Severe Weather in a Changing Climate

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FOREWORD

Climate change is already well underway and is considered by many to be the greatest risk currently facing humanity. Every year we are confronted globally with extreme weather events, that become natural disasters. Our communities in Australia are exposed to just about every hazard this world can throw at them, from earthquakes to storms and cyclones, to bushfires and devastating floods.

We cannot prevent these events happening, but we know more can be done to better prepare communities and make them more resilient and stronger.

Protecting communities requires greater investment in resilience and mitigation planning – be it from governments, businesses, community organisations or individuals – which will reduce the physical, economic and social recovery costs that follow a disaster.

This report reviews and interprets the latest climate science to understand how climate change is impacting the severity and frequency of weather events like tropical cyclones, hailstorms and rainfall, and what is likely to happen in the future. The report also examines the changing physical risks from severe weather patterns, considering past, present and future climates.

Climate change will require broadscale collaboration and co-ordination across all sectors of the community. Climate change is too big for one organisation to solve and it is our hope this report will provide a foundation to drive more conversation, so the necessary change can happen.

CONTENTS

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1. EXECUTIVE SUMMARY

This NCAR and IAG report examines current and future climate change impacts on the Australian climate and weather extremes that produce significant property, personal and economic damage and hardship.

The level of scientific knowledge and available tools has now reached the stage where it is possible to make confident assessments on the impacts of climate change at larger scales and longer time frames, with objective assessment of the associated levels of confidence.

But many personal, government and business decisions require information on climate and weather extremes at more local scales, such as states, cities and towns.

This assessment therefore incorporates a review of the extensive related literature, detailed in Table 1, together with expert judgement on potential local impacts. The expert assessments on local impacts are indicative rather than absolute, and are intended to provide a basis for current planning and for further discussion and assessment, leading to more refined and accurate future assessments.

Key assessments are:

1. The frequency of named tropical cyclones in the Australian region has declined in recent decades; the detail of how this will project into the future is unknown, although globally there is expected to be a further slight reduction in total numbers. However, the frequency of tropical cyclones making landfall throughout the western South Pacific region has increased. Over the past 30 years, the proportion of the most destructive tropical cyclones has increased at the expense of weaker systems, and this change is expected to continue.

   There has already been a southward shift of the regions where tropical cyclones reach peak intensity and this is expected to continue. Tropical cyclone risks are therefore expected to increase most rapidly in the south-east Queensland / north-east NSW regions, followed by the coastal districts south of Shark Bay in Western Australia.

   Marginal decreases in risk for wind impacts may occur in some other regions. Planning for inland penetration of tropical cyclones should be based on substantial increases in both rainfall rate and affected areas. Winds are also likely to decay more slowly, so increased wind-driven rainfall ingress should be expected both at the coast and inland. More intense storms combined with rising sea levels point to increasing storm surge impacts, and these may be very substantial in some regions.

2. Intense short duration rainfall is expected to increase almost everywhere in Australia, resulting in more frequent flooding in urban areas and in small river catchments. Storm rainfall totals from both east coast lows and tropical systems are also expected to increase, leading to increasing flood risk in the larger river catchments. More work is required to fully understand and confidently assess these changes.

3. Areas at risk of large (2.0-4.9cm in diameter) and giant (>5.0cm in diameter) hail should progressively shift southwards, with the largest increase in risk likely to be in the region inland from the Hunter River south through the central and southern New South Wales highlands and central to eastern Victoria. Fewer increases are assessed to affect the south-west of Western Australia while severe hail risk is expected to decrease in Queensland.

1. EXECUTIVE SUMMARY

4. The multi-day impacts of east coast lows on the south-eastern seaboard of Australia are expected to increase because of wind-driven rainfall ingress, flash and riverine flooding. This effect will be compounded by rising impacts from storm surge, waves, and coastal erosion. Summer and autumn east coast low activity is expected to increase, while there will be a decrease in winter-spring systems. There is limited understanding of the rare extreme east coast lows that drive the majority of the impacts over land.

5. Bushfire risk, as measured by the trends in fire danger indices, is likely to increase in almost all locations nationally, leading to more frequent and extreme events, and longer fire seasons. The rate of increase varies by location and will depend on weather system changes and site-specific factors at regional scales.

6. Sea level rise is expected to accelerate around the Australian coastline but at differing rates. It is notable that past assessments of sea level rise are lower than those that recent observations show. Sea level rise will contribute substantially to escalating impacts from storm surge and the impacts on coastal natural systems, buildings and infrastructure. The greenhouse gases that are already present will cause sea level rises to continue well into the next century even if there are significant emission reductions globally through the coming decade.

Table 1 *Summary of the past and future impacts of climate change on metrics of key extreme events in Australia under three future temperature scenarios (changes from pre-industrial period 1850-1900). Present climate represents the recent two decades. This is an expert assessment and includes an estimate of the confidence in the changes from the benchmark values.*

	Metric	Benchmark	Climate Change Impact (confidence level)			
			Present Climate	+1.5^{o}C	+2^{o}C	>+2^{o}C
Tropical Cyclones	Peak wind speeds	Variable between 1973-2007	~5% increase (High)	<10% increase (Med-High)	10%-20% increase (Med-High)	5-10% higher for each 1ºC (Med-High)
	Latitude of maximum intensity	As above	Poleward shift ~1.6° since 1982 (High)	Further poleward shift (Medium)	Further poleward shift (Medium)	Possible further poleward shift (Low)
	Tropical cyclone lifetime	As above	No info	No info	Possible increase of up to 24 hours (Low)	Possible increase over 24 hours (Low)
	Proportion of Australian CAT 4 and 5	As above	~100% between 1975-2010 (High)	Small increase from 2010-2015 (Medium)	Further small increase from 2010-2015 (Low)	Minimal further increase (Low)
	Rain rate within 100km of tropical cyclone centre	As above	Small increase (Low)	~10% increase (Medium)	Further increase (Medium)	~20% increase for +3ºC (Medium)
	Frequency	As above	Small decrease (Medium)	~15% decrease (Medium)	Further decrease (Medium)	~30% decrease for +3ºC (Medium)
	Area of gale force winds	1973-2007	No info	~50% (Low)	~100% (Low)	Further increase (Low)
	Storm surge frequency	Since 1900	Increase (Medium)	Further increase (Medium)	Further increase (Medium)	Potential substantial increase (Med-Low)

	Metric	Benchmark	Climate Change Impact (confidence level)			
			Present Climate	+1.5^{o}C	+2^{o}C	>+2^{o}C
Sea Level Rise	Sea level rise	Since 1880	~24cm - close to global average (High)	~30cm* (Med-High)	~50cm* (Med-High)	More than 1m (Medium)
East Coast Lows	Frequency	Since 1860	Increased but includes a large natural variability component (Medium)	No info	No info	Increasing frequency of intense east coast low impacts (Low)
Extreme Rainfall	Annual maximum 1-day rainfall intensity	1986-2005	Regionally variable generally slightly upward	Regionally variable ~10% (Med-High)	Regionally variable 13-15% (Med-High)	Potentially 40% increase for +4°C (Medium)
	20-year return level of 1-day rainfall	1986-2005	Variable, generally slightly upward (Med-High)	Variable, generally slightly upward (Med-High)	Between 15-20% dependent on the region (Med-High)	Between 10-60% dependent on the region (Medium)
	Footprint of extreme convective rain system	2001-2013	No info	No info	No info	30-80% increase (USA example) (Med-Low)
Large Hail	Frequency of hail >=2.5 cm diameter	1979-2015	Increasing trend in south-east Australia (Med-Low)	No info	No info	Potential increase in southern regions, decreases elsewhere (Low)
Bushfire	McArthur Forest Fire Danger Index	1973-2010	Increasing in all Australian regions especially in the south-east (High)	15-65% increase in number of extreme fire danger days (FFDI>50) for +1°C (Medium)	Further increases typically <10% (Medium)	Increases >30% in southern and eastern Australia (High) Further increases or no changes in other regions (Medium) 100-300% increase in number of extreme fire danger days (FFDI>50) for +3°C (Medium)

** Estimates reflecting Intergovernmental Panel on Climate Change Fifth Assessment Report findings which could quite possibly be low end estimates and therefore underestimate the impact.*

2. INTRODUCTION

Climate change is happening so it is critical that we achieve a common understanding of the increasing risk of the impacts of severe weather on the expanding built environment.

Global changes must be interpreted at a regional and local level to allow for informed discussion on the scale of the impact so mitigation strategies can be better focused.

This report summarises the current state of knowledge on climate change impacts, severe weather and climate extremes that are relevant to Australian property risk. It is based on current knowledge documented in peer-reviewed literature highlighting the significant advances that have been made since the Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC 2013).

This report includes evidence from:

- observed changes to the historical climate (typically from pre-industrial or the mid-19th-century levels),
- modelling experiments of past and future climate change, and
- theoretical assessments based on fundamental understanding of the physics associated with the phenomenon.

Changes that are broadly in line with the 1.5°C and 2°C warming targets from the Paris Agreement are explicitly addressed where possible. Potential changes for scenarios that exceed these goals (>+2°C) are also discussed.

Section 3 of this report (State of the Climate) provides a brief introduction to the state of the climate system and includes general definitions and concepts that are important for understanding the report.

Section 4 (Changes to extremes for different temperatures) contains the main results about changes in property-risk-relevant extreme events in Australia. Because changes to specific weather extremes (eg tropical cyclones (TCs)) are likely to be distributed unevenly across Australia, regional interpretations are included to help improve understanding of potential community impacts.

As the regional interpretation is an input for specific scenarios for insurance loss modelling, the >+2°C climate change scenario is nominally chosen to represent +3°C.

Expert judgement has been used in cases where there are conflicting research findings or a lack of data for Australia, particularly in the regional level interpretation.

3. STATE OF THE CLIMATE

3.1 Natural Climate Variability and Forced Climate Change

Natural climate variability is an intrinsic characteristic of the climate system and is related to internal and external natural processes across the full range of spatial and temporal time scales.

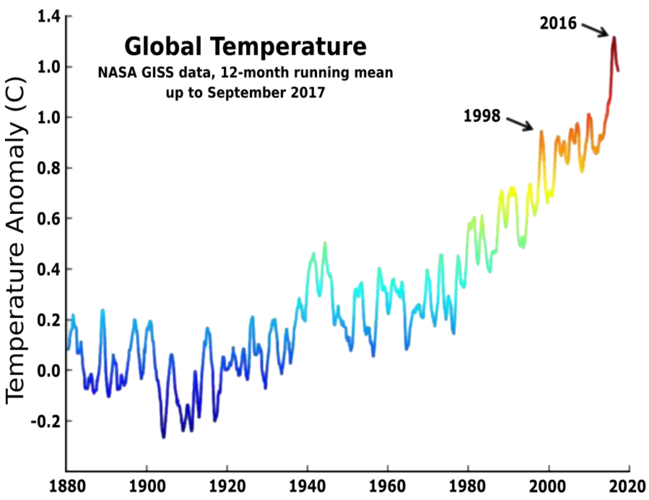
The internal processes are caused by heat exchanges between the ocean and the atmosphere (eg, El Niño Southern Oscillation, Interdecadal Pacific Oscillation) or by chaotic behaviours that are inherent in the climate system.

Natural external processes that cause variabilities include changes in the earth's orbit around the sun, changes in solar activity, or volcanic activity.

Anthropogenic forced climate change is caused by human effects on the climate system, including greenhouse gas emissions, emissions of aerosols and land use changes. These changes would not have occurred without human activities and are superimposed on top of natural climate variability.

The warming that has been recorded since the 1950s cannot be explained by considering natural processes alone and human activities are *extremely likely*[1] to have been the dominant cause of the warming observed since the mid-20th century (IPCC 2013).

3.2 State of Climate Assessment



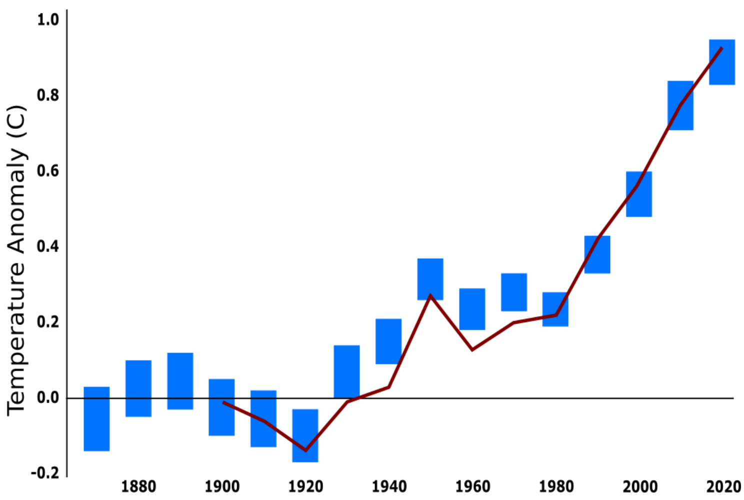


Fig. 1 *Global observed mean temperature increase relative to pre-industrial conditions (modified from NASA 2017). The two extremely strong El Niño years of 1998 and 2016 are highlighted (left). Decadal minimum and maximum anomalies relative to pre-industrial conditions (bars), and the decadal median anomalies (line) (modified from EEA 2018) are shown (right).*

Since the pre-industrial period (1850-1900), the average global mean temperature (averaged per decade ending in 2017) has risen by 0.94°C (Fig. 1, right) due to increasing greenhouse gas emissions and deforestation (NOAA 2017). The largest part of the warming has occurred since 1970.

[1] IPCC definition indicating a 95-100% probability

3. STATE OF THE CLIMATE

The effect of climate internal variability (see Section 3.1) is also evident in Fig. 1, especially in years with strong El Niño events (eg 1998 and 2016: Fig. 1, left) which are associated with above average warm temperatures. Global warming peaked in 2016 with temperatures ~1.3°C warmer than the average temperatures in the pre-industrial area. The last four years (2015-2018) have been the warmest on record, and 2019 is on track to make this five (NOAA 2019). Australian temperature has increased by just over 1.0°C since 1910, at a similar rate as the global average (Bureau of Meteorology and CSIRO 2018).

Mean temperatures in almost all land areas, including Australia, are expected to increase at slightly higher rates than the global average (IPCC 2013, Seneviratne et al. 2016) whereas high-latitude regions will experience much higher temperature increases.

In the Paris Agreement of December 2015, the international community agreed on:

"Holding the increase in the global average temperature to well below 2℃ above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5℃ above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change."

No agreement has been reached as to when global warming might reach the 1.5/2°C (above pre-industrial levels) Paris targets, although there is consensus that it is *extremely unlikely*[2] to remain below the targets. Global mean temperatures may reach or exceed 1.3ºC in 2019 (NOAA 2019). Raftery et al. (2017) stated that there is a 90% likelihood that temperatures will rise between 2°C and 4.9°C by 2100. They estimated that there is a 5% chance that global temperatures will remain below 2°C, and only a 1% chance to remain below 1.5°C. King and Henley (2018) estimated that under current emissions, global warming will reach 1.5°C around 2024 and 2°C around 2036. In a special report[3], IPCC said there is a very high risk that global temperature will exceed the lowest threshold agreed in the Paris Agreement climate targets, and that overshooting may happen by the 2040s (IPCC 2018).

Limiting global temperature to the Paris Agreement target of 1.5°C (above pre-industrial levels) can only be achieved under ideal conditions with:

- rapid and large-scale global political commitments to decarbonisation,
- strongly accelerated growth in low carbon technology, and
- the development of efficient and large-scale carbon capturing technology by mid-century (Sanderson et al. 2017).

Fig. 2 shows the rapid decrease in carbon emissions that must occur in the near future to limit global warming to 1.5°C or 2°C. There is little evidence that major emitters are willing to adopt measures that will achieve this level of decrease.

[2] IPCC definition indicating a of 0-5% probability

[3] In a note released in January 2018, the IPCC restates that draft texts of the report can change substantially and do not necessarily represent the IPCC's final assessment of the state of knowledge.

3. STATE OF THE CLIMATE

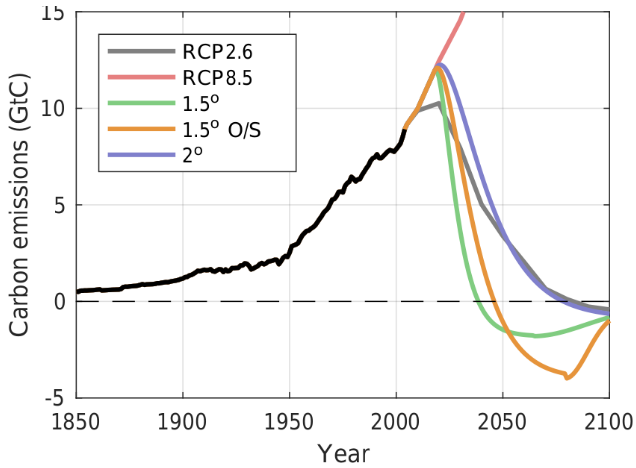


Fig. 2 *Total carbon emissions trajectory (fossil fuel, cement, and land use) for scenarios leading to 1.5°C warming (green), 2°C warming (purple), and the representative concentration pathways (RCP2.6) and RCP8.5 scenarios (grey and pink lines). The black line shows observations from 1850 to 2005. The orange line indicates that temperature overshoots 1.5°C but then drops back by the end of the century (source Sanderson et al. 2017).*

A 2°C target is therefore unlikely to be achieved, and will therefore significantly increase the risk for catastrophic events, even compared to 1.5°C warming. For example, King et al. (2017) investigated the difference between a 1.5°C and 2°C global warming on Australian extremes. They showed that events such as the record warm summer of 2012-2013 and associated bleaching of the Great Barrier Reef in 2016 would be 87% more likely in a 2°C world compared to 60% for 1.5°C (Fig. 3). Impacts on precipitation extremes were less clear in their study.

Australian extremes under global warming

EXTREME EVENT	ASSOCIATED IMPACTS	Chance of event per year: NATURAL WORLD	CURRENT WORLD	1.5°C WORLD	2°C WORLD
Angry summer 2012/13	Severe Heatwaves, Power Blackouts, Bushfires	3%	44%	57%	77%
Coral Sea Heat early 2016	Worst coral bleaching event on record	0%	31%	64%	87%
Queensland Rain December 2010	Widespread floods, Dozens of deaths	1%	2%	1%	1%
Australian Drought 2006 – Low rainfall	Water restrictions, Reduced crop yields	1%	2%	3%	3%
Australian Drought 2006 – High temperatures	Water restrictions, Reduced crop yields	1%	35%	52%	74%

Fig. 3 *Changes in the likelihood of Australian extreme events in the current, 1.5°C and 2°C warmer world compared to a natural (pre-industrial) world (modified from King et al. 2017).*

Warming higher than 2°C rapidly increases the risk for global-scale disruptive events and for unforeseeable threshold changes in the climate system. These so-called tipping-point events are associated with positive feedbacks that cause accelerated and perhaps irreversible changes, regardless of human activities.

One example is the collapse of the Greenland Ice Sheet. In recent years, this ice sheet has experienced rapid increases in summer melt, reaching all-time records in June 2019. If the melting continues to a full melt of the ice sheet, the resulting global average sea level rise would be ~7.4 m. Paleoclimatic records show that Greenland was deglaciated for extended periods during the Pleistocene epoch (2.6 million years ago to 11,700 years ago; Schaefer et al. 2016) but our understanding of important processes that contribute to the melting do not (so far) allow an estimate of threshold temperatures that would result in a collapse of the ice sheet (van den Broeke et al. 2017).

3.3 Extreme Events Under Climate Change

The frequency and intensity of weather and climate extremes will change at a much higher amplitude than more common events. This is because small changes in the mean climate lead to dramatic changes in the extremes.

An example of this is shown in Fig. 4 for Northern Hemisphere maximum summer temperature anomalies within a baseline period (1951-1980) and a recent climate period (2004-2014).

3. STATE OF THE CLIMATE

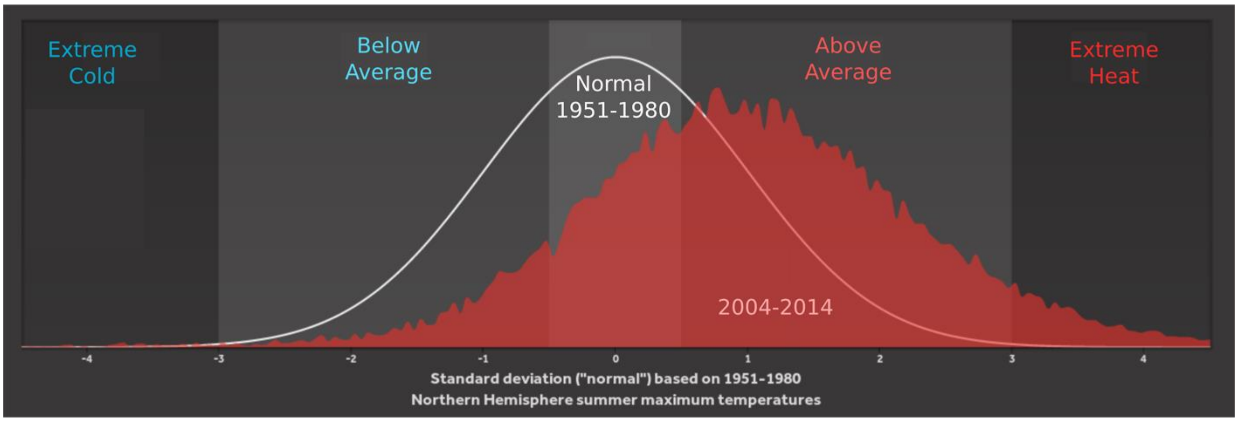


Fig. 4 *Climate change has shifted the odds of extreme heat as shown for the Northern Hemisphere maximum summer temperature anomalies to climate normal average (1951-1980) (modified from WXshift: http://wxshift.com/climate-change/climate-indicators/extreme-heat (March 2018)).*

Extreme heat events, defined as a temperature anomaly of three standard deviations above the mean, occurred 0.4% of the time in the baseline period (which already included a global warming component). In the recent period, the occurrence increased by a factor of 20 to 8.1%. Many climate extremes undergo similar changes (see Section 4 of this report).

Not all climate extremes are equally well-recorded through historical observations and not all are well-simulated in state-of-the-art climate models. Fig. 5 shows an expert assessment of our current knowledge of climate change impacts on climate extremes (Vose et al. 2014).

A general rule is that the larger the extent or time period of the extreme, the better it is recorded. For example, especially small-scale and short-period extremes related to severe convection are not well-observed. Similarly, our understanding of the effects of climate change on small-scale extremes is often more limited than for larger-scale extremes, although there are exceptions, such as extreme TCs and associated extreme winds and waves.

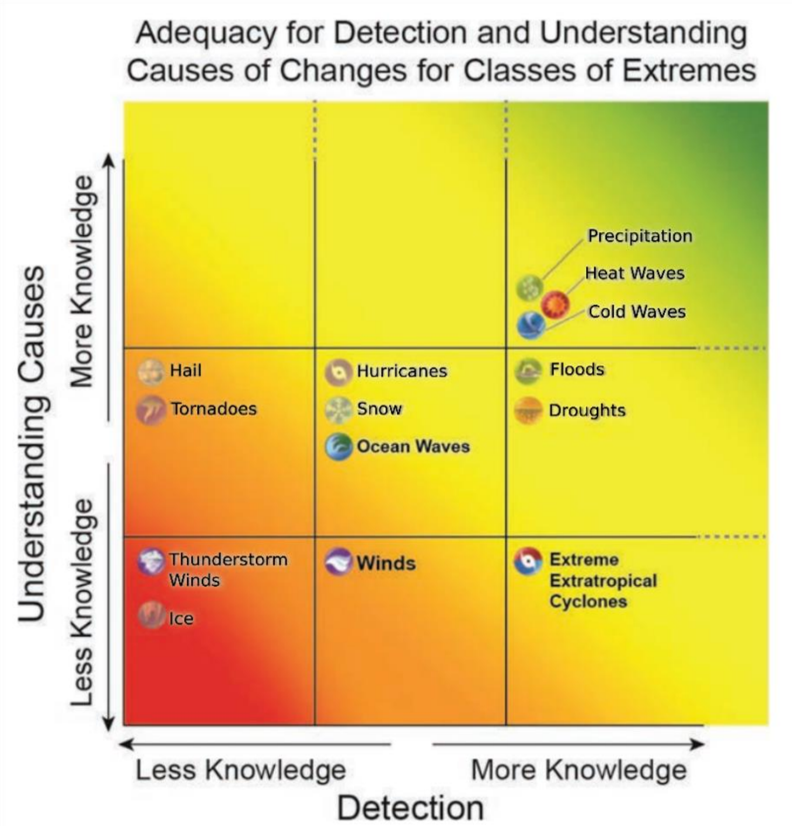


Fig. 5 *Expert assessment of the state of knowledge regarding changes in various climate extremes. The horizontal axis shows how skilful historical changes can be detected while the vertical axis refers to our understanding of the physical processes that drive changes (source Vose et al. 2014).*

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

4.1 Tropical Cyclones

Background

The world has entered a new era of global TCs in which economic and insured losses are doubling every 15 years (Kunreuther and Michel-Kerjan 2009, Smith and Katz 2013, Pielke Jr et al. 2008).

Changes to exposure and vulnerability dominate the trend (Weinkle et al. 2012, Höppe and Pielke 2006, Stewart et al. 2003) but changes to the TCs themselves (Walsh et al. 2016a), together with sea level rise (Solomon et al. 2007) have compounding the effects. Indeed, Estrada et al. (2015) quantified the present climate change contribution to rising USA hurricane costs at US$136 million per year. This section summarises our understanding of historical and future TC changes and explores scaling for global temperature with a focus on Australia.

Given that climate influences all stages of the TC life cycle, the entire TC life cycle is expected to be affected by climate change. Starting with TC formation, there is no theory linking TC formation to the mean state of the climate (Sharmila and Walsh 2017). A large empirical modelling effort has led to numerous genesis potential indices but these have substantial issues. For example, Bruyère et al. (2012) highlighted the extreme sensitivity of these indices to the region selected. Such indices also rarely account for non-stationarity in the TC-climate relationships, such as the increasing threshold onset temperature for formation with warming (Johnson and Xie 2010), thereby limiting their application to climate change studies.

The theoretical basis for TC intensity is far more established. TC potential intensity is directly related to the sea surface temperature (SST; Emanuel 1991, Holland 1997) with a climate sensitivity of TC maximum wind speed of 5% per degree Celsius rise, shown in observational and modelling studies (Strazzo et al. 2015). Circulation acts as a modifier to these thermodynamic effects, operating through wind shear and vertical oceanic overturning.

In addition to these advances in theoretical understanding and empirical modelling, numerical models apply physics to our understanding of TCs and climate. Global climate models commonly perform well in capturing the geographic distribution of TCs, their frequencies, and inter-basin differences (eg, Strachan et al. 2013), but there are notable variations between models (Shaevitz et al. 2014, Camargo 2013). Recent global models use 10-25km grid spacing, at which many key damaging TC parameters start to become resolved (eg Shaevitz et al. 2014, Bacmeister et al. 2016), including TC clustering and TC rainfall (Villarini et al. 2014). Yet Gentry and Lackmann (2010) found a grid size of the order of 1km is needed to capture the peak wind speeds of the most intense TCs.

Looking to the future, it appears the dominant effect of increasing greenhouse gases on TCs will be through the increasing upper ocean temperatures (Zhao et al. 2013). The long-term impact of future predicted increases in ocean temperatures is hotly debated (eg Holland and Webster 2007). However, some consensus is emerging, summarised for the global basins by Christensen et al. (2013) and Knutson et al. (2019b), reproduced in Fig. 6. This consensus suggests that there will be higher TC intensities and TC rain rates but fewer TCs globally.

Separating the climate influence on TCs into thermodynamic and dynamic contributions offers a useful framework for understanding future changes. Global climate model projections agree on a future climate that is warmer and more humid, but disagree on changes to environmental winds (Deser et al. 2012). This disagreement worsens for changes on regional scales.

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

Confidence in thermodynamically-driven changes to TCs, such as potential intensity and rainfall, is therefore far higher than for circulation-driven changes such as wind shear and steering flow.

There is consensus on a thermodynamically-driven future increase in global and regional maximum wind speeds and on the global incidence of high-intensity TCs (Villarini and Vecchi 2013, Murakami et al. 2012, Hill and Lackmann 2011). In addition, Holland and Bruyère (2014) found a relationship between anthropogenic warming and an increasing proportion of the strongest TCs, and a decreasing proportion of weaker TCs. Lee et al. (2016) provided evidence that changes in the incidence of rapid intensification could be driving these proportional shifts. Indeed, Emanuel (2017) suggested a future increase in the incidence of rapidly intensifying TCs just offshore that would present a challenge for future forecast and emergency preparation.

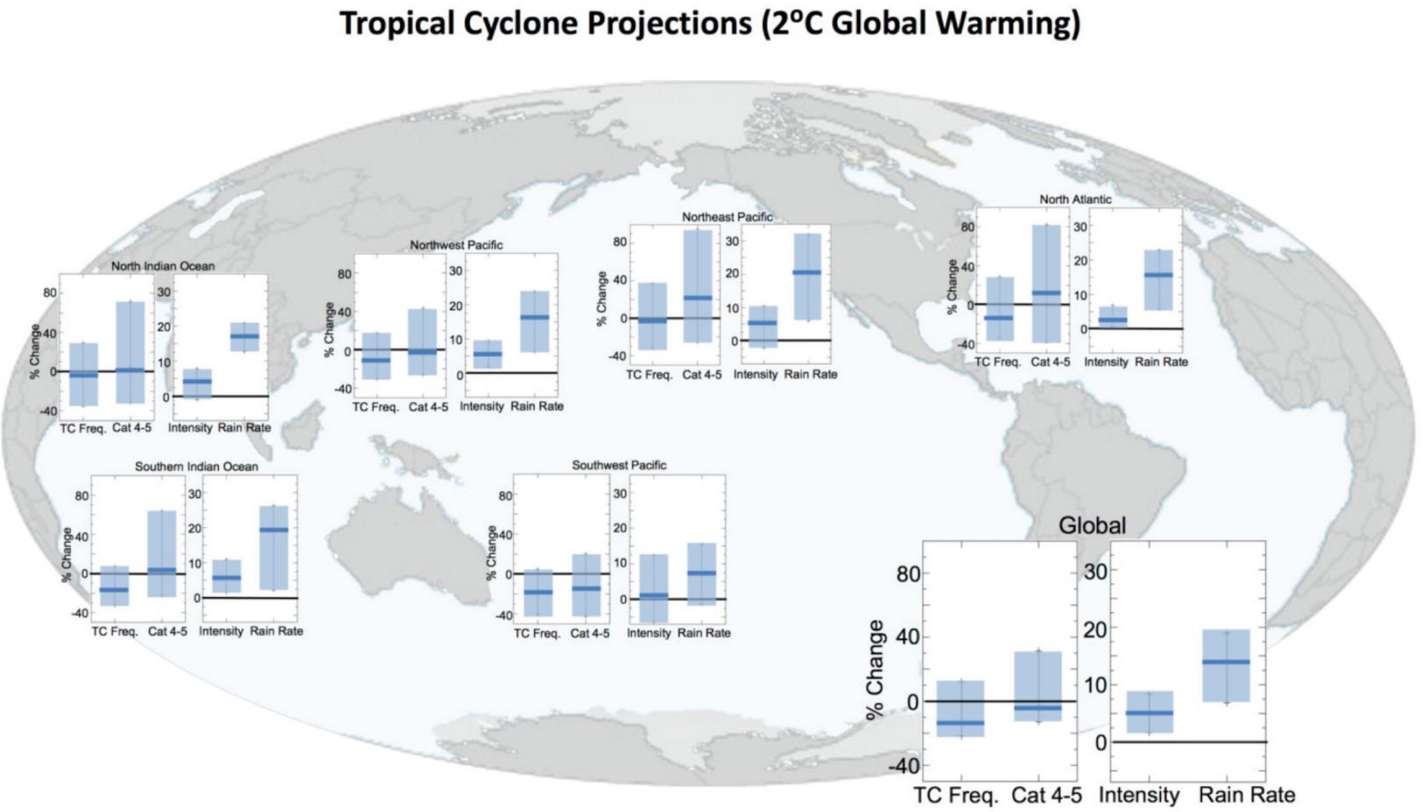


Fig. 6 *Consensus future projection of tropical storm characteristics under a 2°C global warming scenario (Knutson et al. 2019b).*

In addition to these changes to frequency and intensity, other important changes to TC activity are anticipated. There is consensus on a 5-20% thermodynamically-driven increase in TC rain rate within 100km of cyclone centre by the end of this century (Christensen et al. 2013, Walsh et al. 2016a, Villarini et al. 2014, Knutson et al. 2019b). As moisture content increases with warming, so does moisture convergence for a given mass convergence into the cyclone. The expected increase in wind speeds may lead to further increases in moisture convergence beyond Clausius-Clapeyron scaling (Knutson et al. 2010).

Lifetime maximum wind speeds are now occurring at higher latitudes than in the past (Kossin et al. 2014), associated with a global expansion of the tropics. Should this continue, these high-latitude locations will experience TC impacts. Rising seas will bring more frequent storm surge events, all other factors being equal. Finally, there is a lack of climate theory for TC size but high-resolution simulations by Sun et al. (2017) indicate a future expansion of the area subject to gale force winds.

Changes in Australia

Observed changes

Focusing on historical change in Australia and an analysis of historical TC records, Callaghan and Power (2011) found a decrease in eastern Australian landfall frequency over recent decades but did not reference the distribution of intensities. However, a more recent analysis found that the significance of the trend is sensitive to the specific period analysed (Hartmann et al. 2013). Our confidence in historical change is therefore limited by the lack of a long and consistent observational record. Kuleshov et al. (2010) found no trend in the numbers of minor or moderate TCs in the Australian region since 1981, but a significant increase in the numbers of strong (central pressure below 945hPa) TCs. Malan et al. (2013) also found an historical increase in strong TC activity as measured by the number of major (> Saffir-Simpson Category 3) storm days. Holland and Bruyère (2014) found that globally anthropogenic warming has increased the proportion of the strongest TCs and decreased the proportion of minor TCs. These changes are significant at the 99% level for both the South Pacific and South Indian Ocean basins.

It is possible that TCs are living longer, with an associated increased likelihood of reaching their maximum potential intensities. Kossin et al. (2014) found that the increasing latitude of lifetime maximum intensity (LMI) over the past 30 years applies to both the South Indian and South Pacific basins, primarily associated with a southward shift of the sub-tropical jet and associated reduction in wind shear.

There is not a good understanding of historical change in other key TC characteristics such as size and rainfall for the Australia region, primarily due to a lack of data. Lavender and Abbs (2013) explored historical TC rainfall trends and found a signal of significant drying due to TCs over the east coast of Australia. However, recent work by Bruyère et al. (2019a) found that major flooding associated with TC Debbie-like cyclones was significantly enhanced as a result of oceanic warming.

Projected changes

A challenge for projecting South Pacific TCs is that their frequency appears to be more sensitive to circulation change than other basins (Sharmila and Walsh 2017). As stated earlier, circulation changes are not well understood. This is reflected in the lack of model agreement in future TC frequency found by Camargo (2013). However, Hartmann et al. (2013) and Walsh (2015) found some agreement on a future decrease in TC frequency in the South Pacific and South Indian basins, with some studies suggesting that the Southern Hemisphere has the strongest signal for a frequency decrease (Sugi et al. 2012, Tory et al. 2013, Murakami et al. 2012). Bell et al. (2013) suggested that the decrease in TC frequency will continue with increasing CO_2 due to reduced ascent and increased wind shear.

For the South Pacific and South Indian basins, they found a 15% decrease in TC frequency with 1.5°C of warming under $2xCO_2$, increasing to 30% reduction with 3°C of warming under $4xCO_2$. A similar study by Held and Zhao (2011) agreed. Yet uncertainty remains, as evidenced by model resolution dependence of the TC response to warming (Wehner et al. 2015) and the inability of current generation models to resolve small, short-lived TCs ("midgets") that are commonly found in the Australian region.

A slight increase in the lifetime maximum wind speed appears robust across studies (Walsh et al. 2016b), Uncertainty remains, particularly on the role of tropical tropopause temperatures (Ramsay 2013). Holland and Bruyère (2014) suggested a continuation of proportional increases in the strongest TCs in the future, but also suggested an upper limit to the proportion that they referred to as 'saturation', imposed by basin geography.

Should the lifetime maximum intensities continue to migrate poleward, as suggested by Kossin et al. (2014) and Lavender and Walsh (2011), cities along sub-tropical eastern and western Australian coasts will experience TCs more often than in the past, with extratropical transitioning storms also extending their impacts to higher latitudes. This scenario may become more likely given the finding of Lavender and Walsh (2011) that average TC lifetime extends by 12 to 24 hours with 2 to 3°C of warming. Regarding landfall, Parker et al. (2018) found a 5 to 10% increase in eastern Australian landfall wind speed under an end-of-century RCP8.5 scenario.

A future increase in TC rainfall rate appears robust across many studies, driven by the strong thermodynamic change signals. The Parker et al. (2018) study found increases in landfall hourly TC rain rates over eastern Australia of up to 27% by the end of this century.

Given that Australia is recognised as holding the world record storm surge of 13m, associated with Cyclone Mahina in 1899 (Nott et al. 2014), an important question is how likely such events will be in the future. New simulation technologies are being developed to assess rare surge events for any coastal location (Bruyère et al. 2019a; Lin and Emanuel 2016). Lin and Emanuel (2016) generated 2,400 synthetic TC surge events for Cairns using wind fields from the TC model of Emanuel et al. (2006) to drive a surge model. They found under current climate conditions the 0.01% (1 in 10,000 year) surge to be 5.7m, generated by a TC that was only slightly more intense than Cyclone Yasi but with a slightly different track. Storm surge risk associated with TCs will increase (ie return periods will contract by an order of magnitude) due to increasing sea levels associated with global warming (eg Lin and Emanuel 2016, Woodruff et al. 2013).

Finally, an idealised modelling study by Lavender et al. (2018) suggested caution in extrapolating empirical associations with temperature from past climate. They showed that relationships between SST and TC intensity, size, rainfall and surge may be far from linear.

Regional Interpretations for Risk Assessment for Australia and New Zealand

For several decades, the (re)insurance industry has used a catastrophe modelling approach for risk assessment purposes. This framework simulates physically plausible peril events from the very frequent to the very rare and therefore considers a much broader range of possible events than the historical record.

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

Recently the catastrophe modelling framework is also being used for wind risk assessment as an alternative and more comprehensive approach for engineering considerations on the wind hazard (https://www.ga.gov.au/about/projects/safety/tcha). This is a promising development to improve the alignment between disparate risk modelling approaches.

This section combines the latest available global and basin-wide climate change science with meteorological interpretation that is based upon the collective experience of the authors to derive the regional changes to the frequency and intensity of TCs around the coastlines of Australia and New Zealand.

The key factors and assumptions behind these regional changes are summarised below, followed by an in-depth discussion on the south-east Queensland and north-east New South Wales region, which is expected to have the largest changes in TC risk.

The key factors relevant to the changing climatology of TCs in Australia and New Zealand are:

1. There is high natural variability at seasonal, annual, decadal and multi-decadal time scales at a regional scale and this creates significant challenges to identifying and quantifying trends in TC numbers and intensities. The changes that have been estimated therefore relate to the long-term change in risk, not the risk in any given year.

2. The current climate change signal for the Australian land mass is equivalent to a warming of around 1.2°C since pre-industrial times (Bureau of Meteorology State of the Climate 2018). It is highly likely that the TC climatology of Australia and New Zealand has already changed due to this warming signal.

3. There is likely a greater proportion of strong TCs (Saffir-Simpson Categories 4 and 5) in the most recent decades compared to the 1970s (Holland and Bruyère 2014). In pre-industrial times, approximately 10% of all TCs are estimated to have been Category 4 or 5. Currently, approximately 25% of all TCs reach this peak intensity. It is likely that this rising trend could continue before the upper limit or 'saturation point' is reached. Recently, Bruyère et al. (2019b) analysed trends in TCs in the region south of the equator between 135°E and 180°E using the NCAR Decadal Prediction Large Ensemble (DPLE: Yeager et al. 2018) dataset. They found a 10% increase in the proportion of strong TCs between the decades centred on 1960 and 2010, and a further 10% increase predicted for the decade centred on 2020. Importantly, from a property risk perspective, the less frequent but intense TCs drive the majority of the risk.

4. There has been a poleward shift of the maximum lifetime intensity in the South Indian Ocean and South West Pacific Ocean basins (Kossin et al. 2014). Applied to the east coast of Australia these imply southward shifts in the overland impacts compared to the historical TC impacts. Current research work in progress with the NCAR DPLE dataset is expected to strengthen the science behind these initial estimates. For the west coast south from Shark Bay, the poleward shift is expected to be smaller than off the east coast due to the presence of cooler waters off the west coast that are projected to continue to the end of the present century, although warming slowly (see SST trend map in Fig. 7 based upon ERA-Interim V5.0 data). Based on unverified research, increased strength and prevalence of heat lows in the Pilbara and Gascoyne regions may lead to increased incidence of dry air intrusion that could reduce TC intensity (see Fig. 8 on trends in summer cyclone density).

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

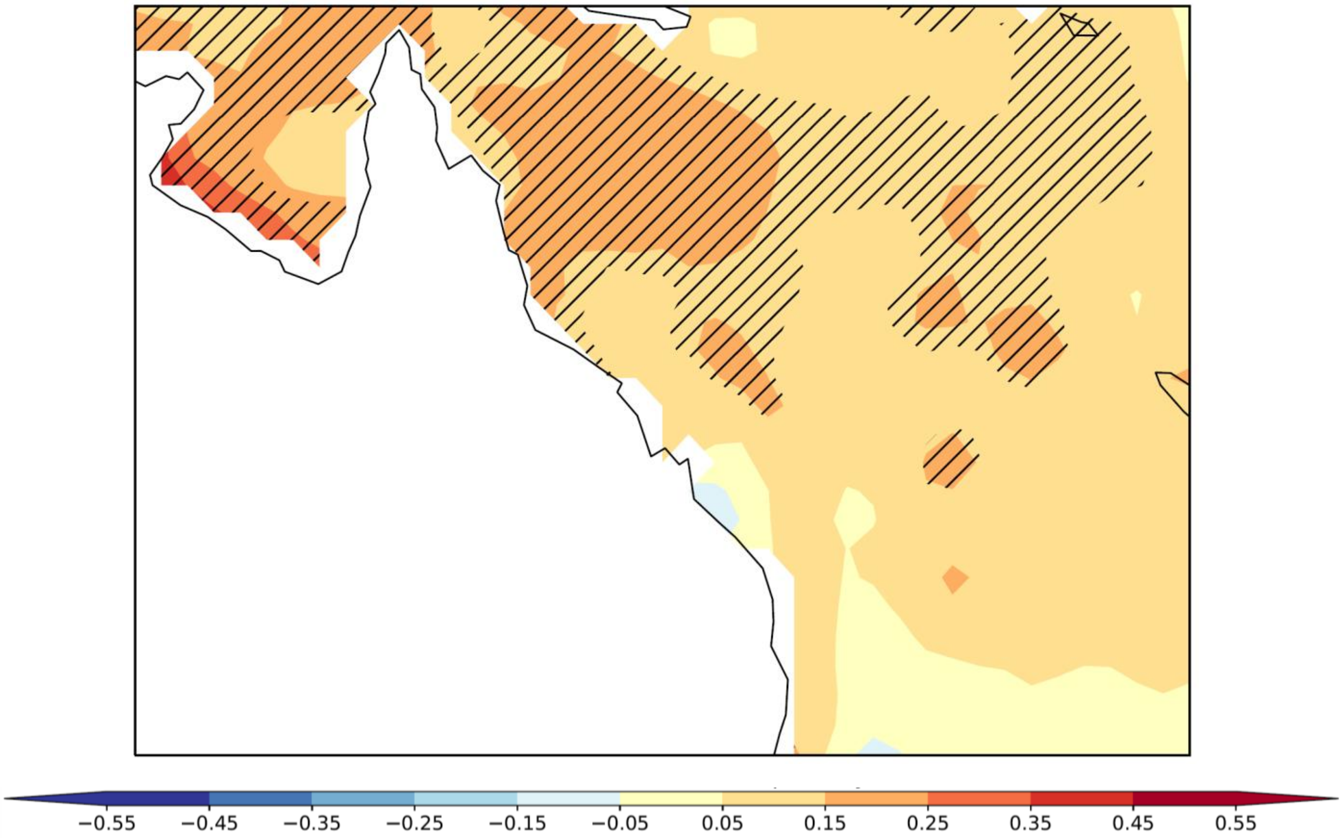


__Fig. 7__ Trends in SST anomalies for the Coral Sea region showing the trends in SST for February in ºC per decade for the period 1979 to 2018. (Source ERA-Interim V5.0)

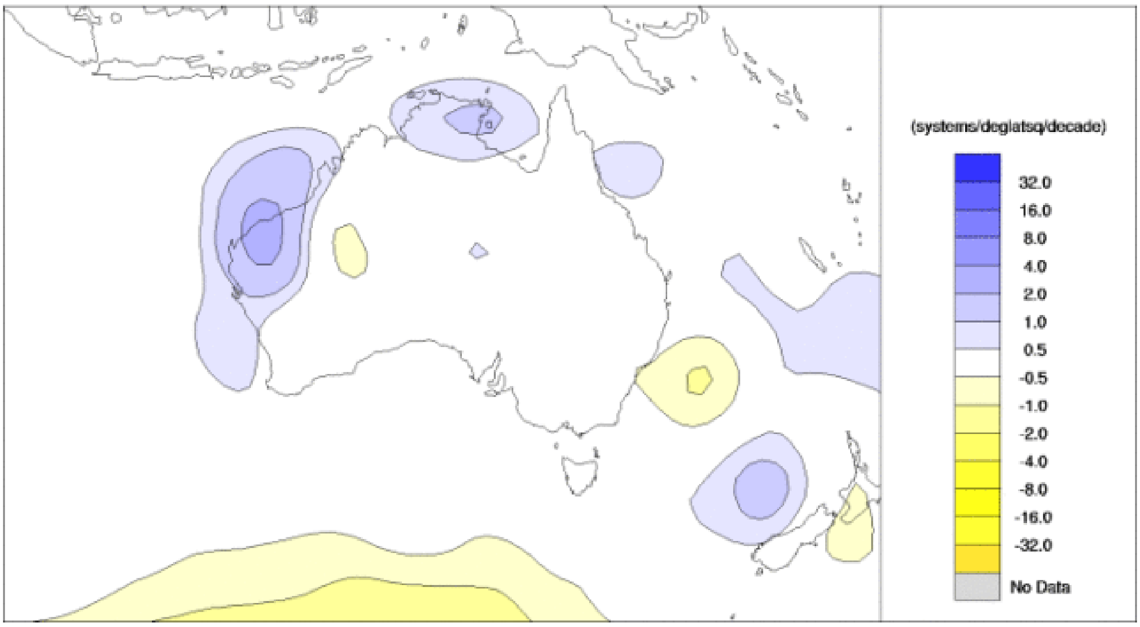


__Fig. 8__ Trend in summer cyclone density between 1950 and 2018 showing the increasing frequencies of cyclones in the form of heat lows for the west Pilbara to west Gascoyne region of Western Australia and tropical lows over the Arnhem Land region of the Northern Territory. (Source Bureau of Meteorology. http://www.bom.gov.au/climate/change/about/lps_trendmaps.shtml)

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

5. TCs in the Australian and New Zealand region are likely to last longer due to the greater heat content of the oceans over which they travel. They are also likely to spend a greater proportion of their life cycle as higher category TCs (Bruyère et al. 2019b). This is particularly the case for the South West Pacific Ocean where a general southward shift of the sub-tropical jet stream could lead to a reduction in the vertical wind-shear over the Coral Sea to northern Tasman Sea region, but there is low confidence in the veracity of such circulation shifts. This increases the chance of TC impact in Australia, New Zealand or other South West Pacific islands. This trend of longer lasting and stronger TCs should continue as the world gets warmer.

6. There is a lack of research concerning potential changes in TC impacts to the lower west coast of Western Australia. One interpretation of the available evidence is that this area is expected to become more vulnerable to transitioning TCs that originate from the central and south-east Indian Ocean – similar to those of TCs Marcelle (1973) and Idylle (1979). There is also the potential for a slight increase in TC Alby-like events due to a slow southward expansion of the favourable South Indian Ocean TC regions and gradual warming of the Leeuwin Ocean Current down the west coast. However, detailed research is required to test the validity of this assessment.

7. The TC seasons are expected to gradually lengthen for the +2°C and >+2°C scenarios, although it is considered that there has already been an extension of the late season TC climate for the Coral Sea. For example, TC Zane (2013) was a minimal Australian Category 3 cyclone that formed in late April and weakened in early May as it crossed the north Queensland coast; and TC Ann reached Australian Category 2 intensity in the Coral Sea in mid-May 2019.

8. With warmer environments, TCs are expected to increase significantly rainfall and run-off quantities. An increase of around 7% in short-term extreme precipitation for each degree Celsius of warming is likely, due to the increased moisture capacity of the atmosphere indicated by the Clausius-Clapeyron relationship (Trenberth et al. 2003, Prein et al. 2017a). Rainfall volumes (Bruyère et al. 2019a, 2019b) and storm run-off extremes (Yin et al., 2018) have been shown to increase at rates significantly higher than the 7% suggested by Clausius-Clapeyron scaling alone due to increased intensity, longer life, expansion of the heavy rainfall area and increased inland penetration of future TCs.

9. The potentially changing nature of the important sub-type of TCs referred to as midgets, which includes TC Tracy that devastated Darwin in 1974, remains an area of large uncertainty due to their small size and the inability of the current generation of climate models to adequately resolve them.

10. For New Zealand, the southward extension of the latitudinal band favourable for TC development and intensification is expected to lead to an increased number of TC-related impacts across the nation. Most impacts are expected to be from tropical systems that are undergoing extratropical transition. The 2017-2018 season may be an early indication that this trend is already underway with a record three extratropical cyclones (ETCs) affecting the island nation.

However, insufficient research means that there remains a high degree of uncertainty in ETC trends. The work of Ramsay et al. (2018) and Knutson et al. (2019a, 2019b) serves as a good launching pad for future, more tailored, studies on TCs and ETCs in the Australian and New Zealand region.

11. The effect of clustering of severe weather events has not yet been investigated. A series of events in close succession, including those below TC intensity, can cause greater damage than individual events.

Fig. 9 summarises the expected regional changes to both the frequency of all TCs and the frequency of the intense TCs (Australian Categories 3, 4 and 5) between the 1950s, after which time most of the observed global warming has occurred, and the +3°C climate change scenario. It is important to note:

- some of the expected changes shown have already occurred with the warming to date;
- the change in TC frequency is likely to be very different between regions around the Australian coastline;
- local changes may differ significantly compared to the broader basin-wide changes; and
- the changes described below only relate to the wind component of TCs and do not include other important risk drivers – such as water ingress, flooding caused by more intense short duration or storm-total rainfall, storm surge, wave impacts and coastal erosion – that are very likely to worsen.

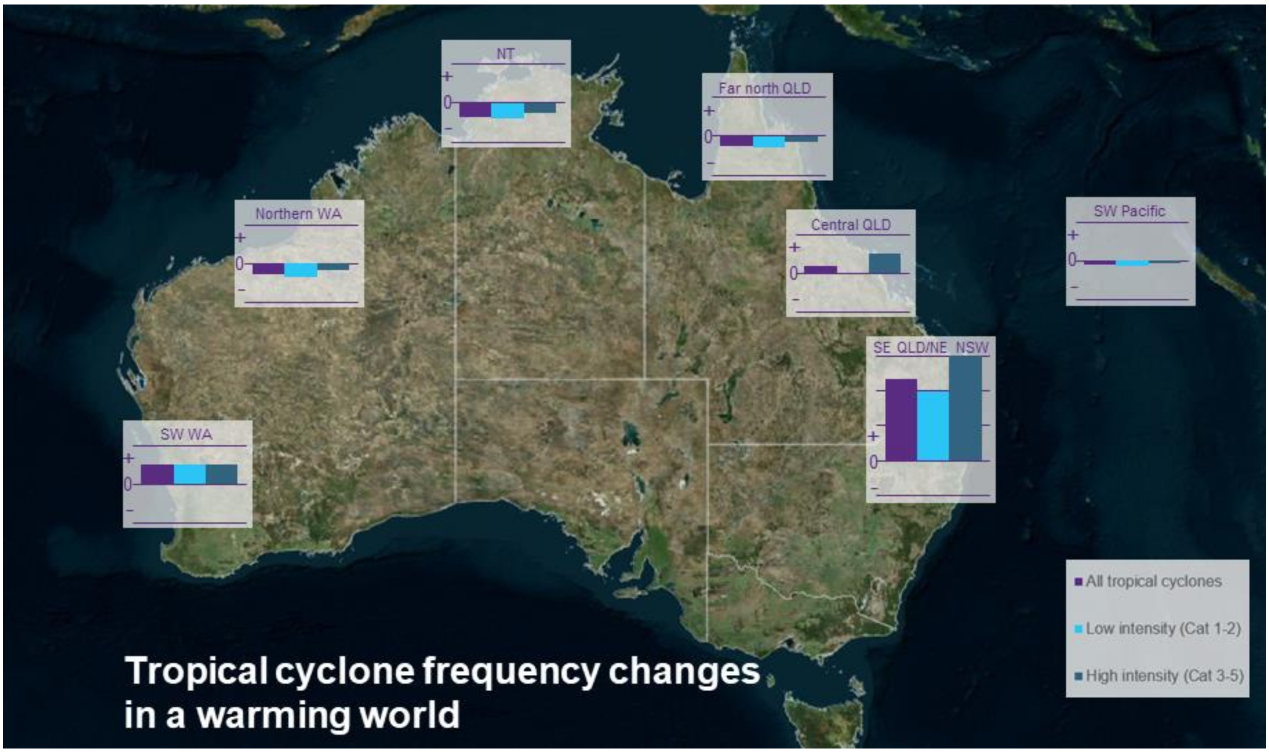


Fig. 9 *summarises the expected regional changes to the frequency of all TCs, low intensity TCs (Australian Categories 1 and 2) and intense TCs (Australian Categories 3, 4 and 5).*

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

Here are the expected changes by region:

- **Central/south-east Queensland and north-east New South Wales**
  In the +3°C scenario and beyond, the southward shift of the LMI moves the highest risk area from the north coast of Queensland southwards into the central coastal region. The southward shift is causing the largest relative change (not absolute change) for the southern margins of the TC-affected regions in south-east Queensland and north-east NSW. Although still likely to be uncommon events, the very rare high category TCs are expected to have a slower decay rate in intensity (ie have a higher intensity) in a warmer climate due to the increased SSTs off the central and south-east coasts of Queensland which are capable of sustaining strong TCs.

- **Far north Queensland, the Northern Territory and northern Western Australia**
  The southward shift of the LMI would tend to marginally reduce the currently high TC wind risks in these regions, although there will remain a relatively high risk of impacts from intense TCs. When increasing rainfall and storm surge-related factors are considered, the total TC-related risk may not decline.

- **South-west Western Australia**
  The waters off the west coast from Shark Bay southwards are cooler than those off the east coast. The warming effects of climate change large enough to maintain severe TCs should be slower to manifest themselves in this region. Nonetheless, it is very likely there will be ongoing warming of the waters off the west coast of Australia which should lead to a commensurate increase in the risk of higher intensity TCs than has been historically observed, although the rate of increase in risk should be slower than for the east coast.

South-east Queensland / North-east New South Wales Case Study

Applying the climate change science and meteorological understanding of TC behaviour specifically to the south-east Queensland to north-east NSW region reveals substantial changes in future climate risk, even if the total number of high category TCs across the broader South West Pacific region does not change substantially. The ability of the oceans and atmosphere across the southern Coral Sea and northern Tasman Sea to sustain higher intensity TCs further south and for longer periods of time, coupled with increasing storm-total rainfall and rising sea levels, leads to a faster increasing risk compared to the regions further north.

The ten most significant TCs that have affected the south-east Queensland to north-east NSW region since 1954 (Table 2 and Fig. 10) reached an average peak intensity of around 950hPa at a mean latitude of 21.5ºS, with the average SST close to the time of maximum intensity being 27.3ºC, from the NOAA Extended SST Reanalysis version 4. They had an average central pressure of 977hPa when they reached 27ºS and the average SST at the time of these TC events was 26.0ºC off the Brisbane coast.

In Fig. 7, the observed change in SSTs between the mid-1950s and the most recent five-year period (2015-2019), in the peak TC month of February, shows SSTs at the mean latitude where these TCs have historically reached maximum intensity have warmed by between 0.7-0.8ºC.

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

At the latitudes from Brisbane down to the north-east of New South Wales, the observed warming has been around 1.0°C. The study on Maximum Potential Intensity by Holland (1997) stated that the rate of increase of TC intensity is in the order of -30hPa per degree Celsius of warming when all other conditions are favourable with SSTs between 26°C and 28°C.

This would imply that the current state of warming seas off south-east Queensland and north-east New South Wales would support TCs approximately one category stronger than the sea temperatures of the 1950s.

Table 2 *Selected details of the 10 most significant TCs since 1954 that have affected the south-east Queensland to north-east New South Wales region, along with some relevant SST estimates from the NOAA Extended SST Reanalysis version 4 dataset.*

		At Maximum Intensity				At 27°S		At Coastal Impact
Cyclone Name	**Year**	**Central Pressure (hPa)**	**Latitude (°S)**	**Longitude (°E)**	**SST (°C)**	**SST (°C)**	**Central Pressure (hPa)**	**Central Pressure (hPa)**
Coolangatta	1954	960	-27.24	153.75	26.45	26.45	960	962
Unnamed	1957	953	-15.8	150.8	28.55	25.45	960	990
Dinah	1967	945	-24.7	153.2	26.45	25.65	954	
Daisy	1972	959	-23.6	154.4	27.25	25.85	996	994
Zoe	1974	968	-21.6	155.9	26.65	25.95	983	986
Simon	1980	950	-22.5	150.8	28.25	26.85	979	
Abigail	1982	947	-21.5	162.4	27.35	26.85	990	
Fran	1992	940	-18.1	164.6	27.65	26.05	990	992
Rewa	1993	920	-18.7	154.2	27.75	24.85	990	
Violet	1995	960	-22.2	158.1	26.95	26.55	970	

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

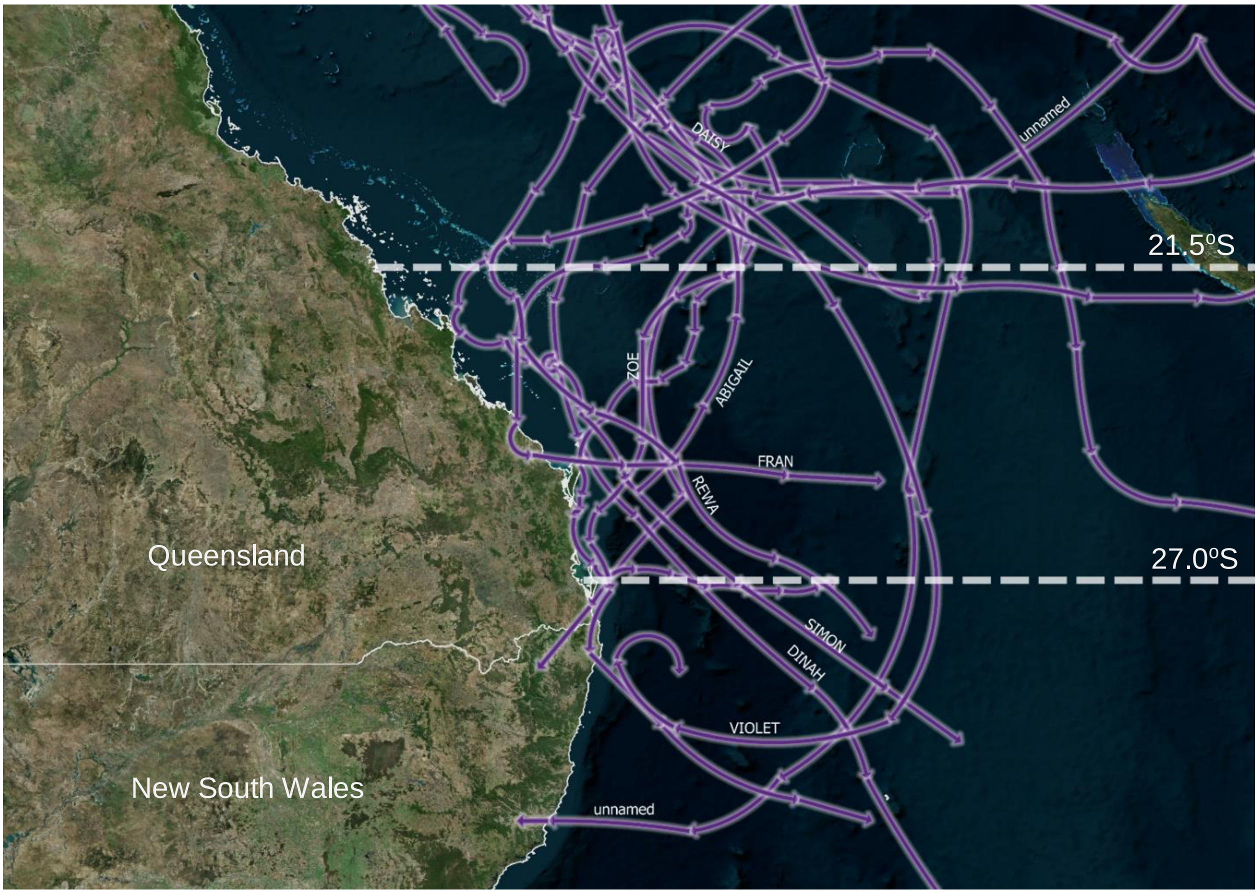


Fig. 10 *Tracks of the ten most significant TCs to have affected the south-east Queensland and north-east New South Wales region since 1954. The horizontal dashed lines show the mean latitude of maximum intensity for this set of TCs (21.5°S) and the latitude of Brisbane (27.0°S).*

Two recent TCs have demonstrated that very severe TCs can occur at the latitudes of south-east Queensland. On 10 March 2009, Severe TC Hamish was observed to have a central pressure of around 952hPa (Australian Category 4) at 24.7°S just to the east of Fraser Island; and Severe TC Oma was analysed at 973hPa (Australian Category 3) at 27°S on the morning of 23 February 2019 in the southern Coral Sea.

It must be noted that there is considerable uncertainty in the derivation of the regional insights noted above and this highlights a pressing need for in-depth research to reduce these uncertainties. IAG and NCAR have a current project underway to quantify the changing TC risk profiles across eastern Australia, specifically south-east Queensland and north-east New South Wales, using the DPLE and Large Ensemble Numerical Simulation (LENS) datasets.

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

4.2 Extreme Precipitation and Flooding

Background

The IPCC states in its AR5 report (IPCC 2013) that, based on historic observations, there are likely more land regions where the number of heavy precipitation events has increased than decreased. The recent detection of increasing trends in extreme precipitation and discharge in some catchments implies greater risk of flooding at a regional scale. This trend of increasing frequency and intensity of extreme precipitation events will very likely continue and intensify with rising temperatures in many regions. When viewed from an insurance perspective, the extremes that produce damage tend to be much rarer than those discussed in scientific literature, with trends in rainfall that occurs only once every 30 years roughly equating to the 99.999th percentile for extremely damaging events. From an insurance perspective, events close to the 99th percentile typically produce only modest levels of damage.

The rate at which extreme precipitation will intensify is theoretically related to the water-holding capacity of the atmosphere. Air can hold approximately 7% more water vapour for each degree Celsius of warming, which translates to a theoretical increase in short-term extreme precipitation by approximately the same rate (Trenberth et al. 2003, Prein et al. 2017a). These rates can, however, be strongly modified by changes in storm characteristics, such as size, translation speed or non-linear storm dynamics (Westra et al. 2014, Prein et al. 2017b). Extreme precipitation increases higher than 7% per degree Celsius of warming can occur for cold season extremes due to a transition from stratiform to convective rainfall for temperatures above ~10°C (Berg et al. 2013).

Furthermore, the atmospheric circulation patterns that trigger heavy precipitation events are also likely to change, thereby either enhancing or partially offsetting thermodynamic effects. The changes in atmospheric circulation patterns are a major source of uncertainty, while thermodynamic changes are more certain (Shepherd 2014).

It is important to realise that changes in extreme precipitation rates are decoupled from changes in mean precipitation. This means that extreme precipitation can intensify significantly with climate change in regions that experience drying on average (Giorgi et al. 2011, Ban et al. 2015, Prein et al. 2017a).

Frequency changes in extreme precipitation are expected to show even higher rates than intensity changes where higher return level events experience a stronger increase (see Section 3.2). Fig.11 shows the increase of the 20th century 100-year flood at the end of the 21st century under a >+2ºC scenario. In the Murray Basin (Fig.11), for example, the 100-year current climate flood is projected to occur every 5-25 years at the end of the century, which is a 400-2000% increase in frequency. Similar large projected increases have been reported for other regions (eg Prein et al. 2017a, 2017b).

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

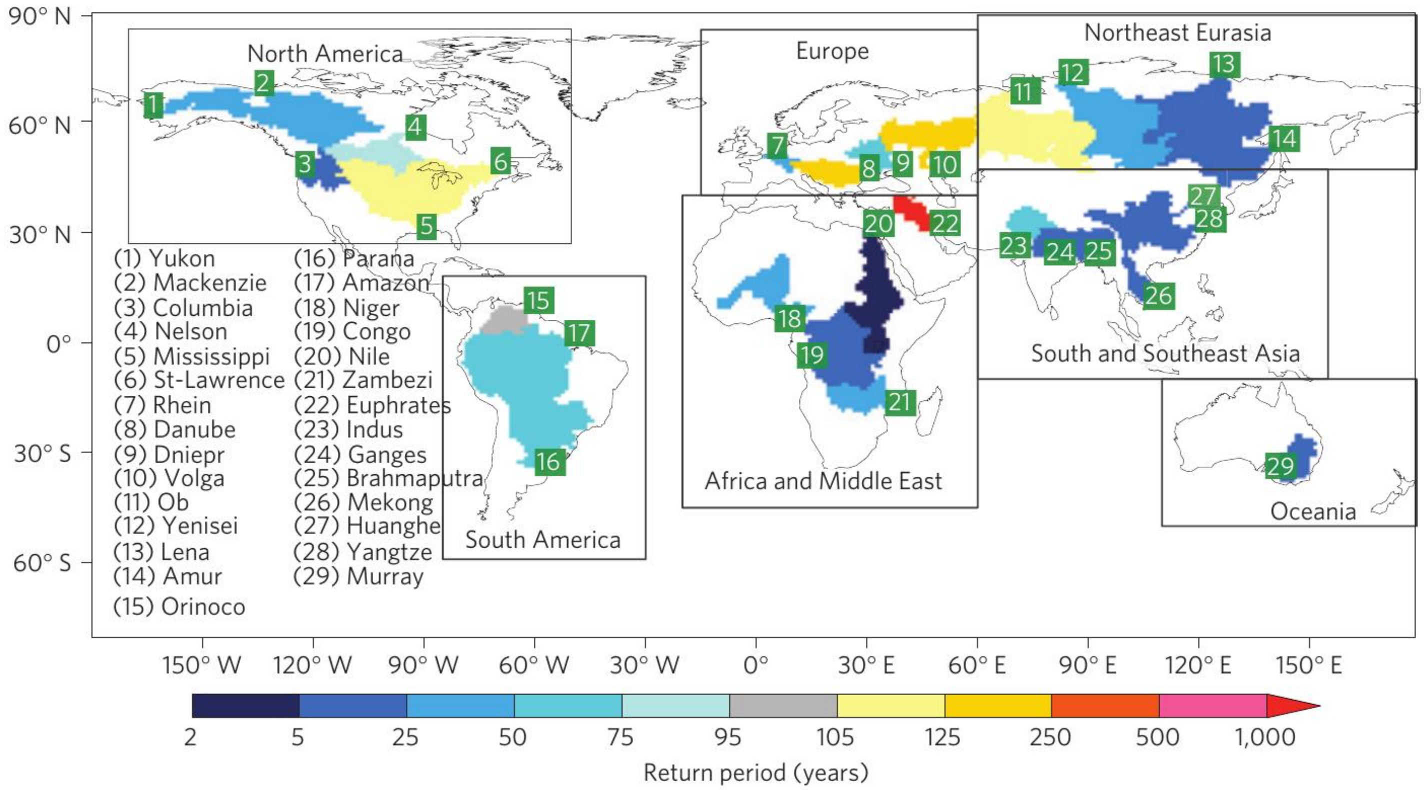


Fig. 11 *Projected return period of the 20th century 100-year flood at the end of the 21st century under the RCP8.5 scenario at the outlets of 29 selected river basins. The colour of each basin indicates the multi-model median return period at basin outlets (source Hirabayashi et al. 2013).*

Changes in Australia

Assessing climate change impacts on extreme precipitation in Australia and its regions is more uncertain than the above generalised global estimates due to the large natural variability in Australian rainfall on annual to decadal timescales.

Observed changes

Observed changes in heavy precipitation in Australia are consistent with global studies but the existing climatology of severe convective storms across Australia is poor and complicates the detection and attribution of historic changes in extreme rainfall.

The fraction of Australia that receives a high proportion of its annual rainfall (greater than 90% of daily precipitation) from extreme events (greater than 90th percentile) has increased since the 1970s (Gallant et al. 2013). The east coast has experienced a significant decrease in extreme rainfall events since 1950 (Gallant et al. 2014) while parts of Victoria and the west coast have seen increases (Fig. 12).

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

Wasko et al. (2016) showed that total precipitation and the maximum precipitation intensity increases with temperature in Australian observational records, while the storm's spatial extent decreases.

This indicates that flood severity increased over the observational record since extreme precipitation became more intense and spatially concentrated.

Observed changes in precipitation measurements are consistent with changes in annual maximum streamflow (Ishak et al. 2013). Ishak et al. (2013) attributed most of the decreasing flood magnitudes to natural climate variability, indicating that forced climate change impacts on extreme precipitation are small compared to internal variability in the observational records. This is in line with other studies showing that extreme rainfall time series are strongly affected by climate variability, with El Niño Southern Oscillation (ENSO) being the dominant driver (King et al. 2013, King et al. 2014). Changes in ENSO due to climate change are uncertain and generally within the range of natural variability (Chen et al. 2017).

The most robust change signal is an intensification of eastward-propagating warm sea surface anomalies that is a characteristic of very strong El Niño events (Cai et al. 2015). At the same time, extreme La Niña events are also projected to increase in frequency, resulting in more frequent ENSO-related catastrophic extreme events in warmer climates. However, these results are associated with considerable uncertainties.

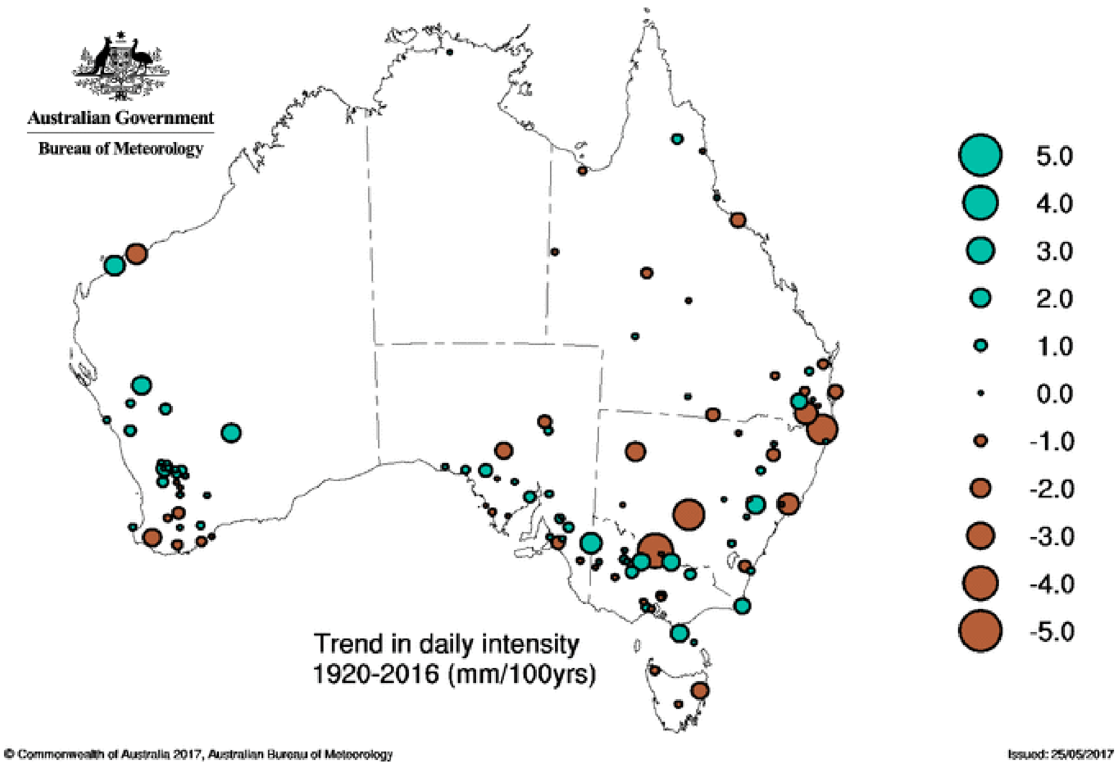


Fig. 12 Trend in daily rainfall intensity 1920–2016 (mm/year, source Bureau of Meteorology).

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

A typical assumption in engineering is that floods are occurring randomly over time. This assumption is very likely invalid as has been shown by McMahon and Kiem (2018) for flood events in south-east Queensland. They showed that ~80% of historic large floods in this region occurred within sets of 5-year periods followed by 35-year periods of lower flood occurrence. This cyclic behaviour is most likely related at least in part to the Interdecadal Pacific Oscillation (IPO; Power et al. 1999), which highlights the importance of including natural variability in flood risk assessments.

Projected changes

CMIP5 global climate models (GCM) simulate a consistent increase in various extreme precipitation indices over Australia with high confidence (see Fig. 13; CSIRO and Bureau of Meteorology 2015). These results are consistent with global estimates (see Section 4.2) and show that:

1. changes in extreme precipitation are increasing in all regions independent of changes in mean precipitation, even in regions with strong drying trends (eg, Western Australia);

2. changes increase in magnitude for more intense extreme events and for higher emission scenarios and are less evident under RCP2.6; and

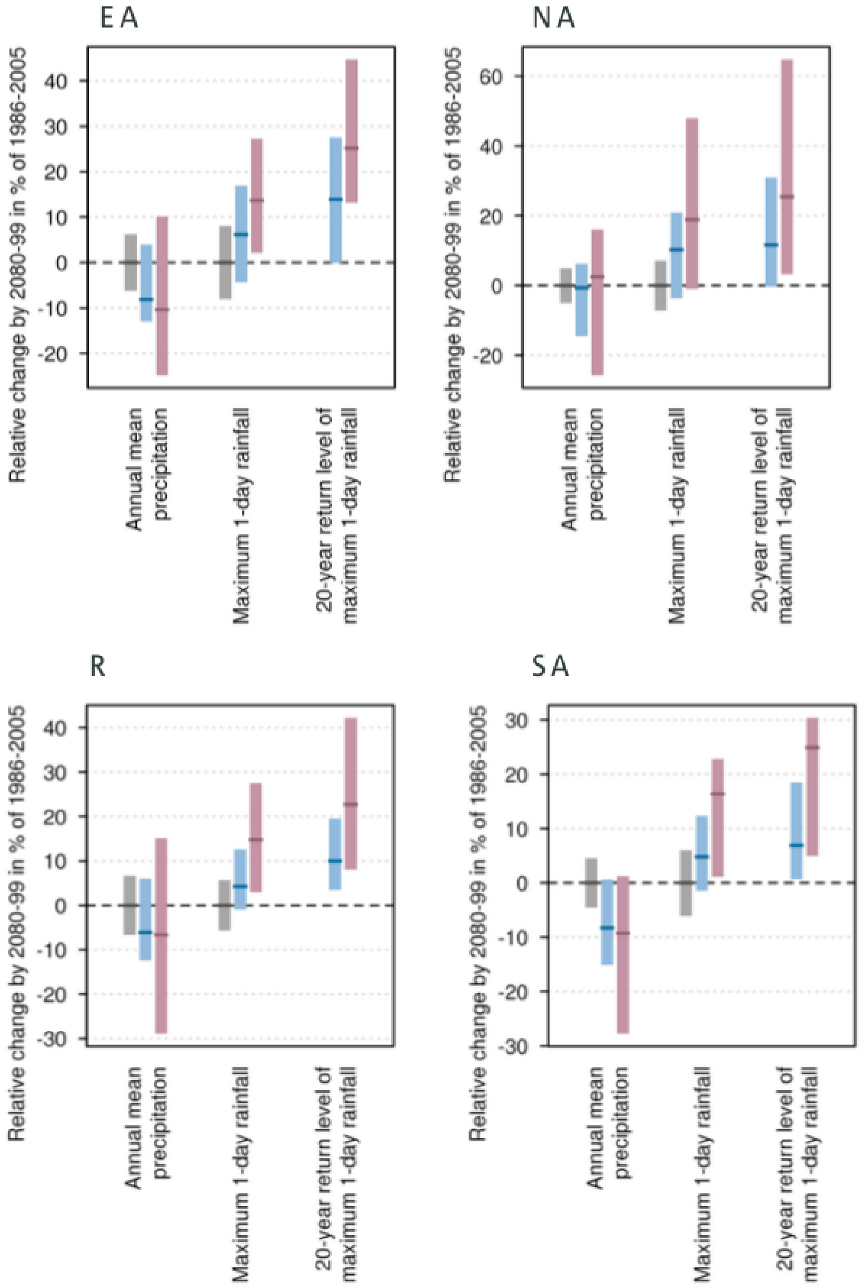


Fig. 13 *Changes to extreme rainfall in East Australia (EA), North Australia (NA), Rangelands (R), and South Australia (SA). Each panel shows projected change in 2080–99 for annual mean precipitation, annual maximum 1-day rainfall, and 20-year return level of annual maximum 1-day rainfall in percent of the 1986-2005 average. The horizontal tick denotes the median and the bar denotes the 10th to 90th percentiles of the CMIP5 results. Scenarios are shown in grey (natural variability), RCP4.5 (blue) and RCP8.5 (red) (source CSIRO and Bureau of Meteorology 2015).*

3. tendencies for these increases are already detectable in 2030. The confidence for increases in daily extreme rainfall should only be reduced to ‘medium confidence’ in Western Australia where the strong drying trend could offset some of the increases in extremes.

Regional and sub-daily estimates in extreme precipitation changes from GCMs should be treated with care due to the coarse grid spacing, which does not resolve the spatial scales that cause extreme rainfall events in the real world. However, damaging flooding often occurs from local severe storms that are not resolved by the relatively coarse climate models used in the above studies.

Higher-resolution regional models can help to close this gap. Within the NARCliM project (Evans et al. 2014), several GCMs were dynamically downscaled with regional climate models (RCMs). Evans et al. (2014) used a two-way nested approach with a 50km grid-spacing outer domain over Australia and Oceania, and a 10km grid-spacing nest over south-east Australia. The 10km NARCliM simulations should be used with some caution as they use a relatively small domain, which might not be large enough to simulate the local weather accurately. Bao et al. (2017) used the 50km NARCliM ensemble to study the scaling between temperature increases and daily precipitation increases in Australia. Consistent with Evans et al. (2014), they showed a systematic increase in extreme rainfall over Australia. The scaling rates generally increase for higher extreme percentiles. The 99th percentile of daily precipitation increases close to ~7% per degree Celsius of warming while the 99.9th percentile shows even higher rates (Fig. 14).

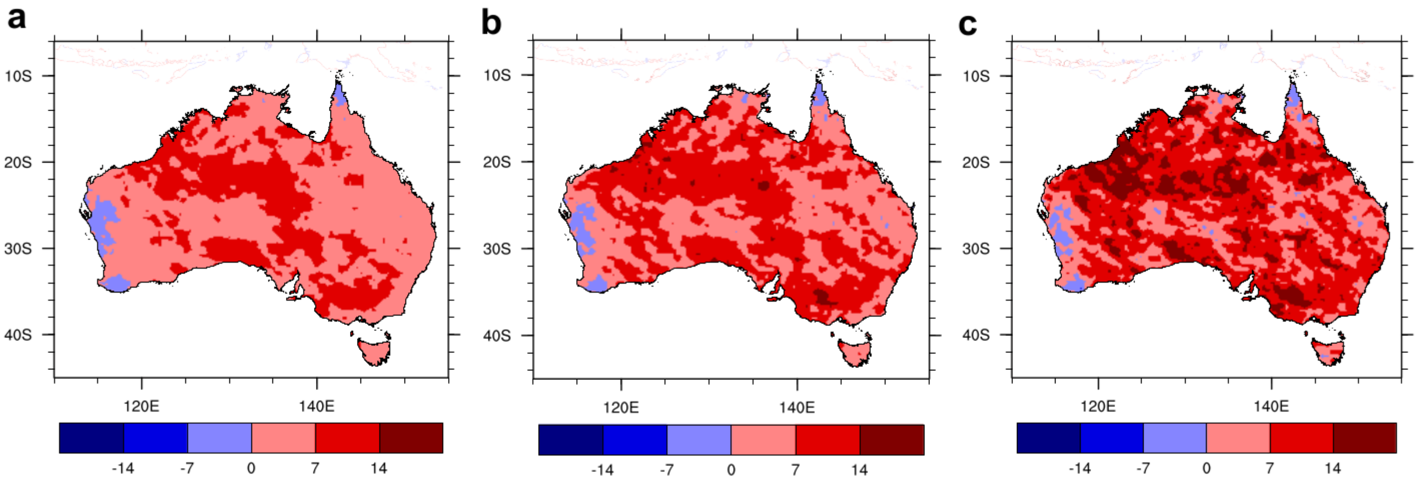


Fig. 14 *Projected future climate scaling rates for the ensemble mean daily precipitation 99th (a), 99.5th (b), and 99.9th (c) percentile climate scaling rates (%/°C) from NARCliM between 2060–2079 and 1990–2009 under the A2 scenario (source Bao et al. 2017).*

Recent advances in computational resources and atmospheric model development enable RCM simulations in convection-permitting resolutions (≤4km horizontal grid-spacing), which explicitly resolve issues related to deep convective storms (Prein et al. 2015). These models have been shown to provide more reliable simulations of sub-daily precipitation extremes and surface-atmosphere interactions (eg coastlines, orography). Since no convection-permitting climate simulations have been published for Australia (so far), a summary of relevant convective extreme studies from other areas is presented.

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

Sub-daily precipitation extremes might intensify at faster rates than daily and multi-day extremes due to dynamical and thermodynamical changes in convective storms (Kendon et al. 2014, Ban et al. 2015, Prein et al. 2017b).

Prein et al. (2017b) analysed these kinds of changes for mesoscale convective systems (eg squall-lines, TCs), which are the main cause of warm-season flooding in North America. They showed an increase in peak hourly precipitation that is approximately 7% per degree Celsius of warming and an increase in storm frequency of at least 400%. The largest changes occur in storm-total precipitation volume which can increase by up to 20% per degree Celsius of warming. This results in an almost doubling of rainfall volume at the end of the century under a high-end emission scenario.

Wind-driven rain – that is rain that is given a horizontal velocity component by the wind – can be particularly damaging to buildings due to its entrainment into building facades (Blocken and Carmeliet 2004, Cyclone Testing Station 2018, Henderson et al. 2018, Boughton et al. 2017).

While there is a good understanding of increases in rainfall extremes in the future, changes in wind hazards are less certain, and very little research has been done regarding climate change effects on wind-driven rain. In general, confidence in future changes in wind hazards depends on the storm type. Much of the wind-driven rain damage in Australia comes from either TCs, east coast lows or severe convective storms.

Wind-driven rain events might therefore intensify due to an increase in TC wind speed. Walsh et al. (2016b) showed that large-scale frontal system-related events are projected to decrease in northern and southern Australia and increase along the east coast. Projections for wind-driven rain events associated with convective storms and summertime east coast lows are highly uncertain.

Regional Interpretations for Risk Assessment for Australia

This section only contains reference to riverine flooding caused by the changes to rainfall regimes. Changes to rainfall regimes are more fully discussed in the individual sub-sections within this report dedicated to the phenomena that produce them, such as TCs and east coast lows. Antecedent conditions, clustering of events and hydrological processes (such as response to vegetation, mitigation measures and changes to watercourse characteristics), are not considered in this discussion.

From a property damage perspective, community flood risk is driven by very rare events that exceed the typical land planning threshold of 1% annual exceedance probability (AEP). However, there is very little information and research on the extreme rainfall scenarios that drive floods of this rarity at catchment scales.

The hazard component of financial riverine flood risk models requires numerical estimates of river flood AEPs and needs to be linked to related coastal and estuarine storm surges. These are strongly influenced by sea level rise changes that incorporate regional variations to the global trends, along with adjustment factors to cater for sea level variations linked to the naturally occurring climate oscillations that could be in effect at the time of the storm surges.

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

For river flooding, the general trend is for an increase in flood risk related to increases in daily and sub-daily rainfall intensity with the minimum rate of increase being of the order of 7% per degree Celsius of warming. Only a small number of detailed dynamical studies has been conducted on the impact of future extreme rainfall events on Australian river flooding.

For the larger and less populated Australian river catchments, a 7% increase per degree Celsius of warming is applied as the minimum likely future catchment-wide rainfall increase. Catchments which respond to sub-daily rainfall events could well experience significantly greater increases in catchment-wide rainfall (Wasko et al. 2016).

For larger rivers which respond to multi-day rainfall events, the predicted trends in 20-year flood return periods are available for a few rivers are assumed to also be applicable to rarer floods. The trends in return periods of floods for the larger river systems have some of the largest uncertainties of all the climate change-affected severe weather phenomena, because the hydrological responses of the major river systems are affected by numerous factors.

In the lower reaches of several east coast river systems, the effects of rising sea levels and storm surge must also be considered. A recent paper by Dyer et al. (2019) outlined how this approach is applied to selected east coast river systems.

The key factors relevant to the changing climatology of river flooding in Australia include the following (noting there are many more factors to consider including mitigation strategies, changing vegetation types and other demographic factors):

1. Natural variability across Australia has masked trends overall. However Wasko et al. (2016) showed that total rainfall and maximum precipitation intensity are expected to increase with temperature, regardless of future changes in storm sizes. This will increase flood severity for the smaller catchments but the impact is less clear for the larger catchments.

2. For the east to south-east of Australia, the NARCliM downscaled extreme precipitation model is used as a guide.

3. Observed trend in river flows, based on the Bureau of Meteorology's observed Hydrological River flow trends, is used as a guide to ongoing trends.

4. The USA work of Prein et al. (2017b) is applied to Australian regions that are considered to have similar climates to parts of the USA.

5. For New Zealand, the New Zealand Ministry of Environment Climate Change report is used as a guide, supplemented by the Clausius-Clapeyron equation trends linked to temperature rises.

For the short east coast rivers that respond to sub-daily rainfall, all flood return periods are expected to become more frequent. These events are expected to vary by catchment according to their size and the meteorological situations that produce the more significant floods.

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

4.3 Damaging Hail

Background

There is low confidence in observed trends in hail distributions because of data inhomogeneities and inadequacies in monitoring systems (Field et al. 2012). Furthermore, simulating hail in climate models is challenging because climate models are not able to resolve the processes (eg strong convective updrafts) that are necessary for hail development.

Several approaches have been developed to derive hail risk estimates that either use hail observations and claims data (Changnon and Changnon 2000, Xie et al. 2008, Changnon 2009, Barthel and Neumayer 2012); remote sensing data (Witt et al. 1998, Cecil 2009); large-scale environmental ingredients that support large hail development (Brooks 2009, Allen et al. 2015, Prein and Holland 2018); or numerical models (Mahoney et al. 2012, Brimelow et al. 2017).

Although there is considerable uncertainty, current indicators are that climate change will lead to a decrease in the frequency of small hail and an increase for large hail (see Fig. 15; Mahoney et al. 2012, Brimelow et al. 2017, Dessens et al. 2015).

There is consensus that climate change is leading to a higher potential for extreme convective storms (Gensini and Mote 2015, Púčik et al. 2017, Rasmussen et al. 2017).

Brimelow et al. (2017) used a cloud model that explicitly simulates hail embedded in climate model fields to investigate potential changes in hail risk over North America (Fig. 15). They showed that the hail damage potential is increasing over southern regions in March, April and May and over northern latitudes (north of 50°N) and the Rocky Mountains in June, July and August due to increasing buoyancy in future climates.

In the sub-tropical eastern and south-eastern regions of the USA, in contrast, they showed a strong decrease in hail damage potential due to the increase in melting of hailstones.

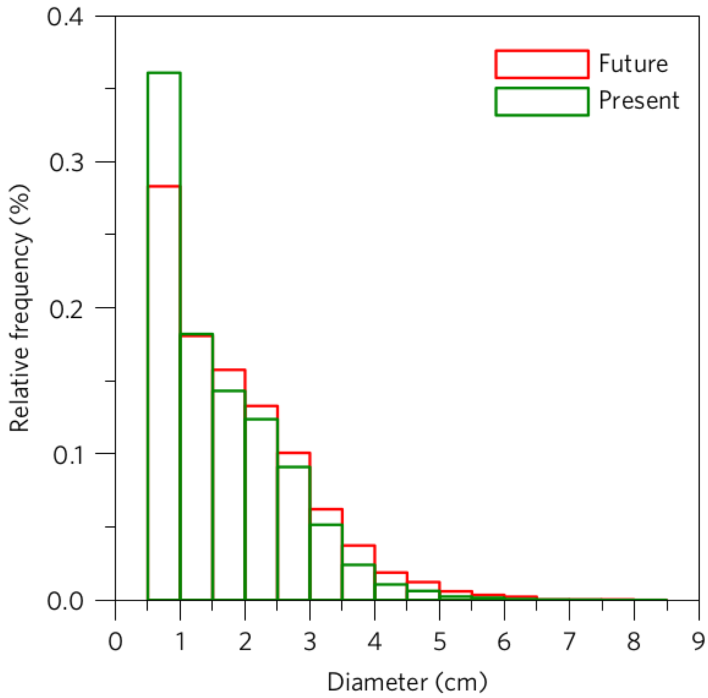


Fig. 15 *Frequency of spring hail over Colorado and the High Plains. Green bars show the relative frequency of different hail sizes in the present climate (1979-2000) and red bars show the distribution in the future climate (2041-2070) under the A2 business as usual scenario (source Brimelow et al. 2017).*

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

Changes in Australia

Observed changes

Observed changes in large hail in Australia are strongly influenced by changes in observational practices and an increase in population density. Fig. 16 shows the Bureau of Meteorology annual hail reports from 1979 to 2015; the general increasing trend of hail observations displayed is more likely to be caused by these changes rather than an increase in underlying hail occurrence.

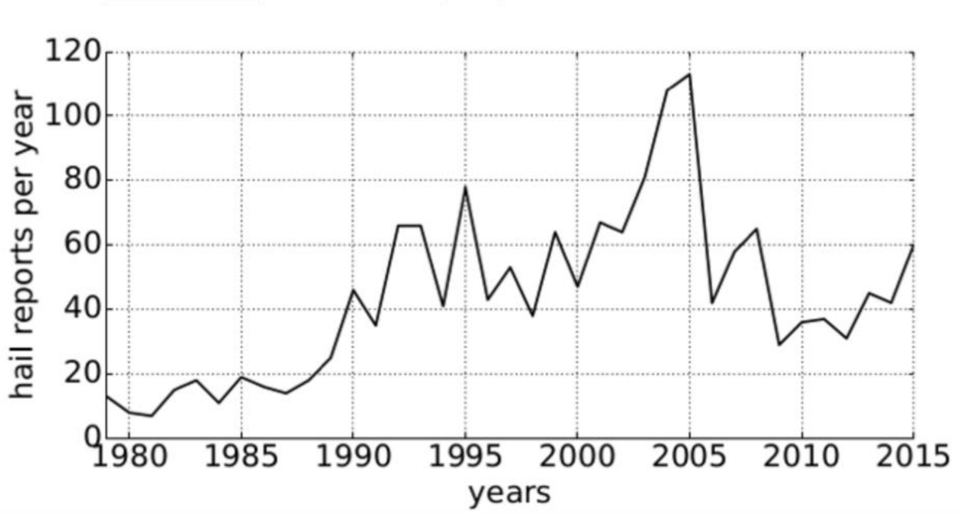


Fig. 16 *Annual frequency of large hail (diameter larger than 2.5cm) from the Bureau of Meteorology Severe Storm Archive dataset (source Prein and Holland 2018).*

It should be noted that in Australia "large hail" is defined as encompassing hail sizes from 2.0cm through to 4.9cm. "Giant hail" covers hail sizes of 5.0cm and greater. IAG's claims experience shows that most damage to property and motor vehicles starts to occur once hail reaches 2.0cm in diameter and the damage increases significantly as the size reaches and exceeds 5.0cm. In any climate change risk assessments, it is therefore necessary to consider potential changes in both large and giant hail.

IAG's claims experience, combined with investigations using the Bureau of Meteorology Severe Weather database and old media reports, highlights that major damaging hail events for Perth, Adelaide and Melbourne have been increasing in the most recent decade. When looking at the areas with the greatest impacts, there are no historical analogues prior to these major events, and these areas have been well-populated for the past century or more without any recorded analogues. For Perth, the hailstorm of March 2010 set a record for giant hail within the greater Perth region, where newspaper records are available for the past 140 years. For Adelaide, the large hail event of November 2016 set a record for hail size in the greater Adelaide area. In Melbourne, the largest hail event on record occurred in March 2010 with additional giant hail events occurring on Christmas day 2011 and in December 2017. All three of these events surpassed prior large hail-producing thunderstorms by a large margin.

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

Sydney and Brisbane have experienced multiple large-to-giant hail events throughout their history so trends here require more detailed investigation.

In an outbreak without precedent in its long historical record, Sydney has recently experienced four major hailstorm events: an event with large volumes of small hail on Anzac Day (25 April) 2015; a large hail event through the northern suburbs in February 2017; a large-to-giant hail event centred on Campbelltown on 15 December 2018; and a multi-cell giant hail event across large parts of Sydney on 20 December 2018. However, the April 1999 giant hail storm across eastern Sydney remains the costliest hail event on record and likely produced the largest reported hail size in the Greater Sydney region.

Allen and Karoly (2014) showed that there is a significant impact of ENSO on the distribution and frequency of severe thunderstorm environments in Australia. This agrees with assessments of Prein (2019) who showed a significant increase in large hail risk in south-eastern and south-western Australia during El Niño events.

Projected changes

Very little work has been performed to investigate potential future changes in Australian hail and severe convective storm risk. Allen et al. (2014a, b) assessed changes in hail environmental ingredients in two coarse-resolution GCM simulations and showed that severe thunderstorm environments significantly increased in the two models for northern and eastern Australia until the end of the century under a business-as-usual scenario (RCP8.5). This is a response to an increase in convective available potential energy (CAPE[4]) from higher moisture and warmer SSTs in the proximity of hail environments. An increase in CAPE is a likely consequence of climate change (eg Romps et al. 2014, Gensini and Mote 2015, Prein et al. 2017b).

However, other environmental changes, such as changes in wind shear and freezing/melting level heights, are also essential for future hail risk determinations, as well as the effects of topographical and meteorological triggers. A more systematic analysis of hail environments than in Allen et al. (2014a, b) with more than two GCMs is necessary to assess future changes in large hail risk and its uncertainties.

To estimate changes in hail risk on local scales, high-resolution climate models are necessary to resolve land-sea contrasts and topographic gradients that are important for hail development. Leslie et al. (2008) used a 1km climate model over the Greater Sydney Basin to assess changes in hail risk between 2001 and 2050 for a middle-of-the-road emission scenario. They also showed significant increases in the key characteristics of severe hailstorms over this region.

Regional Interpretations for Risk Assessment for Australia

The focus on this section is on the large and giant hail components of severe thunderstorms as these are considered to be the dominant drivers of severe thunderstorm risk in Australia. It must be noted that defining hail risks is far more complex than simply tracking changes in hail size.

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[4] CAPE is the amount of energy a parcel of air would have if lifted a certain distance vertically through the atmosphere. CAPE is effectively the positive buoyancy of an air parcel and is an indicator of atmospheric instability, which is used as an indication of severe weather potential.

For example, the physical storm footprint and associated damage is markedly different between a short-lived pulse thunderstorm and a long-lived supercell thunderstorm even though they may both produce the same maximum hail size. Moreover, there are other important risk drivers such as severe wind squalls, intense rainfall and related water ingress and flash flooding that need to be considered.

Projected changes in damaging hail over Australia, defined as hail of 2.0cm or greater, are highly uncertain due to a lack of research focused on this region. Therefore, climate change assessments in this paper are largely based on results from other regions, particularly the USA, and large-scale drivers across Australia that are related to damaging hail occurrence.

The key factors relevant to considering the changing climatology of damaging hail in Australia include:

1. The trends based solely upon hail observations are inconclusive due to data inhomogeneities and inadequacies in the Australian hail monitoring systems (Field et al. 2012). Nonetheless, there are some clues available from this dataset for eastern Australia.

2. Much of the future climate trend projections were determined by extrapolating observed trends in hail environments from the ERA-Interim reanalysis dataset (Prein and Holland 2018), with the mean hail environments across this period serving as a gap-filler for the base climatology of large hail across Australia where other observational datasets were considered inadequate. The ratios between observed large and giant hail for Bureau of Meteorology forecast districts where there are sufficient observations to estimate relationships, as provided by Prein (2019) based upon his analysis of the Australian Severe Thunderstorm database, are also considered.

3. The IAG-sponsored Greater Sydney hail modelling work of Leslie et al. (2008) is specifically applied to the Greater Sydney and surrounding regions out to the year 2050 and serves as a guide for the +2°C hail risk estimates. Consideration is also given to the work of Brimelow et al. (2017) for North America which showed a predicted trend to larger hail sizes in continental and mid-latitude regions and decreases in sub-tropical environments under the RCP8.5 climate change scenario.

4. IAG's combined hail claim experience for the Perth, Adelaide and Melbourne areas is used as tentative evidence of the likely southern shift in the areas of greatest hail risk. It is noted that a much longer length of record is needed to derive statistically significant results. It is also important to note that by the time there is sufficient length of claims data to demonstrate statistical significance, the changes will have been in effect for a decade or more.

The main trend imposed on the current Australian climatology of damaging hail is to shift the hail risk regions southwards down the eastern coast and ranges, based upon:

- The predicted southward shift of the sub-tropical jet stream;
- The general increases expected in atmospheric instability (CAPE) with increased heating and stronger updrafts expected in severe thunderstorms in a warmer environment;
- Rising melting levels in the thunderstorm environments which should reduce large hail in near-tropical areas with lesser effects on damaging hail southwards;

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

- Changes in thunderstorm triggers in a warming climate linked to the southward shift of the sub-tropical ridge axis and deepening of the eastern Australian inland trough; and

- Observed tentative trends in large and giant hail using the Australian severe weather database and IAG's claim experience across southern regions, but noting significant limitations in both sources of data.

Fig. 17 describes the regional changes to large and giant hail storm frequencies across Australia between the base climatology and the approximately +3ºC climate change scenario.

Based on large-scale drivers, the largest projected changes to the current climate hail climatology in a warmer Australia are likely to be concentrated over eastern to south-eastern New South Wales and eastern Victoria, especially in the following areas: Melbourne; the mountainous parts of eastern Victoria; the southern to central ranges and coastal plains of New South Wales; and the Australian Capital Territory.

These trend estimates are based on the predicted deepening of the east coast trough; southward shift of the north-east New South Wales to southern Queensland dry-line; and increased coastal moisture availability from the observed rapidly warming East Australian Current. The southward shift of the sub-tropical ridge axis could also affect the location, frequency and intensities of the severe thunderstorm-triggering coastally-trapped southerly changes that frequent the New South Wales and south-east Queensland coasts.

Increases are also applied to the agricultural and west coastal areas of south-west Western Australia, although the starting point is from a much less frequent base. Here the west coast trough is expected to deepen and lead to a southward shift of the location of the coastal crossing point when the trough is at its deepest. This is typically when it triggers severe thunderstorms, due to increasing low level shear, coupled with rapidly rising maximum temperatures and increased moisture availability from the warming Leeuwin Current off the west coast of Western Australia, and the warmer seas off the Pilbara and Gascoyne coasts. An expected higher hot season melting level in this region could partially offset other factors, although this is expected to only reduce the occurrence of smaller size hail. The impact on damaging large and giant hail is less clear. There are tentative indications that the steering flows of severe thunderstorm are becoming more meridional during the warmer seasons.

Studies available for other parts of the world indicate these risks are most likely to increase. These increases might be partially offset by reduced hail risks for large parts of tropical and central Australia, including most of Queensland where increased daytime heating and CAPE could be offset by the rising atmospheric melting levels, based on research from the USA (Brimelow et al. 2017).

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

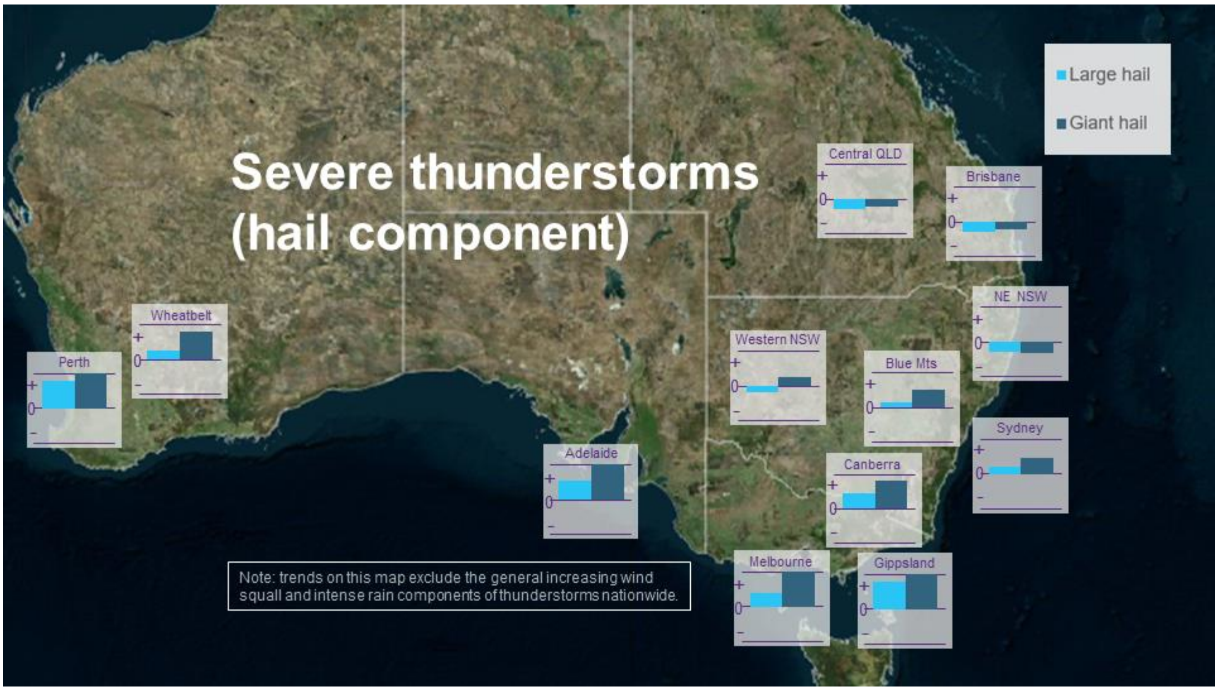

***Fig. 17** Schematic graphs showing the relative change in large and giant hail storm frequency between the 1950s and the +3ºC climate change scenario.*

4.4 East Coast Lows

Background

East coast lows are systems that bring heavy rain and/or high winds to the eastern Australian coast. Their impact range has typically been from Fraser Island to the Victorian border, but this was somewhat arbitrarily defined by Hopkins and Holland (1997) and used by subsequent studies. Other nearby areas experience similar systems.

East coast lows are relatively infrequent phenomena that are noted for their extreme characteristics and high impacts. These characteristics have been described in several studies (eg Holland et al. 1987, Hopkins and Holland 1997, Mills et al. 2010, Dowdy et al. 2013a, Pepler et al. 2014, Louis et al. 2016). They include:

- Heavy rains on the poleward side, resulting from moist tropical air being advected around the low and into the coastal region. These rains may extend for some distance down the coast, but extreme rains are often constrained to a narrow rainband (~100km across) and are marked by a sharp transition to fine conditions to the north of the centre.

- Damaging winds that may exceed tropical storm force and are typically located in a narrow (usually <100km) zone poleward and westward of the centre.

- Localised ocean currents and waves may cause considerable damage to coastal foreshores, including structures.

- Storm surge is rarely much over 1-2m, as the primary damaging wind direction is along the coast – the exception may be surges produced by a small, intense low right on the coast.

- The occurrence of a wide range of sizes and lifetimes of storms, from small, intense storms that lasted 10-15 hours (eg the Sygna storm, Bridgeman 1986) to large, long-lived systems that may impact the east coast for days.

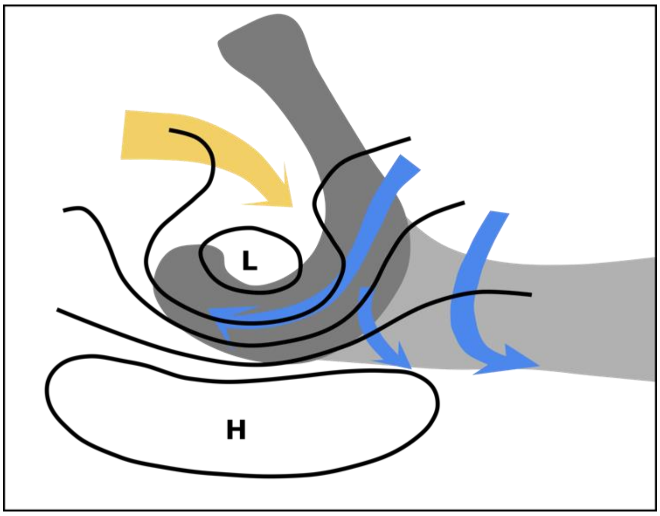

Fig. 18 *Schematic of the environmental flow around one type of east coast low: Solid lines indicate the surface pressure pattern; darker (lighter) shading indicates convective (stratiform) cloud; the brown arrow indicates subsiding dry air flow; and the blue arrows indicate rising, moist tropical air (modified from Holland et al. 1987).*

- They are often accompanied by rapid intensification, which satisfies the 'bomb' criteria of Sanders and Guyakum (1980).

The conditions associated with east coast low development include (Fig. 18):

- A characteristic cut-off low and/or split jet configuration (eg Holland et al. 1987, Dowdy et al. 2013a).

- The presence of a strong anticyclone or ridge on the poleward side, with the east coast low cradled in an Easterly Dip being one of the more common configurations (eg Holland et al. 1987).

- Development over an area of strong SST gradients (typically >4ºC in 50km) associated with eddies along the East-Australian Current (eg Hopkins and Holland 1997, McInnes et al. 1992, Chambers et al. 2014, 2016).

East coast lows are an Australian phenomenon, but there are similar systems elsewhere (see Dowdy et al. 2013a for details). Examples include: the 'Northeasters' of the USA north-east coastal region; the Hawaiian Kona storms; storms off the east coast of South America; and perhaps even the explosively-developing storms that affect Europe from the Atlantic.

Climatology

Three known observational databases have been developed, and two of these are still available (Speer et al. 2009, Pepler and Coutts-Smith 2013). However, systematic study of these systems is hampered by the variety of definitions employed.

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

The Bureau of Meteorology defines east coast lows as intense lows off and near the coast (http://www.bom.gov.au/nsw/sevwx/facts/ecl.shtml). More objective definitions include the following:

- Holland et al. (1987) introduced three types based on their basic characteristics and development mechanisms;
- Hopkins and Holland (1997) introduced a fourth type of low, then focused on Type 2 East Coast Cyclones, which they defined based on their rainfall and wind characteristics; and
- Speer et al. (2009) defined six types of Maritime Low based largely on their surface characteristics (these included systems that would not normally be considered an east coast low).

Others have developed automated east coast low identification methods based on various surface pressure characteristics (Browning and Goodwin 2013, 2016, Dowdy et al. 2011, Murray and Simmonds 1991). Dowdy et al. (2013a, 2013b) defined east coast lows empirically based on upper level characteristics known to be associated with their development.

Pepler et al. (2015) compared some of these automated systems and used three such systems in considering potential future changes. All of these latter approaches are not capable of identifying the small, intense systems that have historically had major impacts, despite their small size.

This variety of definitions is reflected in assessments of the impacts of such storms. While there is no doubt about systems with major impacts such as the 1974 Sygna Storm (Bridgeman 1986) or the 2007 Pasha Bulker Storm (Mills et al. 2010), different studies have attributed a wide range of characteristics to east coast lows in general, describing (Hopkins and Holland 1997, Speer et al. 2009, Callaghan and Power 2014):

- The estimated number of systems per year has varied from 2.5 to 22.
- The proportion of east coast floods or heavy rains caused by east coast lows has been assessed to vary from 16% to 57% and even up to 100%.
- Some studies include transitioning TCs under east coast lows; others have them as a separate system.

Given this level of ambiguity, it is recommended that these previous studies be used to develop a consistent approach applicable to both re-analyses and climate modelling studies. An excellent starting point would be the Dowdy et al. (2013a) approach, complemented by inclusion of SST characteristics. The resulting data base should then be used to develop a comprehensive climatology, an assessment of past and current changes, and perhaps a quasi-analytic approach to defining potential impacts as has been done for TCs. This is further discussed in a following section.

Above concerns aside, some useful climatological information is available.

Seasonal occurrence

Taken together, east coast lows exhibit a maximum occurrence in winter (Hopkins and Holland 1997, Callaghan and Power 2014) and this is reflected by a secondary peak in deaths from freshwater flooding (Fig. 19, right). This overall seasonal variation may be regionally- and system-dependent. Hopkins and Holland (1997) found that the maximum occurred in summer for a small region along the east coast of New South Wales, and the maximum from tropical transition obviously occurs in summer (Speer et al. 2009, Callaghan and Power 2014).

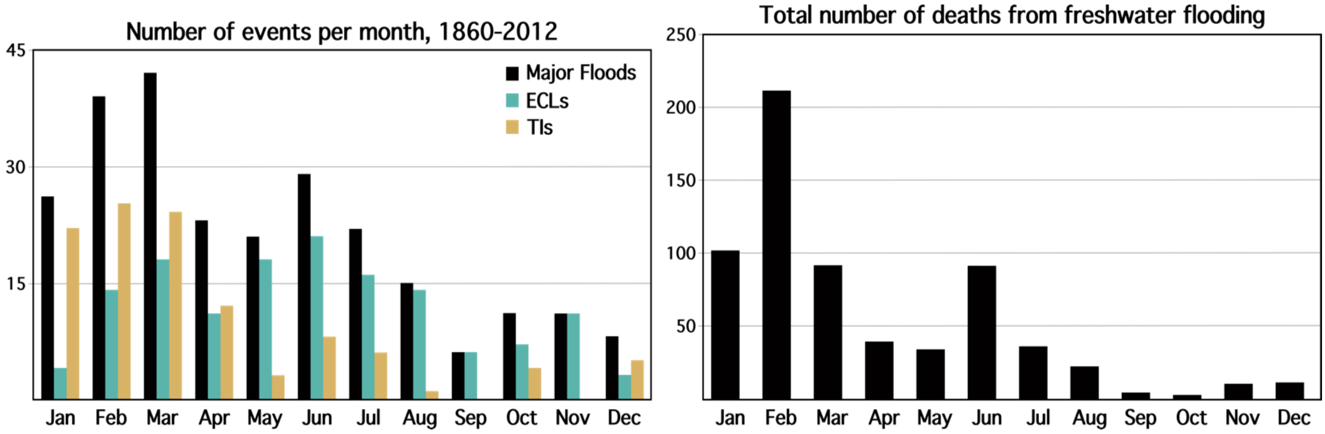

Fig. 19 *Seasonal east coast low occurrence variation.* ***Left panel:*** *Monthly occurrence of east coast lows, TIs (Tropical Interaction - essentially transitioning tropical lows or cyclones) and Major Floods (the sum of the previous two).* ***Right panel:*** *bimodal peak in deaths associated with major flooding events (modified from Callaghan and Powers 2014).*

Interannual and interdecadal variation

There is good evidence for a close association between east coast lows and related flooding and freshwater drownings, and the ENSO cycle (Fig. 20, Chiew et al. 1998, Power and Callaghan 2016, Browning and Goodwin 2016). Micevski et al. (2006) and Power and Callaghan (2016) also found a longer period fluctuation in phase with the Interdecadal Pacific Oscillation, which Power and Callaghan showed resulted in long-period variations in decadal occurrences of 7 to 26 floods, 2 to 15 east coast lows and 3 to 114 deaths.

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

Changes in Australia

Observed changes

Hopkins and Holland (1997) found a significant increase in the number of east coast lows from 1958-1992, but this may have been due to a natural fluctuation in frequency.

It also was not reproduced in the modelling study by Browning and Goodwin (2016). Hopkins and Holland (1997) also found no trend in heavy rain occurrences and a decrease in the frequency of extreme convective rain events.

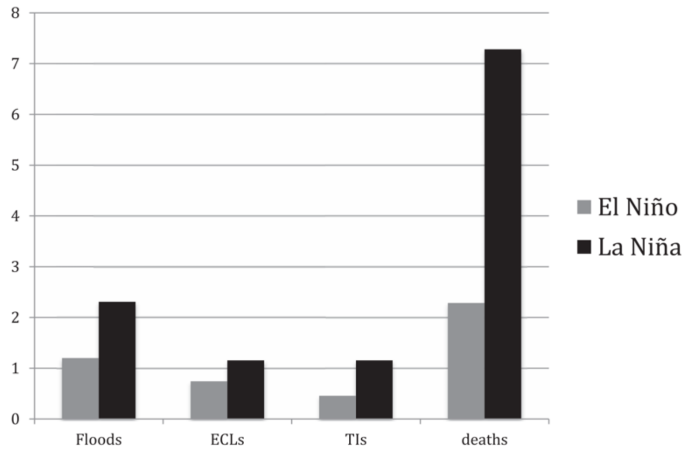

Fig. 20 Increased occurrence of coastal floods, east coast lows, Tropical Interactions and related deaths during El Niño and La Niña years (from Power and Callaghan 2016).

By comparison, Powers and Callaghan (2016) found a significant, 50% increase in frequency of major floods since 1860 arising from east coast lows (Fig. 21). Part of this increase may be a result of increasing populations and improved observing systems. Also, a closer examination of the changes indicates that rather than a linear trend, there was a marked shift upwards around 1950 followed by nearly constant, or perhaps declining, frequency. This is in agreement with Franks (2002) who found a marked climatic change from low to high flood frequency around 1945.

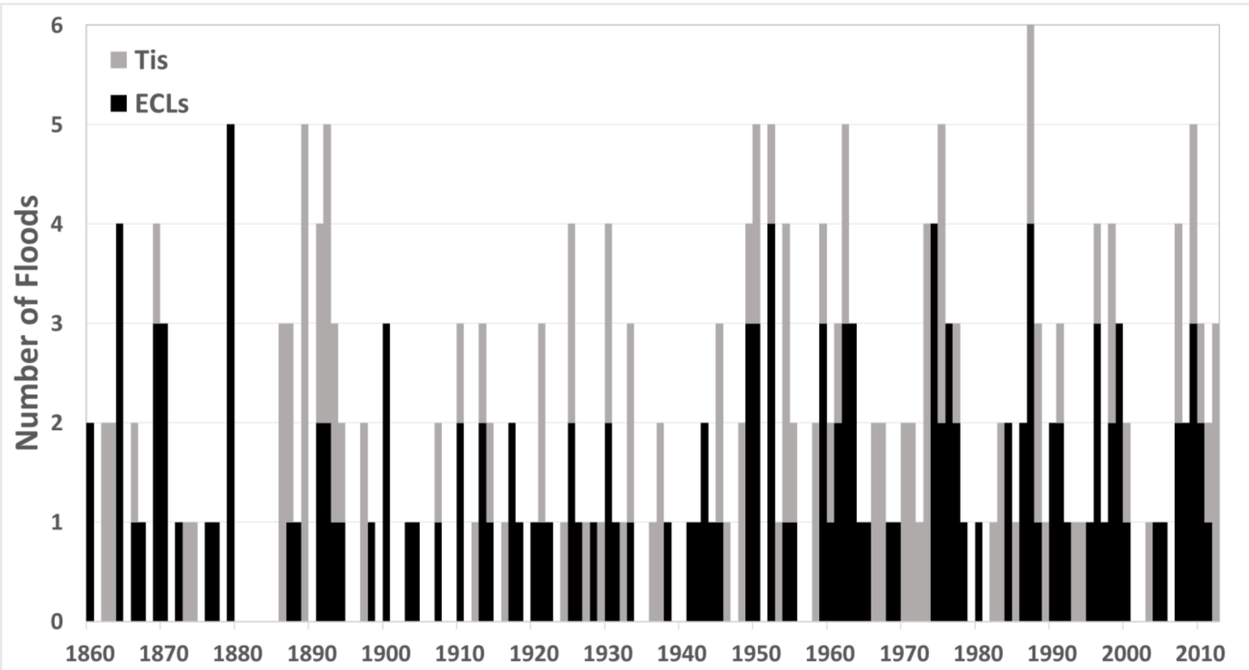

Fig. 21 Annual frequency of east coast lows (black) and Tropical Interactions from 1860 (modified from Power and Callaghan 2016).

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

Projected changes

Future variations associated with anthropogenic climate change have been assessed by Dowdy et al. (2013b) and Pepler et al. (2016). Both used the Dowdy et al. (2013a) upper-air diagnostic approach while Pepler et al. (2016) also added three other surface low diagnostic tools. Both found a significant decrease in the frequency of intense east coast lows during the 21st century. However, these assessments go against the observed trends in east coast lows. Further, the models used have coarse resolution (50km or more), which cannot resolve many east coast lows and the high SST gradients critical to east coast low development and impact (see, eg McInnes et al.1992). So these trends should be regarded as preliminary indications only.

Given the importance of potential changes in east coast lows with climate change, it is recommended that this subject be a priority for research. This should:

- develop an agreed definition of an east coast low, perhaps based on potential vorticity, which should perhaps differentiate distinctly different systems, such as TCs undergoing extratropical transformation, small Sygna-like systems, and large easterly dip systems;

- develop a climate change approach valid for each type of system, which may include a substantial component of expert judgement, given the poor capacity of climate models to resolve the damaging components of these systems; and

- examine expanding the statistical atmospheric relationship of Dowdy et al. (2013a) for use in re-analyses and climate models by including information on SSTs (particularly strong gradients).

Regional Interpretations for Risk Assessment for Australia

Risk assessment models for east coast lows would need to cover all wind, rain and oceanic-related damage driver elements and rely on consistent definitions for each type and climatology databases as described earlier.

The estimated changes to east coast low risk are based solely upon those types known to produce significant damage and/or river and flash flooding along the east coast inland to the ranges, and sometimes further west, of New South Wales and south-east Queensland.

The more common but predominantly offshore types are of less interest as they result in far less damage to properties on the mainland and coastal fringe. Trends in these non-damaging east coast lows can mask the more important trends in the rarer, but very damaging, east coast lows.

The east coast lows of greatest interest tend to be most closely aligned to those described in Holland et al. (1987), although there are several other definitions used. Trends in “bombing” east coast lows, along the lines of Sanders and Guyakum (1980), are particularly relevant.

The base climatology is a mix of that provided by Speer (2009) and Pepler and Coutts-Smith (2013), relating the east coast low events back to historical insurance claim records of significant damage along the coast and ranges of eastern Australia.

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

Even so, to adequately quantify trends, a rigorous look at the climatology followed by higher resolution modelling studies of future changes is needed. In the interim, the future trends are adapted from the work of Dowdy et al. (2013a) and Pepler et al. (2016).

The predictions are generally for a decline in both overall and wintertime east coast lows, without specifying the sub-types.

Offsetting this is a predicted increase in summertime and intense east coast lows. This is likely to be supplemented by those with tropical origins, including TCs that have completed extratropical transition or have undergone structural changes as they move into south-east Queensland and northern New South Wales.

It is noted that none of the future climate modelling studies have been completed at a high enough resolution to resolve the intense small-scale secondary lows within the larger east coast lows that typically produce much higher damage, as observed in the Pasha Bulka east coast low in 2007 and the Sygna storm in 1974. The changes in the intensity and duration of their associated rainfall is also not in a usable form for quantifying trends in risks.

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

4.5 Bushfire

Background

Bushfire is a result of interactions between weather, climate, vegetation and people.

This complex interaction makes it challenging to simulate, especially since most global fire activity is directly attributable to people. In an observational study covering 1979 to 2013, Jolly et al. (2015) showed that fire weather seasons have lengthened by 18.7% globally, resulting in a doubling of the global burnable area affected by long fire weather seasons.

In their 2009 review paper, Flannigan et al. stated that climate change will lead to a general increase in area burned and fire occurrence, but the spatial variability of this result is large. Moritz et al. (2012) showed that GCMs simulate an increase in fire risk in warm climates for the period 2010 to 2039 and some decreases in tropical and sub-tropical climates (Fig. 22 upper panel). However, GCM agreement for this result is low, which indicates large uncertainties in changing fire hazards for limited global warming.

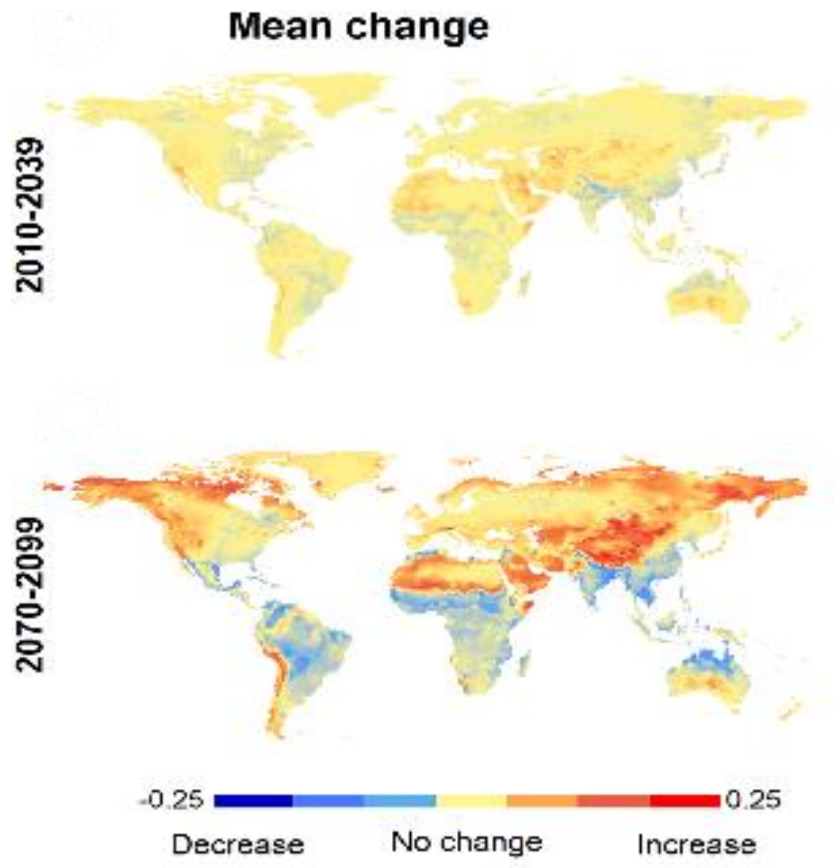

Fig. 22 *Ensemble mean change in predicted fire probability from 16 CMIP3 GCMs for 2010–2039 and 2070–2099 time periods compared to the baseline probability (1971–2000; source Moritz et al. 2012).*

At the end of the century, under a high emission scenario, the magnitude of changes and the agreement between models increases substantially (Fig. 22 lower panel). Increases in fire risk are projected for most mid-to-high latitude regions and decreases are found in the tropics.

Changes in Australia

Observed changes

The McArthur Forest Fire Danger Index (FFDI; McArthur 1967) is used to monitor fire weather in Australia, based on daily temperature, wind speed, humidity and a drought factor (Lucas 2010). The annual cumulative FFDI shows increases at almost all sites with significant increases at 42% of the sites within the period 1974-2015 (Bureau of Meteorology and CSIRO 2016; Fig. 23).

The increase is particularly strong in south-east Australia and is primarily related to temperature increases. Societally and economically, severe fire conditions that can lead to extreme bushfires with devastating effects are particularly important. These events typically have FFDI>40 resulting in a very high chance of house destruction (Bradstock and Gill 2001). Historic information suggests an increasing occurrence of extreme bushfires in recent decades (Sharples et al. 2016).

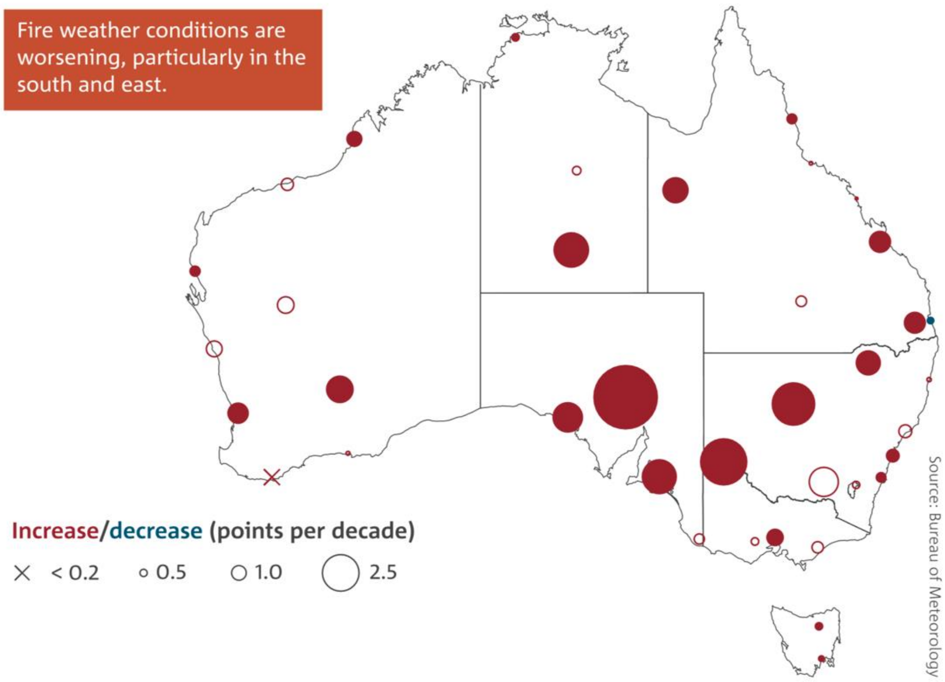

Fig. 23 *Trends in the annual 90th percentile of FFDI. Trend magnitudes correspond to the size of the marker with filled markers showing significant trends for the period 1974-2015 (Source Bureau of Meteorology and CSIRO 2016).*

Projected changes

There is high confidence that climate change will lead to an increase in the average FFDI and a higher frequency of days with severe fire danger in southern and eastern Australia (CSIRO and Bureau of Meteorology 2015, Moritz et al. 2012, Clarke et al. 2011).

This will result in reduced intervals between fire events, a higher fire intensity, lower fire extinguishments and an increase in fire spread (Hennessy et al. 2007).

Hennessy et al. (2005) estimated that by 2050, the frequency of extreme fire danger will increase by 15-70% in south-east Australia. Similar increases are predicted for the Bay of Plenty, Wellington and Nelson regions in New Zealand (Pearce et al. 2005).

Very little work has been done on changes in extreme bushfires but there is a large potential that they will significantly increase in frequency in the future (Sharples et al. 2016).

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

Under 4°C warming, the frequency of days with FFDI>40 has the potential to increase by more than 200% in eastern Australia during the fire season (Clarke et al. 2011). Lucas et al. (2007) suggested that the number of extreme fire danger days (FFDI>50) could increase by 15 to 65% by 2020. By 2050, the increases could be as high as 100 to 300% (relative to 1990).

Furthermore, an extension in the length of the fire season will reduce the window of opportunity for fuel-reduction burning to winter (Hennessy et al. 2007). These changes are due to increasing temperatures and drying in these regions.

Little change in fire hazard is expected in tropical and monsoonal north Australian regions (medium confidence) while changes in arid inland areas are uncertain (CSIRO and Bureau of Meteorology 2015).

Regional Interpretations for Risk Assessment for Australia

There is compelling information that bushfire is one of the fastest growing climate risks facing Australia (Sharples et al. 2016). However, there is limited information in the literature about trends in the extreme and catastrophic bushfires that typically drive most of the property bushfire risk.

The FFDI, or similar indices, is widely used as a measure of the atmospheric conditions that drive bushfire occurrence and severity. However, there are many other aspects that need to be considered, including available biomass, fuel moisture, land use and demographics, bushfire prevention and combat activities. The Bureau of Meteorology and CSIRO (2016, 2018) have provided simple observed trend maps of the 90th percentile of the FFDI for a small number of locations (Fig. 23) as well as the observed trend in summed daily FFDI for the period between 1978 and 2017 (Fig. 24).

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

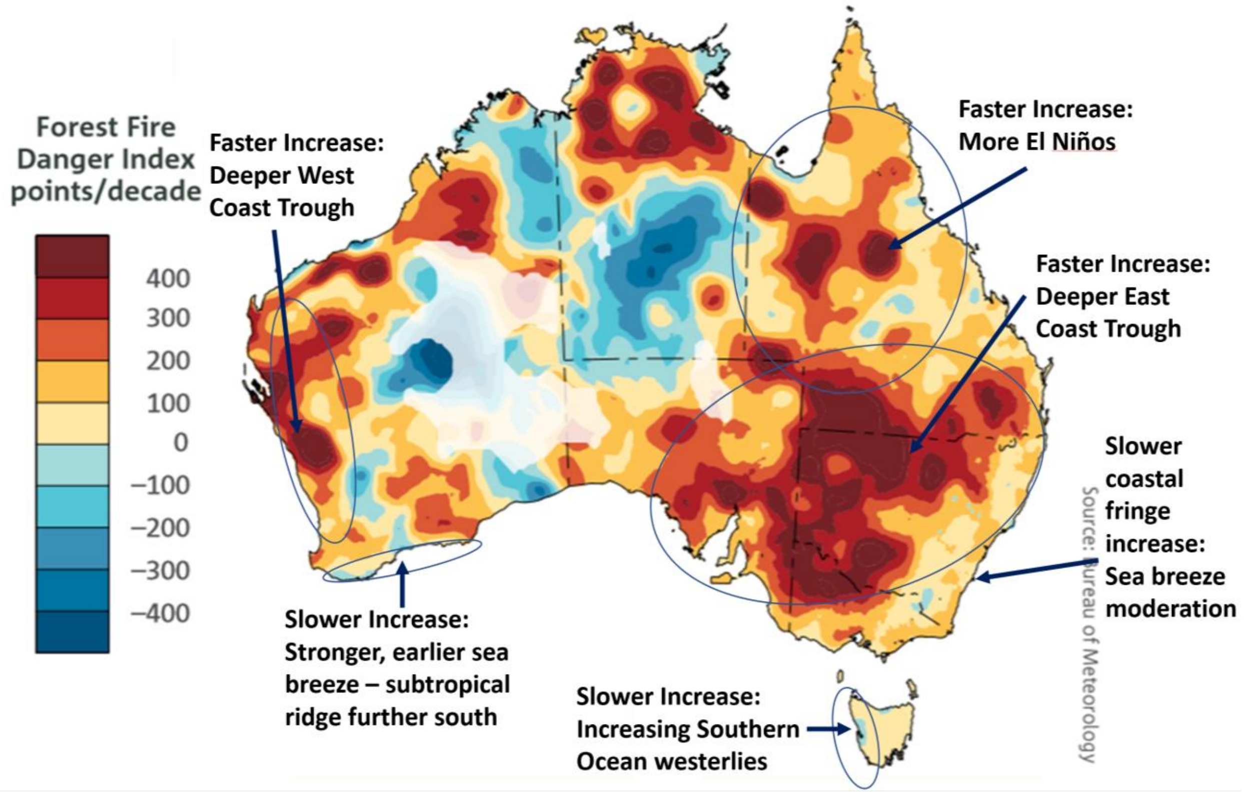

Fig. 24 *Meteorological modifiers likely to regionally amplify or temper the rate of increase of bushfire risk, superimposed upon the Bureau of Meteorology's observed trend map of the sum of daily FFDI in points per decade, between 1978 and 2017.*

Noting the limitations mentioned above, the FFDI data can be combined with known trends in weather systems to produce an initial view of changes to bushfire risk at a regional level. This is illustrated in Fig. 24 and summarised below:

1. The future climate predictions across Australia from the available science are inconsistent in terms of the measures of fire danger used and how they are likely to change in the future. Although the maps in Bureau of Meteorology and CSIRO (2016, 2018) serve as a guide, the predictions from Lucas et al. (2007) using the CSIRO MK3 high scenario results for spot locations then applied to the surrounding districts are used as the initial basis for the changing bushfire risk. This is checked against the Sharples et al. (2016) research.

2. For Tasmania, the work of Fox-Hughes et al. (2015) serves as a general guide to expected trends for the south-east of Australia.

3. For Perth and the south-west of Western Australia, the Climate Council Report on Western Australian bushfires (Steffan et al. 2015) is used as a guide, adapted to be consistent with the remainder of Australia.

4. Consideration is also given to the meteorological modifiers likely to be present on the days when there are some of the more extreme bushfire conditions. For the more populated South West Land Division of Western Australia, these include the presence of a deeper west coast trough, which becomes deeper due to the increased heating of the land and amplifies the bushfire risks, and the corresponding increase in the strength of the south coast sea breeze for Western Australia as the sub-tropical ridge shifts southwards with the warming climate, tempering the rate of increase in risk.

5. For a large part of south-eastern Australia, the warming climate supports a more persistent east coast trough which tends to support longer periods of high bushfire risk conditions. This is slightly tempered on the east coastal margins by the persistent sea breeze effects.

6. For large parts of Queensland, the trend towards a faster increase in SSTs in the central equatorial Pacific Ocean relative to the Coral Sea produces more El Niño-type weather patterns that support longer hot and dry spells across eastern Australia, conducive to the repeated occurrence of severe bushfire conditions.

7. For the west coast of Tasmania, the rate of increase in bushfire risk is tempered by the observed trend of increasing speed of the Southern Ocean westerly winds.

There is significant scope for next generation models like NARCliM (1.5 and 2.0) to provide a more comprehensive and granular base for establishing fire weather risk indices and understanding the impacts of climate change.

4.6 Sea Level Rise

Background

Sea level rise is a combination of the thermal expansion of warming ocean water, meltwater run-off from ice sheets and glaciers, and changes due to rises and subsidence of the Earth's crust.

Globally, sea level has risen by 240mm from 1880 to 2017 and it continues to increase by approximately 3mm per year (Church and White 2011, Sweet et al. 2017, Nerem et al. 2018). The rate of increase has accelerated over time at a rate of $0.084 \pm 0.025 mm/yr^2$ and is expected to continue to accelerate (Nerem et al. 2018). The rate of increase since 1993 is close to the upper end of CMIP3 and CMIP5 GCM projected changes. The component since 1960-70 is directly attributable to anthropogenic climate change (Slangen et al. 2016).

It is very likely that areas that are already affected by coastal erosion and inundation will continue to be affected in the future (Field et al. 2012). Local sea level rise can deviate significantly from the global mean due to differential heating of ocean areas; changing wind systems and ocean currents; and land movements (Fig. 25; Nicholls and Cazenave 2010). Until the end of the century, climate models project an increase in sea level of 45 ± 17cm for the RCP2.6 scenario and 75 ± 23cm for the RCP8.5 scenario (IPCC 2013).

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

Empirical estimates of sea level rise for the end of the century suggest much larger increases with values up to 1.8m (Vermeer and Rahmstorf 2009). It is important to realise that except for the RCP2.6 scenario, the sea level will continue to rise after 2100. Global temperature increases beyond 2^{o}C increase the risk of rapid increases in sea level due to melting of major parts of ice sheets in Greenland and Antarctica. The global sea level could potentially rise by ~70m if both ice sheets completely melt (Alley et al. 2005). It is uncertain when this may occur, but transitions can happen rapidly once tipping points are crossed.

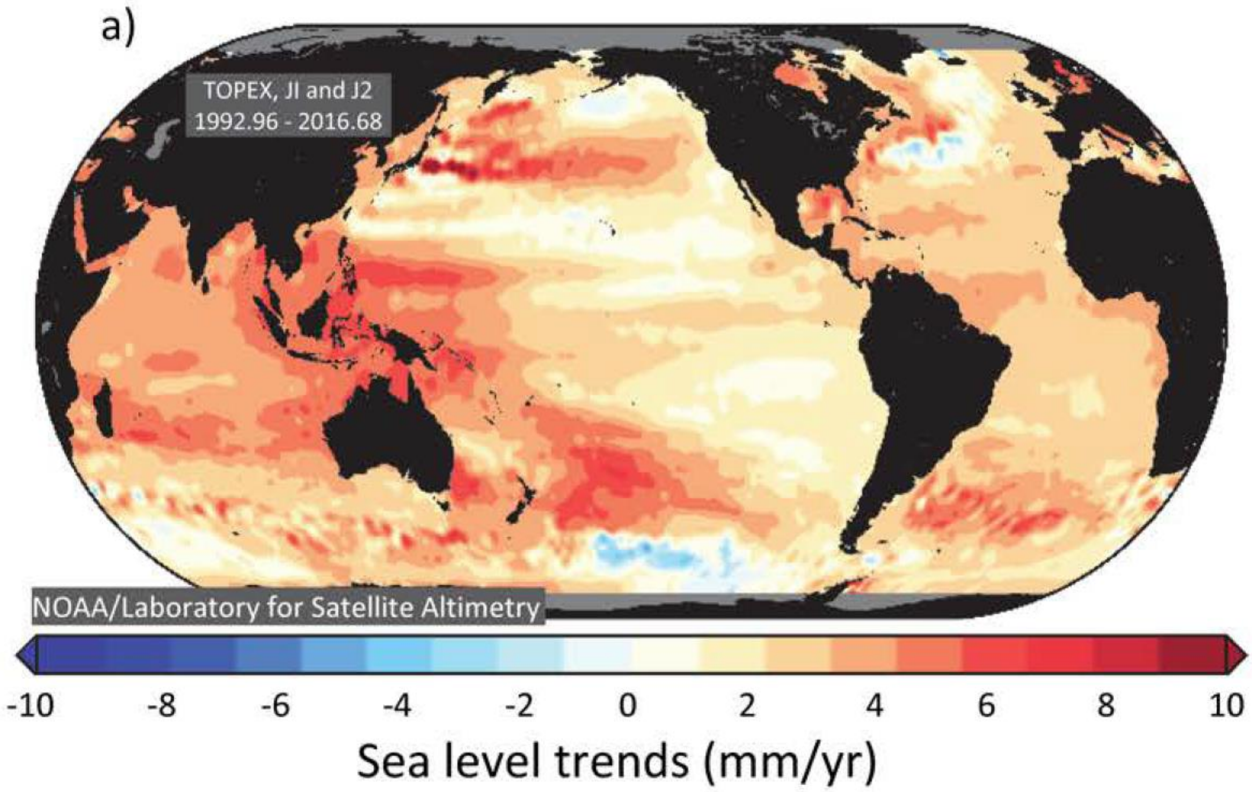

Fig. 25 *Satellite observations of regional sea level trends for the period October 1992 to July 2016 (source Sweet et al. 2017).*

Changes in Australia

Observed changes

Most of Australia experienced above global average sea level changes during the recent decades, with hotspots in the Tasman Sea and northern and Western Australia where rates were up to four times the global average (Nicholls and Cazenave 2010). Removing the influence of ENSO on sea level rise reduces the difference in trends between locations (White et al. 2014). Further removing the influence of Glacial Isostatic Adjustment (ongoing movement of land once burdened by ice-age glaciers) and atmospheric pressure effects results in Australian sea level trends that are close to the global mean trends from 1966 to 2010.

Projected changes

Australia is projected to continue to experience above global average sea level rise throughout the 21st century with rates up to 30% above the global average (Fig. 26; Slangen et al. 2012). The highest increases are simulated in the Tasman Sea. Different emission scenarios differ in the amount of regional sea level rise but are consistent in the spatial patterns. Slangen et al. (2012) identified the steric contribution (sea level rising because of changes in ambient temperature and salinity) as the dominant source of regional variability. However, an improved representation of ice sheets and glaciers in next-generation earth system models that can simulate extreme ice loss scenarios might change this assessment.

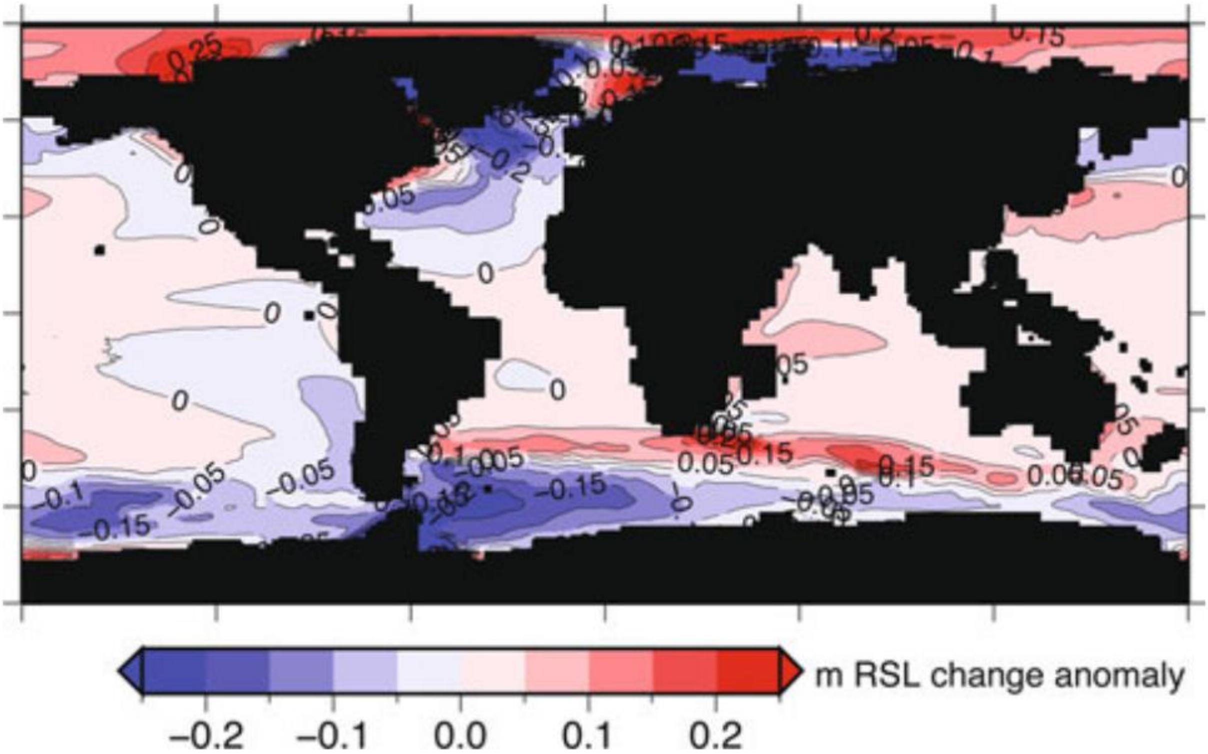

Fig. 26 *GCM ensemble mean sea level anomaly relative to global mean sea level changes under the A1B emission scenario (0.47m) between the periods 1980–1999 and 2090–2099 (source Slangen et al. 2012).*

As discussed in Section 3.3, moderate changes in the mean can have dramatic effects on extremes. Wahl et al. (2017) investigated changes in the return period of the 100-year extreme sea level under the RCP4.5 emission scenario until mid-century. For Australia, they showed that the historic 100-year extreme sea level height could occur annually for a large number of sites along the Australian coastline (see Fig. 27). Rapid changes are predicted especially for the densely-populated Australian east and south-east coasts, as well as the New Zealand North Island.

4. CHANGES TO EXTREMES FOR DIFFERENT WARMING SCENARIOS

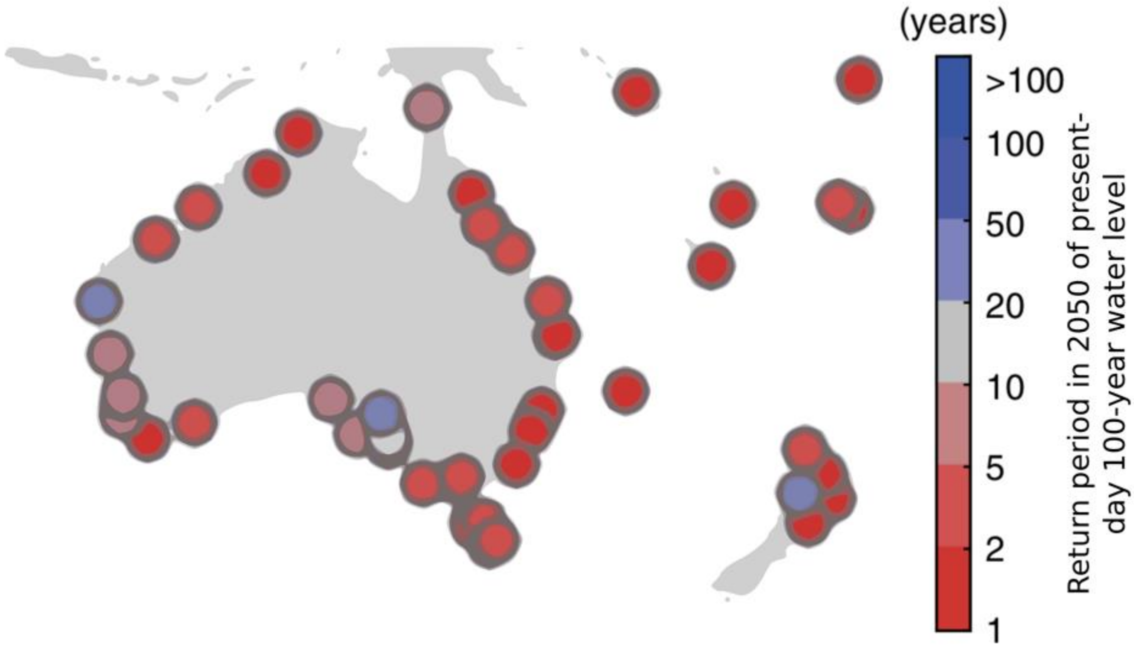

Fig. 27 *Changes in the 100-year return period of extreme sea level height until mid-century under RCP4.5 (source Wahl et al. 2017).*

Regional Interpretations for Risk Assessment for Australia

Sea level rise, combined with changes in weather patterns, has a compounding effect on coastal risks such as storm surge, riverine flooding, wave action, coastal erosion and recession.

The key guidance in quantifying regional sea level rise impacts is derived from the NOAA Sea Level Rise Report (Sweet et al. 2017) and observed trends as documented by the Bureau of Meteorology and CSIRO (2016, 2018). The key considerations are summarised below:

1. The NOAA (2017) Table 5 intermediate–high values are used, given the observed rate of increase in global greenhouse gas emissions is following the RCP8.5 scenario.
2. The observed trends in regional sea level rises are applied through to 2040 under the +2^{o}C scenario. Thereafter, it is kept constant out to 2070 under the +3^{o}C scenario, as a greater- than-average rate of increase in regional sea levels is not sustainable in the long term.
3. Some subjective adjustments are made to account for the expected southward shift in TC impacts on both the east and west coasts.
4. Slight changes are made to account for the expected increased risks of summertime east coast lows and reduced risk of wintertime east coast lows, as well as a general southward shift in the mean tracks of mid-latitude lows and frontal systems.
5. The future estimates used, particularly for the +3^{o}C scenario, are likely to be conservative in the face of emerging cryospheric research into ice sheet collapse and weakening of the Antarctic ice sheet grounding mechanisms (ICCI 2016).

5. CONCLUSIONS

This paper provides a comprehensive review of the latest climate change science in the Australian region, with a focus on weather and climate perils that drive property risk.

Climate change is not just about the future: there is already solid evidence that there have been measurable changes to weather and climate extremes with the warming to date.

Although the impacts of climate change at larger geographical scales and longer time frames are quite well understood, they can mask nuances that can differ significantly at a regional and local level.

That has driven the approach to preparing this report. It combines the extensively-available literature with well-considered expert judgement to gain a better understanding of how climate change influences the various perils in the Australian region (as summarised in Table 1).

From this continental scale information, this report goes one step further to derive regional scale insights that aim to provide meaningful direction and trigger further collaboration and co-ordination amongst communities, academia, businesses and government. The key assessments are:

1. The frequency of named tropical cyclones in the Australian region has declined in recent decades; the detail of how this will project into the future is unknown, although globally there is expected to be a further slight reduction in total numbers. However, the frequency of tropical cyclones making landfall throughout the western South Pacific region has increased. Over the past 30 years, the proportion of the most destructive tropical cyclones has increased at the expense of weaker systems, and this change is expected to continue.

   There has already been a southward shift of the regions where tropical cyclones reach peak intensity and this is expected to continue. Tropical cyclone risks are therefore expected to increase most rapidly in the south-east Queensland / north-east NSW regions, followed by the coastal districts south of Shark Bay in Western Australia.

   Marginal decreases in risk for wind impacts may occur in some other regions. Planning for inland penetration of tropical cyclones should be based on substantial increases in both rainfall rate and affected areas. Winds are also likely to decay more slowly, so increased wind-driven rainfall ingress should be expected both at the coast and inland. More intense storms combined with rising sea levels point to increasing storm surge impacts, and these may be very substantial in some regions.

2. Intense short duration rainfall is expected to increase almost everywhere in Australia, resulting in more frequent flooding in urban areas and in small river catchments. Storm rainfall totals from both east coast lows and tropical systems are also expected to increase, leading to increasing flood risk in the larger river catchments. More work is required to fully understand and confidently assess these changes.

3. Areas at risk of large and giant hail should progressively shift southwards, with the largest increase in risk likely to be in the region inland from the Hunter River south through the central and southern New South Wales highlands and central to eastern Victoria. Fewer increases are assessed to affect the south-west of Western Australia while severe hail risk is expected to decrease in Queensland.

5. CONCLUSIONS

4. The multi-day impacts of east coast lows on the south-eastern seaboard of Australia are expected to increase because of wind-driven rainfall ingress, flash and riverine flooding. This effect will be compounded by rising impacts from storm surge, waves, and coastal erosion. Summer and autumn east coast low activity is expected to increase, while there will be a decrease in winter-spring systems. There is limited understanding of the rare extreme east coast lows that drive the majority of the impacts over land.

5. Bushfire risk, as measured by the trends in fire danger indices, is likely to increase in almost all locations nationally, leading to more frequent and extreme events, and longer fire seasons. The rate of increase varies by location and will depend on weather system changes and site-specific factors at regional scales
.

6. Sea level rise is expected to accelerate around the Australian coastline but at differing rates. It is notable that past assessments of sea level rise are lower than those that recent observations show. Sea level rise will contribute substantially to escalating impacts from storm surge and the impacts on coastal natural systems, buildings and infrastructure. The greenhouse gases that are already present will cause sea level rises to continue well into the next century even if there are significant emission reductions globally through the coming decade.

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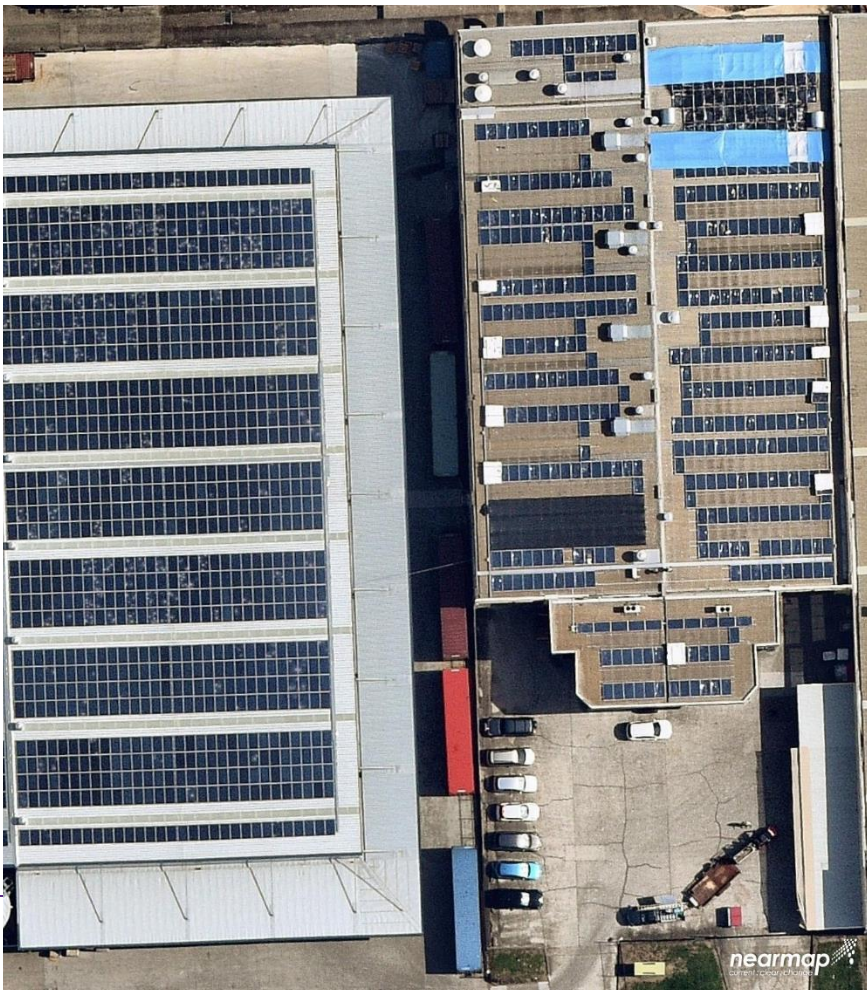
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