorial Indian Ocean that affects the climate of Australia. See the glossary of the Technical Report for further details.) The new scheme presents the forecast probabilities as maps based on forecasts at grid-points located 7.5 degrees latitude and 10 degrees longitude apart across the South Indian and South Pacific Oceans. In terms of forecast skill, the statistical model developed for IOCI3 represents the current 'state of the science' for a two-week tropical cyclone forecast.

Further reading: Section 6.2 of Technical Report.

Forecasts can be viewed on the MeteoFrance website at: www.meteo.nc/espro/previcycl/cyclA.ph

4 Application of IOCI3 Research

Information from IOCI's independent and objective research permits policymakers to implement sound and rational regional policies in response to climatic changes. IOCI has informed policy in areas related to water, fisheries, agriculture, health and emergency services, and also informs decision making in the mining and petroleum sectors.

In particular, IOCI research has influenced crucial decisions to secure alternative water sources for Perth in response to SWWA's drying trend. IOCI1 and 2 showed that the drying was not temporary or cyclical – hastening and strengthening the case for a Perth desalination plant. IOCI research also informed the decision by the Government of Western Australian in July 2011 to approve a $450 million expansion of SWWA's second desalination plant to meet the region's urgent need for a new water source. The Department of Water also uses IOCI data extensively when de-rating[29] water sources based upon rainfall projections for SWWA. More recently, the Department of Water has used IOCI data to inform its recommendations on aspects of forestry-related to catchment management (that is, how dense forest cover should be on lands rehabilitated after mining activities).

IOCI has assisted the Department of Agriculture and Food to understand, under future climate scenarios, which land uses would best suit different parts of Western Australia. The Department passes this advice onto farmers to inform their investment decisions. Information from IOCI has also indicated that some areas in SWWA will, in future, no longer be too wet for crops. Knowing that these areas will be just dry enough in future has been a factor behind the Department of Agriculture and Food's research on crops that can be sustained in relatively wet areas.

The Department of Mines and Petroleum uses IOCI research to inform mine safety and environmental regulation. This Department has been involved with the IOCI since its first stage. However, IOCI3 work in NWWA, where major mining and energy infrastructure is located, is expected to provide information with particular relevance to this sector. For example, local rainfall information helps determine the best location for mine tailings dams, by helping to gauge whether they could be breached (and thereby release pollutants). Rainfall information from IOCI can indicate whether mines would have sufficient drainage, and whether infrastructure for power, water, gas and transport (roads, rail and ports) may withstand likely weather scenarios.

The Department of Health needs information on how future temperature and rainfall changes may influence public health through the rise of new disease vectors (for example, Ross River virus); or by causing bushfires or other emergencies to become more frequent. Along with the Fire and Emergency Services Authority**,** this Department relies on IOCI climate scenarios to allow it to develop appropriate strategies and policies for the future. For example, baseline climate information from the IOCI underpinned the development of the Department's 2007 publication, Health Impacts from Climate Change.

IOCI3 scientists have also applied their research and methods to address problems related to climate risk and climate change adaptation (Box 4), including climatologies of fire danger and heat stress. Another example (Box 7) is the application of the self-organising map method to investigate the possible association between certain weather systems and low returns of western rocklobster larvae (puerulus).

Further reading: Section 7 of Technical Report.

[29] Downgrading expected long-term average inflow.

BOX 7 APPLYING IOCI3 RESEARCH: A CLIMATE CONNECTION FOR THE PUERULUS PROBLEM?

IOCI3 scientists applied the methods they used to investigate SWWA's changing weather systems to another question: the possible climate-related causes of low returns of puerulus, the larvae of western rocklobsters. Low puerulus return rates can lead to low recruitment of rocklobsters for this economically valuable fishery, an important fisheries management issue in Western Australia.

Collaboration with scientists from the Western Australian Marine Science Institution and the Western Australia Department of Fisheries led IOCI3 scientists to focus their inquiry on the July to December half-year. Using a self-organising map,[30] they produced 35 weather maps of the continuum of synoptic types over the 1948 to 2010 period. The July to December weather systems observed ranged widely in nature, from deep low-pressure systems to those with bands of very high pressure. IOCI3 scientists compared these weather types with data on puerulus settlement.

They found that low puerulus settlement correlated significantly with a weather type characterised by strong offshore winds, conditions thought to make the return of pueruli more difficult. However, this association is not a simple one, and likely depends on a host of other oceanic and population factors. Nonetheless this IOCI3 research contributed to continuing efforts to understand the causes and effects of low puerulus returns – efforts with potential relevance for management decisions.

[30] See Technical Report Section 4.1.1 for further detail on these methods.