Australian Government
Bureau of Meteorology

The Senate Standing Committee on Environment and Communications'

Inquiry into recent trends in and preparedness for extreme weather events

Submission by the Bureau of Meteorology

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The Senate Standing Committee on Environment and Communications'
Inquiry into recent trends in and preparedness for extreme weather events

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Contents

1 Introduction.. 1

2 The Role of the Bureau of Meteorology.. 4

3 Responses against the Terms of Reference

(a) Recent trends in the frequency of extreme weather events, including but not limited to drought, bushfires, heatwaves, floods and storm surges

(b) Based on global warming scenarios outlined by the Intergovernmental Panel on Climate Change and the Commonwealth Scientific and Industrial Research Organisation of 1 to 5 degrees by 2070:

(i) Projections on the frequency of extreme weather events, including but not limited to drought, bushfires, heatwaves, floods and storm surges ………….. 6

Detecting changes in weather and attributing them to climate change.7

Temperature Extremes………………………………………………….8

Fire Weather …...……………………………………………………12

Rainfall Extremes ….……………………………………………………14

Tropical Cyclones and Severe Storms ...……………………………19

Sea Level Extremes...………........20

(ii) The costs of extreme weather events and impacts on natural ecosystems, social and economic infrastructure and human health…………………………25

(iii) The availability and affordability of private insurance, impacts on availability and affordability under different global warming scenarios, and regional social and economical impacts; ……………………………………… 25

(c) Assessment of the preparedness of key sectors for extreme weather events, including major infrastructure (electricity, water, transport, telecommunications), health, construction and property, and agriculture and forestry……………………… 25

(d) An assessment of the preparedness and the adequacy of resources in the emergency sector to prevent and respond to extreme weather events …………….. 26

(e) The current roles and effectiveness of the division of responsibilities between different levels of government (Australian, state and local) to manage extreme weather events ……………………………………………………………………………. 26

(f) Progress in developing effective national coordination of climate change response and risk management, including legislative and regulatory reform, standards and codes, taxation arrangements and economic instruments …………. 30

(g) Any gaps in Australia's Climate Change Adaptation Framework and the steps required for effective national coordination of climate change response and risk management ……………………………………………………………………………..30

References ……………………………………………………………………………….. 31

Attachment A: Submission by the Bureau of Meteorology to the Productivity Commission Inquiry into the Barriers to Effective Climate Change Adaptation, 26 July 2012.

List of Figures

Figure 1: Number of severe weather-related warnings issued by the Bureau from July 1997 to June 2012. Note that caution is required in inferring trends in this time series as factors beyond the occurrence of significant weather events may also contribute to these numbers. Source: Bureau of Meteorology……………………………………………………………..……..2

Figure 2: Number of hottest-day-of-the-month (highest maximum) records at 43 Australian climate reference stations with daily data from 1910; for each year (orange line) and each decade (grey boxes), and the 11-year average (black line). The average for the 10-year period (2002–2011) is shown in darker grey. Source: Bureau of Meteorology and CSIRO…………………………………………………………………………………………………8

Figure 3: Number of coldest-day-of-the-month (lowest maximum) records at 43 Australian climate reference stations with daily data from 1910; for each year (orange line) and each decade (grey boxes), and the 11-year average (black line). The average for the 10-year period (2002–2011) is shown in darker grey. Source: Bureau of Meteorology and CSIRO………………………………………………………………………………………………..9

Figure 4: Shift in the distribution of Australian temperatures. The BLUE line is the distribution of standardised monthly temperature anomalies (departure from the long-term average) for the period 1951–1980. The light red line represents monthly temperature anomalies for the period 1981–2010 while the dark red line represents temperatures for the period 2001–2010 only. Standardisations are performed against the reference periods accordingly. The frequency of occurrence is expressed as a probability density function. The labels inserted in the graph indicate the percentage of time that temperatures exceed the norm by one and two standard deviations, for each of the three periods. Source: Fawcett et al. 2013 (submitted)……………………………………………………………………………………………10

Figure 5: Trends in annual cumulative Forest Fire Danger Index. Marker size is proportional to the magnitude of trend. Reference sizes are shown in the legend. Filled markers represent trends that are statistically significant. The marker for Laverton has been moved west to avoid overlap with Melbourne Airport. Source: Clarke et al. 2012……………………………13

Figure 6: April to September (autumn and winter) rainfall deciles from 1997 to 2011 for Australia. This shows whether the rainfall is above average, average, or below average for the most recent 15-year period, in comparison with the entire rainfall record from 1900. Areas of highest on record and lowest on record are also shown. Source: Bureau of Meteorology CSIRO……………………………………………………………………………………………..15

Figure 7: Total annual inflow to Perth dams. In order to provide an accurate comparison Stirling, Wokalup and Samson Brook dams are not included in these data, as these dams only came online in 2001. Inflow is therefore simulated based on Perth dams pre-2001. The 'year' is taken as May to April and labelled year is start (winter) of year. Source: Water Corporation, http://www.watercorporation.com.au/_images/Dams/streamflow_graph_lg.png...................16

Figure 8: Annual total inflows into the River Murray showing the long-term average, and average inflows during the Millennium (1997–2009), World War II (1936–1945), and Federation (1896–1905) droughts. Source: SEACI (South Eastern Australian Climate Initiative)..17

Figure 9: The number of very wet months in each year from 1900 to July 2012. Here 'very wet' is defined as being above the 90th percentile of rainfall. By chance, one would expect one or two of these in every year. The Millennium drought stands out as having no very wet months for 180 consecutive months. Additionally, during the breaking of the drought in 2010–12, only one very wet month was recorded during the cool season – the other 10 being recorded during the warm season. SEACI (South Eastern Australian Climate Initiative)..18

Figure 10: High-quality global sea-level measurements have been available from satellite altimetry since the start of 1993 (red line), in addition to the longer-term records from tide gauges (blue line, with shading providing an indication of the accuracy of the estimates). Sea level rose at a globally-averaged rate of about 3 mm per year between 1993 and 2011, and 1.7 mm per year during the 20th century as a whole. Source: Bureau of Meteorology and CSIRO……………………………………………………………………………………………..21

Figure 11: The rate of sea-level rise around Australia as measured by coastal tide gauges (circles) and satellite observations (contours) from January 1993 to December 2011. Source: Bureau of Meteorology and CSIRO…………………………………………………………………...22

Figure 12: Projected range of global-averaged sea-level rise from IPCC's Third and Fourth Assessment Reports relative to 1990. Lines and shading show projections from the Third Assessment Report (dark shading is model average envelope for all emission scenarios; light shading is envelope for all models and all emission scenarios; outer lines include additional uncertainty for changes in land ice and sediment deposition). Bars plotted at 2095 show projections from the Fourth Assessment Report. The magenta bar is the range (at 90% confidence) of model projections and the red bar is the extended range, allowing for a potential additional contribution from Greenland and Antarctic ice sheets. The red arrow indicates that the upper bound is poorly quantified. Source: Antarctic Climate and Ecosystems CRC Report Card…………………………………………………………..……..23

Figure 13: Projected increase in frequency of flooding events from the sea for a sea-level rise of 0.5 m. Source: Antarctic Climate and Ecosystems CRC Report Card..……………………24

Figure 14: Focus of the Bureau's role and interaction within the emergency management community - police, emergency service organisations, all levels of government, media and the general public. Source: Bureau of Meteorology ……………………………………………27

1 Introduction

We, the Bureau of Meteorology ('the Bureau'), welcome the opportunity to make this submission to the Senate Standing Committee on Environment and Communications' *Inquiry into recent trends in and preparedness for extreme weather events.*

Extreme weather events such as tropical cyclones, severe winds, thunderstorms, hail, floods, heatwaves, droughts and fire are a major threat to the safety, sustainability, prosperity and well-being of Australians.

As Australia's population grows and ages[4], and our asset base expands, more people and assets become vulnerable to the impacts of extreme weather events. For this reason, in recent decades there has been a significant growth in the capability of emergency services and the sophistication of planning and response arrangements associated with extreme weather events. The environmental intelligence services provided by the Bureau of Meteorology have also developed greatly over the last few decades, responding to sharply increased demand.

Over the last decade, the Bureau has been particularly active in issuing severe weather warnings (Figure 1), as Australia has lurched from record drought to record floods and now to record heatwaves. The intensity of each of these events is unprecedented. That they should occur in series within the space of a decade is remarkable.

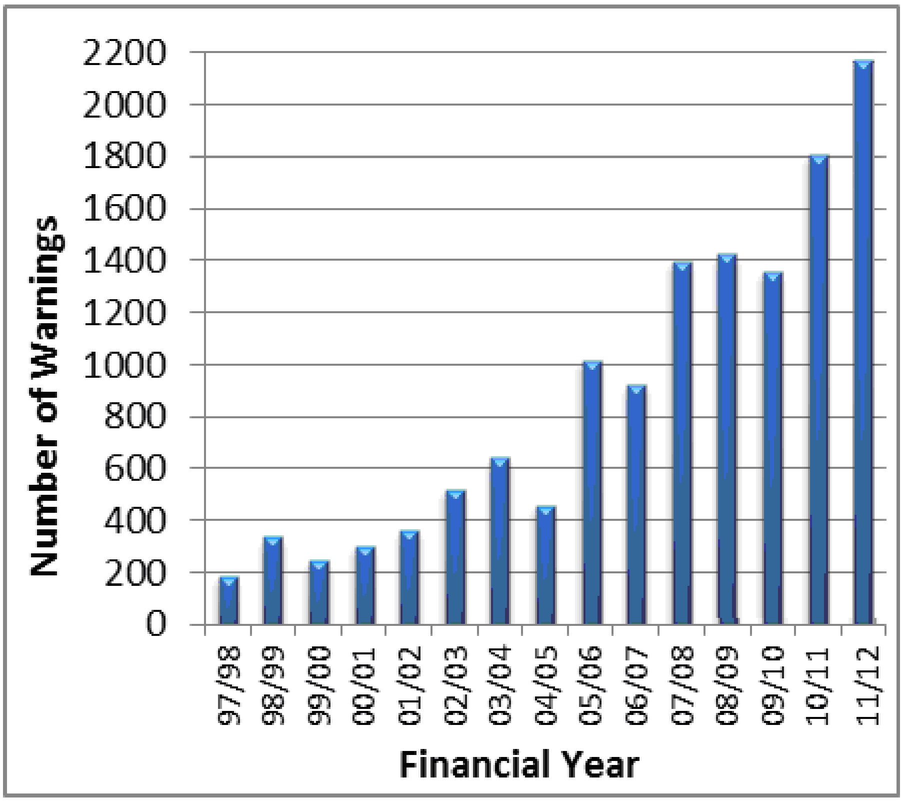


Figure 1: *Number of severe weather-related warnings issued by the Bureau from July 1997 to June 2012. Note that caution is required in inferring trends in this time series as factors beyond the occurrence of significant weather events may also contribute to these numbers. Source: Bureau of Meteorology*

Changes in the global climate system and their effects on extreme weather events are compounding the aforementioned vulnerability increases arising from population and infrastructure growth.

The earth's atmosphere and oceans have warmed considerably over the last century (each by around 1°C). The rate of warming of the entire climate system, including heating of the oceans and melting glaciers and ice sheets, is increasing and further change is now locked in for centuries, whether or not emissions are reduced or even halted in the near term. The rate and magnitude of future changes will be determined by the future level of emissions, and a series of complex environmental feedbacks. However, it is now likely that the average temperature of the earth's atmosphere will have warmed by more than 2°C by mid-century, relative to pre-industrial revolution conditions (noting that an approximate 1°C rise has already been experienced). A rise of 2°C would exceed the commonly quoted "guardrail" level, deemed by experts to be the threshold beyond which dangerous impacts may arise. The latest assessments are now indicating that the atmosphere could warm by as much as 4–6°C by the end of this century if we remain on the current increasing greenhouse gas emission trajectory[28, 29].

Global warming is altering the dynamics of the atmosphere, oceans and land. The enormous excess heat energy accumulating as a result of the greenhouse effect is intensifying the global climate and weather system[39]. As the earth's atmosphere warms, the amount of moisture it can hold also increases (by approximately 6% for every 1°C rise in temperature). As a result, global weather patterns are changing, including the frequency and magnitude of extreme weather events. Long-term observations show that some extreme weather events are now more common and severe than in the recent past, and model projections of future climate change indicate that further changes are likely.

Effective climate change adaptation depends strongly on systematic monitoring of a range of environmental variables and good foresight regarding likely future change. Good foresight implies reliable estimates of the timing, magnitude and potential impacts of extreme weather events. Such knowledge is necessary for coping with the events as they occur, but is also vital for informing the design and timing of mitigation strategies that may be implemented over the course of many years.

Better utilisation of current environmental intelligence assets, and investments in additional assets, could help to identify the most essential and cost effective climate change adaptation options. This would significantly improve the ability of governments, businesses and individuals to reduce the manifold risks posed by climate change, including the increase in frequency and intensity of some extreme weather events.

2 The Role of the Bureau of Meteorology

The Bureau of Meteorology provides Australians with environmental intelligence for their safety, sustainability, well-being and prosperity. We define environmental intelligence as *"conclusions drawn from environmental observations and models to guide decisions and actions by governments, businesses and individuals"*.

In practical terms, this entails providing Australians with the information and related support they need to manage and live within their natural environment, encompassing the atmosphere, oceans, water and land. Central to our mission is the monitoring, assessment and forecasting of Australia's weather and climate system, which has a significant impact on virtually all environmental processes. The Bureau also runs major programs on air quality (including volcanic ash plumes), oceans (including currents, waves, tides and tsunamis), water resources (including water availability and use, and floods) and space weather (aimed at forecasting electromagnetic disturbances on earth from solar activity).

Some of the key functions of the Bureau of Meteorology are:

- monitoring and reporting on current environmental conditions;
- curating and archiving environmental records;
- analysing and explaining historic trends in environmental conditions;
- providing forecasts, warnings and long-term outlooks on environmental phenomena that affect the safety, prosperity and resilience of Australians; and
- encouraging the use of environmental intelligence for social benefit.

On a 24/7 basis, the Bureau provides observations, alerts, warnings and forecasts for extreme weather events such as tropical cyclones, heatwaves, fires, floods, high winds, thunderstorms, hail, tsunamis, ocean waves, tidal surges, air turbulence, volcanic ash and solar-derived electromagnetic disturbances. In so doing, the Bureau helps protect people on the land, at sea and in the air, across Australia's territory and, in some cases, beyond.

Across the world, early warning systems such as those operated by the Bureau have proven to be a very cost effective approach to mitigating loss of life and economic losses arising from extreme weather events. As the Bureau improves the speed, accuracy and dissemination of our extreme weather alerts, warnings and forecasts, we help to reduce the risk of injury and loss of life and property.

Also of great societal value is the continuous monitoring of climate[31] that the Bureau undertakes, along with the curation, publishing and archival of climate data. The national climate record compiled by the Bureau is used to detect changes in Australia's climate, including changes in the frequency and magnitude of extreme weather events. This information is a vital resource for developing appropriate mitigation and adaptation strategies for climate change.

3 Responses against the Terms of Reference

(a) Recent trends in the frequency of extreme weather events, including but not limited to drought, bushfires, heatwaves, floods and storm surges

(b) Based on global warming scenarios outlined by the Intergovernmental Panel on Climate Change and the Commonwealth Scientific and Industrial Research Organisation of 1 to 5 degrees by 2070:

(i) Projections on the frequency of extreme weather events, including but not limited to drought, bushfires, heatwaves, floods and storm surges

A combined response to these two Terms of Reference (a and b) is provided below.

Extreme weather events are those that occur infrequently and comprise historical extremes in indicators such as temperature, rainfall, winds, river levels or sea levels. Many extreme weather events are associated with sustained climatic anomalies such as droughts and sustained wet periods such as La Niña events[8]. In the foregoing, we refer both to short duration ‘weather’ events, as well as to prolonged duration ‘climate’ events.

In Australia, vulnerability to extreme weather has been recently highlighted by several notable events including:

- the ‘Millennium Drought’ of 1997–2009 affecting much of Australia, resulting in a serious water security crisis requiring a major intervention by the Australian Government[24];
- the extensive bushfires across the southeast during 2003, including the Canberra fires which claimed four lives and nearly 500 homes, and the High Country fires in NSW and Victoria, which burned nearly 1.1 million hectares in Victoria alone[6].
- the south-east Australian heatwave in late January 2009, which resulted in an estimated 374 deaths in Victoria[45];
- the Victorian bushfires in early February 2009, which killed 173 people, destroyed more than 2000 homes, burnt approximately 430,000 hectares, and cost around $4.4 billion[46];

- the floods in eastern Australia in early 2011, which resulted in the deaths of 35 people[38] in Queensland alone and cost around $12 billion in lost economic activity (1.7 per cent of GDP) mainly through lower coal and agricultural production[42];
- Australia's most costly tropical cyclone, *Yasi* (category 5), caused around $1.4 billion damage after it crossed the far north Queensland coast in February 2011[27];
- a succession of severe thunderstorms caused widespread havoc to southeast Queensland over a five-day period in November 2008, with violent wind gusts along with localised flooding and hail[3] resulting in loss of life and $309 million damage[27]; and
- the national heatwave currently in progress (January 2013), characterised by record temperatures for the continent and resulting in widespread grass and forest fires[9].

Detecting changes in weather and attributing them to climate change

While changes in the global climate system are clearly evident from observations, resultant changes in weather patterns are more difficult to discern. Weather is inherently variable or 'noisy' and the overall sample size of recorded extreme weather events for any given location is relatively small in comparison with many other climate indicators. Significant changes in the frequency and/or magnitude of extreme events are required before they clearly stand out from the historical record and can be attributed, at least in part, to climate change. Definitive 'attribution' of an individual extreme weather event to climate change alone is problematic as all weather events have multiple influences.

Nonetheless, as shall be shown below, recent observational evidence indicates increases in the frequency of extreme weather events, as would be expected with global warming. Systematic changes are easiest to discern for high temperatures and sea levels, and less clear for rainfall and tropical cyclones.

Temperature extremes

Globally, there has been an overall decrease in the number of very cool days and cold nights, and an overall increase in the number of very hot days and warm nights. This same pattern is observable in Australia as shown in Figures 2 and 3. Averaged over Australia, the frequency of very high temperatures has increased while the frequency of very low temperatures has decreased, with these changes occurring during both the day and the night[17, 44]. Since 1990, strong trends have emerged in the occurrence of record high maximum and minimum temperatures for Australia, with particularly large numbers in the decade from 2001 onwards. Over the period 2001–2011, the frequency of record high temperatures is now running at 2.8 (for maximum temperature) to 5.2 (for minimum temperature) times the rate of record low temperatures[44].

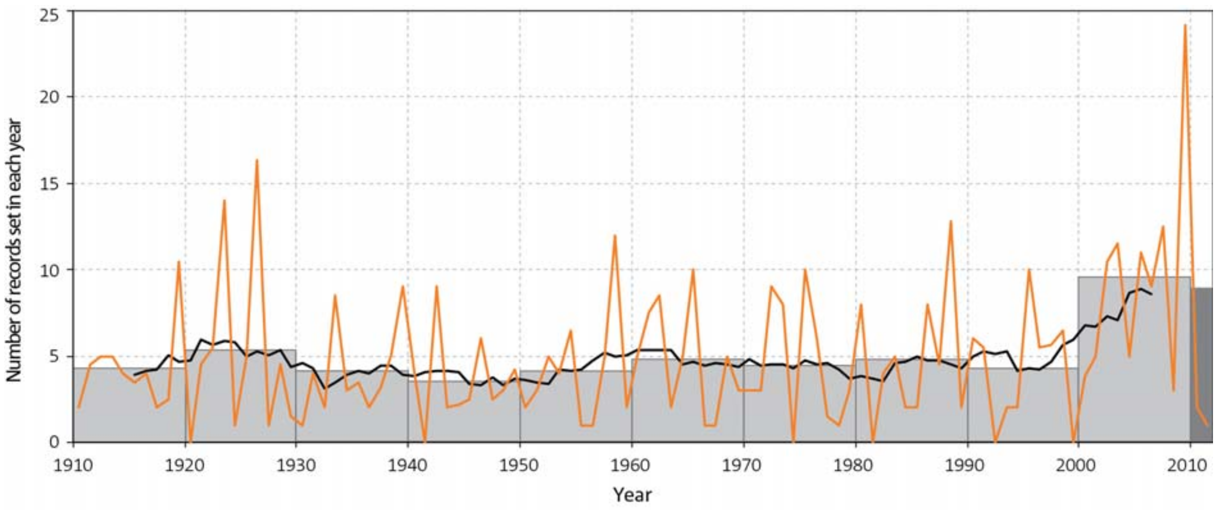
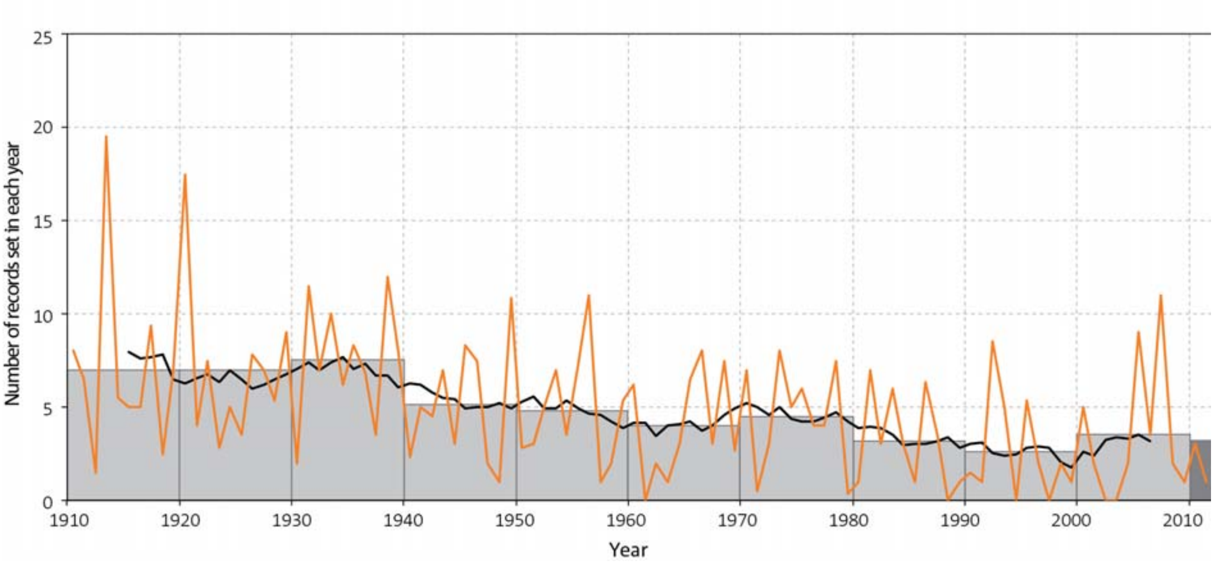


Figure 2: *Number of hottest-day-of-the-month (highest maximum) records at 43 Australian climate reference stations with daily data from 1910; for each year (orange line) and each decade (grey boxes), and the 11-year average (black line). The average for the 10-year period (2002–2011) is shown in darker grey. Source: Bureau of Meteorology and CSIRO.*[10]



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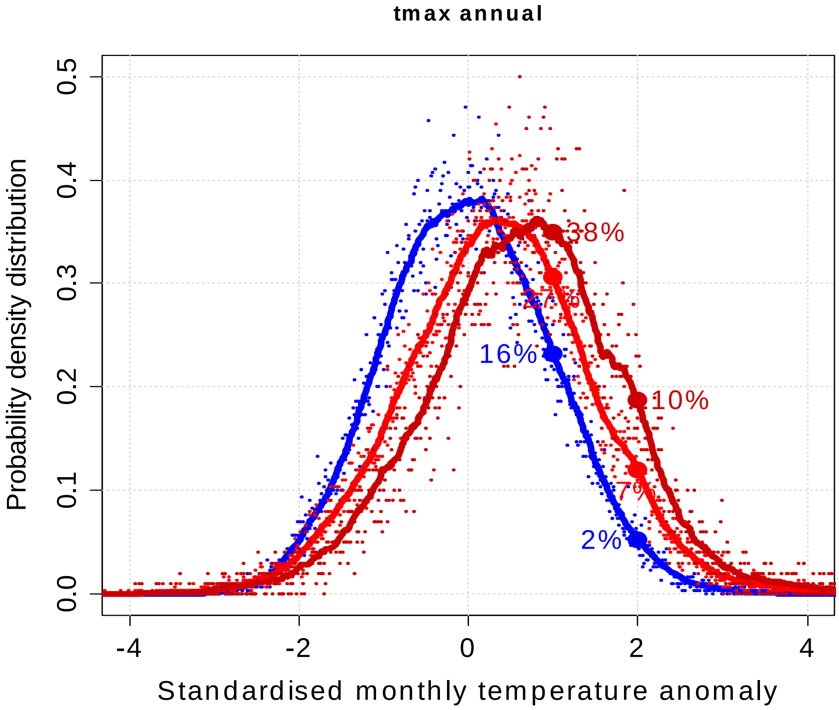
The observed change in the frequency of extreme hot and cold weather is consistent with a shift in the entire distribution of Australian temperatures. Figure 4 shows the distributional shift in the frequency of monthly temperature anomalies (departures from the long-term average) for the Australian continent from 1951 to 2010. This shows that the entire distribution of temperatures has shifted; not just the average. Across Australia there has been a two-fold frequency increase in temperatures greater than 1 standard deviation above the norm (38% of the time lately versus 16% of the time in the past) and a five-fold frequency increase in temperatures more than 2 standard deviations above the norm (10% of the time lately versus 2% of the time in the past). This shift in the distribution clearly indicates the increased likelihood of warmer extremes.

A recent analysis of northern hemisphere heatwaves has shown the frequency of very hot summers has increased approximately tenfold since the 1950s[20], and that a number of recent summer heatwaves (such as the European 2003 and Moscow 2010 heatwaves) have been so extreme that their probability of occurrence without global warming would be close to zero[37, 39, 40].



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Across Australia since the 1950s[2], there has been a slight increase in the duration of heatwaves (measured through multi-day heat indices), and an increase in the maximum temperatures associated with such events. There have, however, been marked regional variations in the frequency of occurrence of heatwaves over that time, with decreases in parts of southern coastal Australia (especially south-western Western Australia), and strong increases away from coastal regions[44]. The decreases in heatwave duration across some parts of southern coastal Australia contrast with increases in the frequency of single-day high temperature extremes at many of the same locations over the same period.

The intense heatwave across almost the entire inland region of Australia during the first two weeks of January 2013 was exceptional, and surpasses the only previous analogue in 100 years of record keeping; recorded during the summer of 1972–1973. The most unusual, and notable, feature of the January 2013 heatwave was the extraordinary duration of widespread extreme heat across the country. Australian daily average temperatures (a measure of the average temperature across the entire continent) during the first two weeks of January 2013 set new records for (i) the warmest single day on record, and (ii) a number of warmest duration (sequence of days) records. The warmest Australian average daily maximum temperature of 40.33°C was recorded on 7 January 2013, followed by the third highest maximum on record of 40.11°C on 8 January. The Australian average daily mean temperature (the average of daytime maximum and night time minimum) for the period of 1 to 14 January 2013 has set a new record for the hottest sequence stretching from 1 to 14 days, all inclusive. A large number of individual site records were broken during the event; as of 18th January 2013, 14 of the 112 stations in the network the Bureau uses for long-term temperature monitoring set all-time records during the event, with a 15th equalling its record. Extreme heat that occurs over long periods, without any meaningful relief, greatly increases the impacts, such as for human health and fire potential.

It is very likely that the observed trends in the frequency and magnitude of warm daily temperature extremes will continue and, depending on emission scenario, potentially accelerate under future global warming[28, 29, 41]. All regions of Australia are likely to experience significant increases in temperature extremes in this century. A robust consensus among global climate projection models, and increased understanding of the mechanisms behind these changes, gives us high confidence in this result[28].

Fire weather

Fire is a natural part of the Australian environment, with some areas (particularly southern and eastern Australia) being prone to catastrophic bushfires. Bushfire threat is typically associated with high temperatures, low humidity, strong winds and high fuel load. Bushfires become catastrophic when all of these conditions occur in combination, such as occurred on Black Saturday (7 February, 2009)[5]. Other examples of devastation from fires include the 1983 Ash Wednesday event in south-eastern Australia, which followed a long dry period due to El Niño, and the 2003 Canberra and 2013 Tasmanian fires.

The annual cumulative Forest Fire Danger Index (FFDI), which essentially ‘sums’ daily fire weather danger across the year, has increased *significantly* across many Australian locations since the 1970s[13] (Figure 5). The number of locations with significant increases is greatest in the southeast, while the largest trends occurred inland rather than near the coast. The largest increases in seasonal FFDI have occurred during spring and autumn. This indicates a lengthened fire season [22, 33, 44].

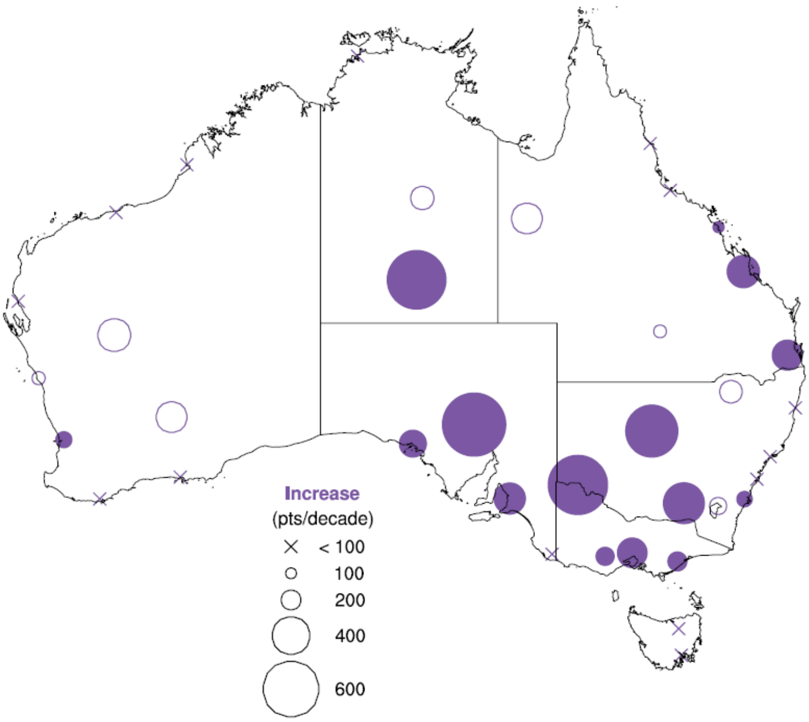


Figure 5: *Trends in annual cumulative Forest Fire Danger Index. Marker size is proportional to the magnitude of trend. Reference sizes are shown in the legend. Filled markers represent trends that are statistically significant. The marker for Laverton has been moved west to avoid overlap with Melbourne Airport. Source: Clarke et al. 2012.*[13]

Projected rising temperatures and likely decreases in winter and spring rainfall across southern Australia (see below) will also contribute to an increased bushfire threat[14]. In addition, climate modelling shows the potential for an increase in the frequency of the summer-time weather systems that are associated with the most extreme and damaging bushfire activity in south-eastern Australia[21]. However, the change in future fire activity is more difficult to determine because fire behaviour depends also on fuel type and accumulation, which may change in the future due to changes in rainfall, fire frequency and other factors[47].

Rainfall extremes

One of the most consistent results from climate modelling since the first IPCC scientific assessment report in 1990 has been the predicted 'intensification' of the hydrological cycle in association with global warming[23, 28]. In essence, this means more heavy rainfall and more severe droughts. As was noted earlier, global warming increases the moisture holding capacity of the atmosphere. This is expected to result in increases in heavy rainfall events and consequent flooding. Climate modelling shows that extreme rainfall intensity, or the amount of rainfall falling on sub-daily timescales, is likely to increase as the atmosphere warms over many regions, including the tropics[28, 35]. On the other hand, global warming is also expected to increase evaporation, leading to more severe drought conditions in 'dry' regions of the globe.

Although we are reasonably confident that there will be more multi-year wet periods and dry periods as a consequence of climate change, we are less certain about the future frequency, timing and spatial extent of those changes. Any such changes in Australian rainfall and drought patterns are dependent on complex changes in the global atmospheric circulation.

Across the north of the Australian continent, rainfall is dominated by tropical weather systems such as the monsoon operating in the summer months. Across the south, extra-tropical weather systems such as cold fronts contribute much of the rainfall[19], but a range of interacting weather systems such as 'east coast lows', 'blocking' systems and tropical moisture intrusions also play a significant role.

Most climate model projections indicate rainfall decreases in southern and eastern Australia during the cooler months, particularly in winter and spring. They also indicate increased drought threat for southern Australia as a result of reduced mean rainfall and higher temperatures. We have less confidence predicting future rainfall changes across northern Australia, as the models do not agree on either increases or decreases in summer (wet season) rainfall. Importantly, the models do consistently project that rainfall intensity will likely increase across Australia. In other words, future rainfall events will likely be heavier, even over regions likely to experience an overall rainfall decline.

Turning to the observations, systematic changes in rainfall patterns in the Australian region have become evident (Figure 6) and recent research suggests that climate change is likely to be the cause for the changes over some regions[43].

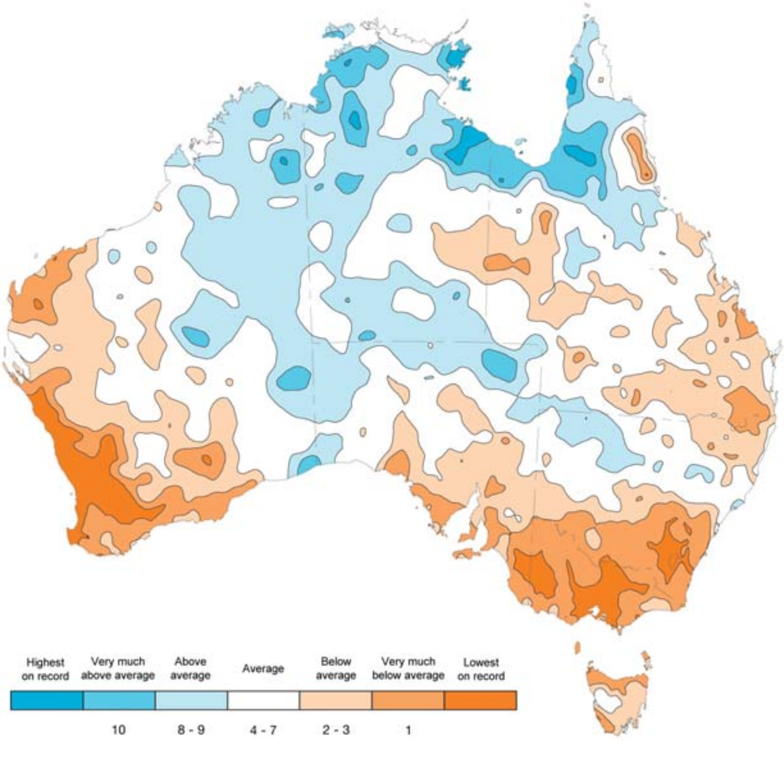
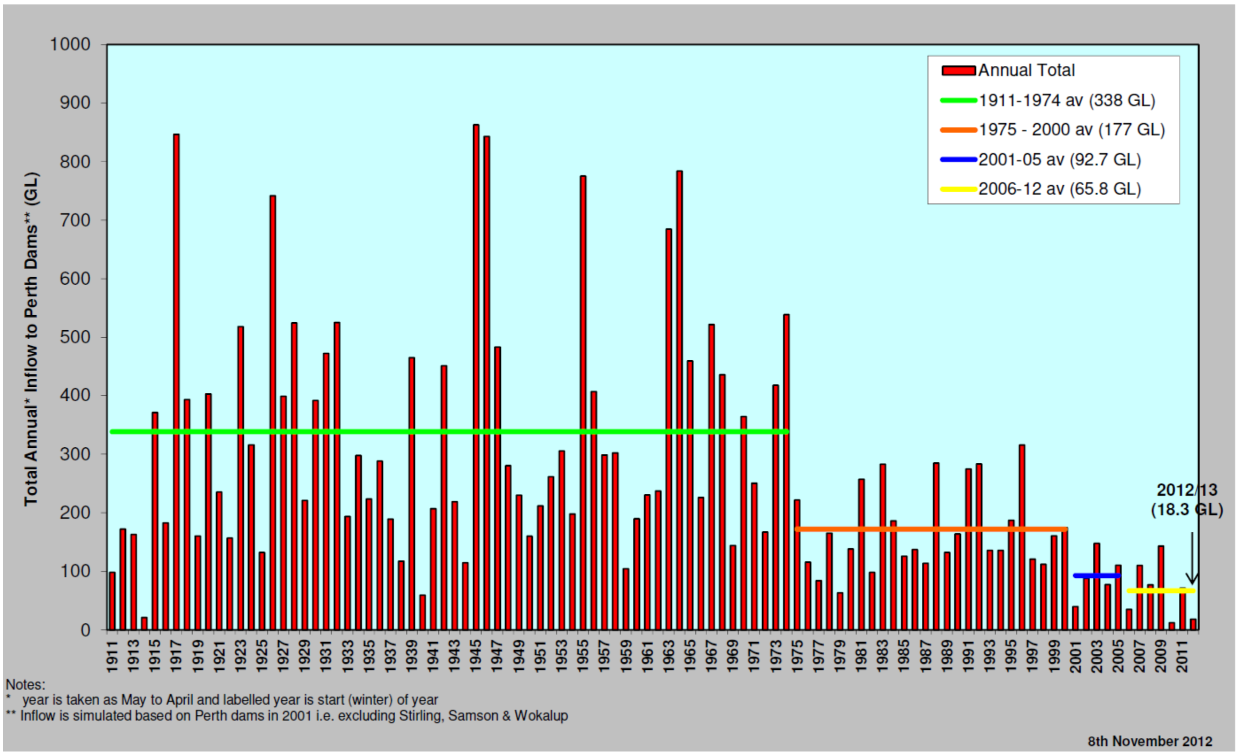


Figure 6: *April to September (autumn and winter) rainfall deciles from 1997 to 2011 for Australia. This shows whether the rainfall is above average, average or below average for the most recent 15-year period, in comparison with the entire rainfall record from 1900. Areas of highest on record and lowest on record are also shown. Source: Bureau of Meteorology and CSIRO.*[10]

The south-west region of Western Australia has experienced a 15% decline in winter rainfall since the 1970s[23]. Similar declines in seasonal rainfall have occurred over the south-east of the continent in late autumn and early winter, since the 1980s[43]. It is worth noting that these decreases in rainfall have led to much larger proportional decreases in river flows, with water storages severely reduced in south-western Australia (Figure 7) and the Murray–Darling Basin (Figure 8).



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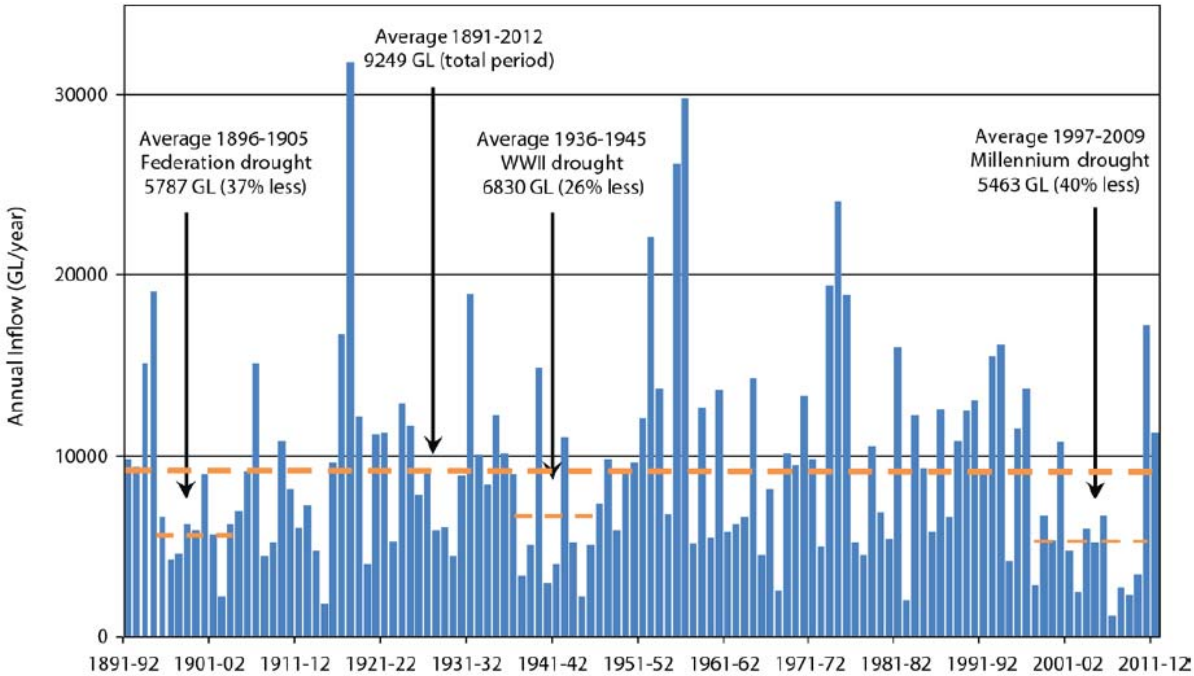

Figure 8: *Annual total inflows into the River Murray showing the long-term average, and average inflows during the Millennium (1997–2009), World War II (1936–1945), and Federation (1896–1905) droughts. Source: SEACI (South Eastern Australian Climate Initiative).*[15]

The observed rainfall changes across the south-western and south-eastern parts of Australia has been shown to be a systematic decline in autumn and winter rainfall, rather than a typical period of drought or severe rainfall deficiency[43]. However the impact of individual drought periods is exacerbated when superimposed on such systematic declines in rainfall. Across the south-east of Australia, the period 1997–2009 (known as the Millennium Drought) was remarkable in its absence of significantly wetter-than-average months that might have otherwise replenished water storages (Figure 9). The systematic decline in autumn-winter rainfall across southern Australia likely exacerbated the severity of the Millennium Drought. The breaking of this drought was quite abrupt, with record spring and summer rainfall in 2010–11. However, the sequence of below average cool season rainfall continued through 2010, 2011, and 2012. In other words, the Millennium Drought was broken by record warm season rainfall and the longer term underlying cool season drying trends have persisted[7, 15].

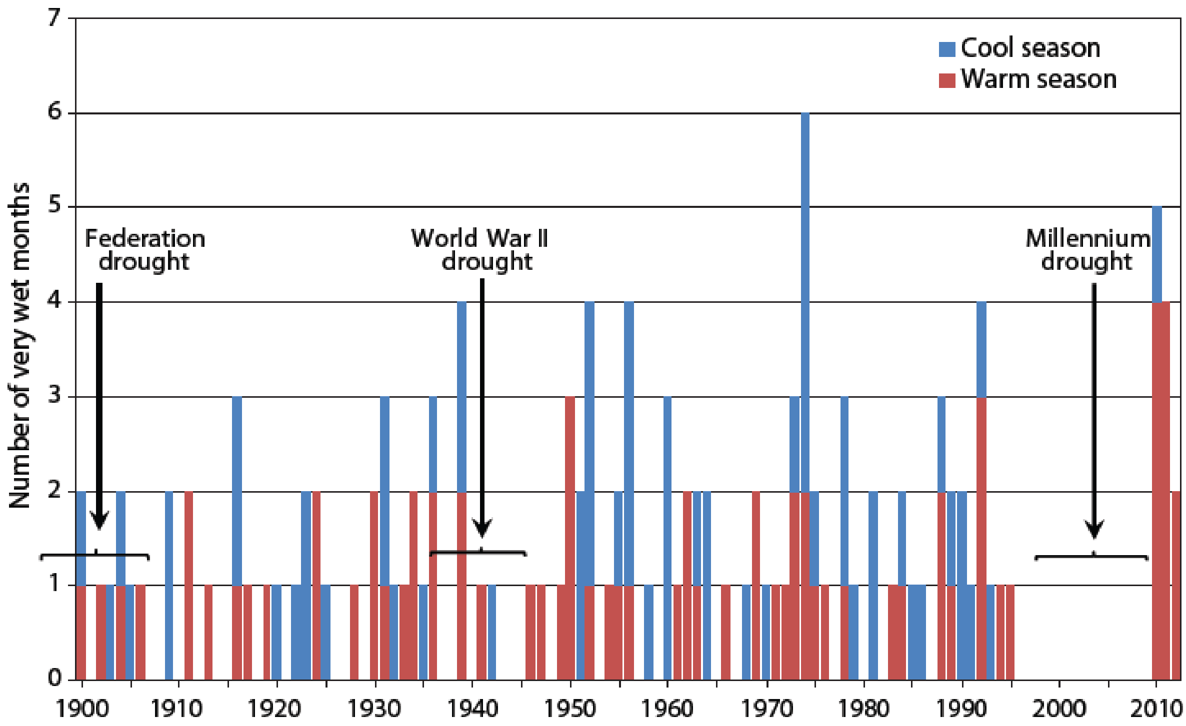

Figure 9: *The number of very wet months in each year from 1900 to July 2012. Here 'very wet' is defined as being above the 90th percentile of rainfall. By chance, one would expect one or two of these in every year. The Millennium drought stands out as having no very wet months for 180 consecutive months. Additionally, during the breaking of the drought in 2010–12, only one very wet month was recorded during the cool season – the other 10 being recorded during the warm season. Source: SEACI (South Eastern Australian Climate Initiative).*[15]

Drought conditions across large parts of eastern Australia were dramatically broken by the La Niña event that began in the spring of 2010. Such events typically cause high rainfall in Australia in association with warmer-than-average sea surface temperatures in tropical waters surrounding Australia and associated changes in atmospheric circulation. The 2010-11 La Niña event was associated with record high sea-surface temperatures in the Australian region and record spring and summer rainfall over much of the Australian continent[7].
The record rainfall over this period resulted in repeated severe flooding in Queensland and Victoria in particular. The record rainfall in the northern tropics was consistent with a general trend of increased rainfall across northern Australia in recent decades. While it remains

difficult to attribute all causes of record-breaking rainfall during 2010 and 2011, it is almost certain that global warming contributed to record sea-surface temperatures during that period.

It is important to note that extreme rainfall and associated flooding can occur on seasonal timescales (e.g. sustained heavier than normal seasonal rainfall over eastern Australia during strong La Niña events), or it can be associated with individual storms (tropical cyclones, east coast lows[16] and other mid-latitude weather systems), or both. We have high confidence in projections of warming and increased atmospheric moisture, and associated increases in heavy rainfall will likely contribute to a generalised increased flood threat during the tropical wet season in the future. It is, however, more difficult to predict the future frequency of severe flooding, due to the inherent, and likely increasing, year to year variability of Australian rainfall.

Modelling studies indicate a very likely future southward shift of the extra-tropical (mid-latitude) storm tracks, suggesting that rainfall from these storms will continue to decrease across southern parts of Australia.

Tropical cyclones

Tropical cyclones have a significant impact on Australia. On average, the Australian region experiences about 11 tropical cyclones per year, but the number varies significantly from year to year. The extreme high winds, storm surges and heavy rainfall associated with tropical cyclones can be particularly destructive at landfall. Additionally, heavy rainfall in decaying tropical cyclones can cause widespread flooding over many parts of Australia, not just those coastal areas affected by cyclone crossings. Tropical cyclones also pose a destructive threat to offshore infrastructure. The impact of a tropical cyclone on the operations of the oil and gas industry is estimated to be several tens of millions of dollars per day[34].

The relatively short time span of consistent records, combined with high year-to-year variability, makes it difficult to discern any clear trends in tropical cyclone frequency or intensity for the Australian region. For the period 1981 to 2007, no statistically significant trends in the total numbers of cyclones, or in the proportion of the most intense cyclones, have been found in the Australian region, South Indian Ocean or South Pacific Ocean[32]. Only limited conclusions can be drawn regarding tropical cyclone frequency and intensity in the Australian region prior to 1981, due to a lack of data. However, a long-term decline in numbers on the Queensland coast[11], has been suggested.

Climate change projections indicate that globally there will be less tropical cyclones in overall number, but that a greater number of particularly intense cyclones will occur. This is consistent with recent findings for the Australian region[1].

Sea-level extremes

Globally, average sea level has risen by around 21 cm over the last century. The rate of sea level rise has accelerated over the last two decades, and is now sitting at close to 3.1 mm/yr[30] (Figure 10). Sea level rise around Australia is slightly greater than the global average and there is considerable variation around the Australian continent (Figure 11). Rates of sea level rise in northern Australia are amongst the highest in the world, with current rates up to 1 cm rise per year. This is at least partially due to the strong influence of the El Niño Southern Oscillation.

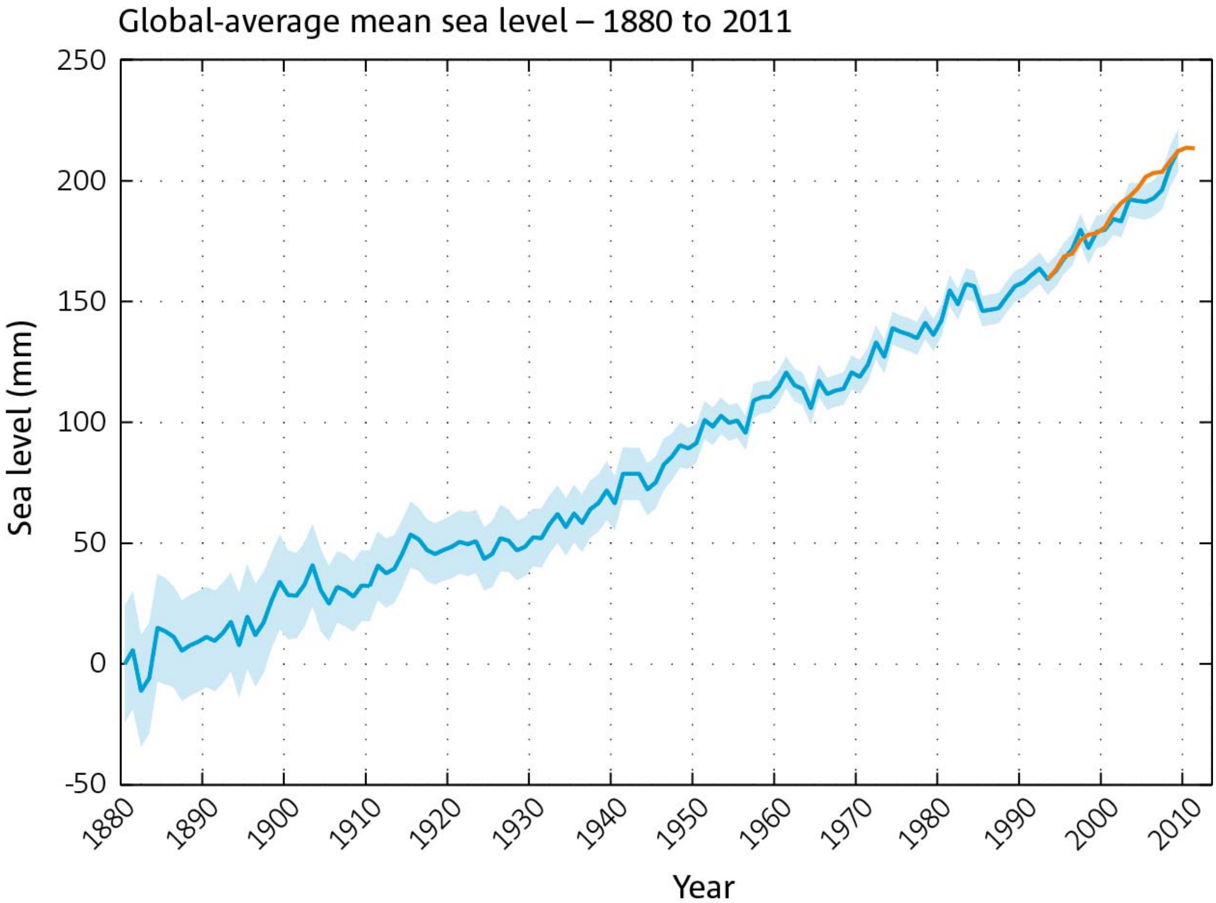

Figure 10: *High-quality global sea-level measurements have been available from satellite altimetry since the start of 1993 (red line), in addition to the longer-term records from tide gauges (blue line, with shading providing an indication of the accuracy of the estimates). Sea level rose at a globally-averaged rate of about 3 mm per year between 1993 and 2011, and 1.7 mm per year during the 20th century as a whole. Source: Bureau of Meteorology and CSIRO.*[10]

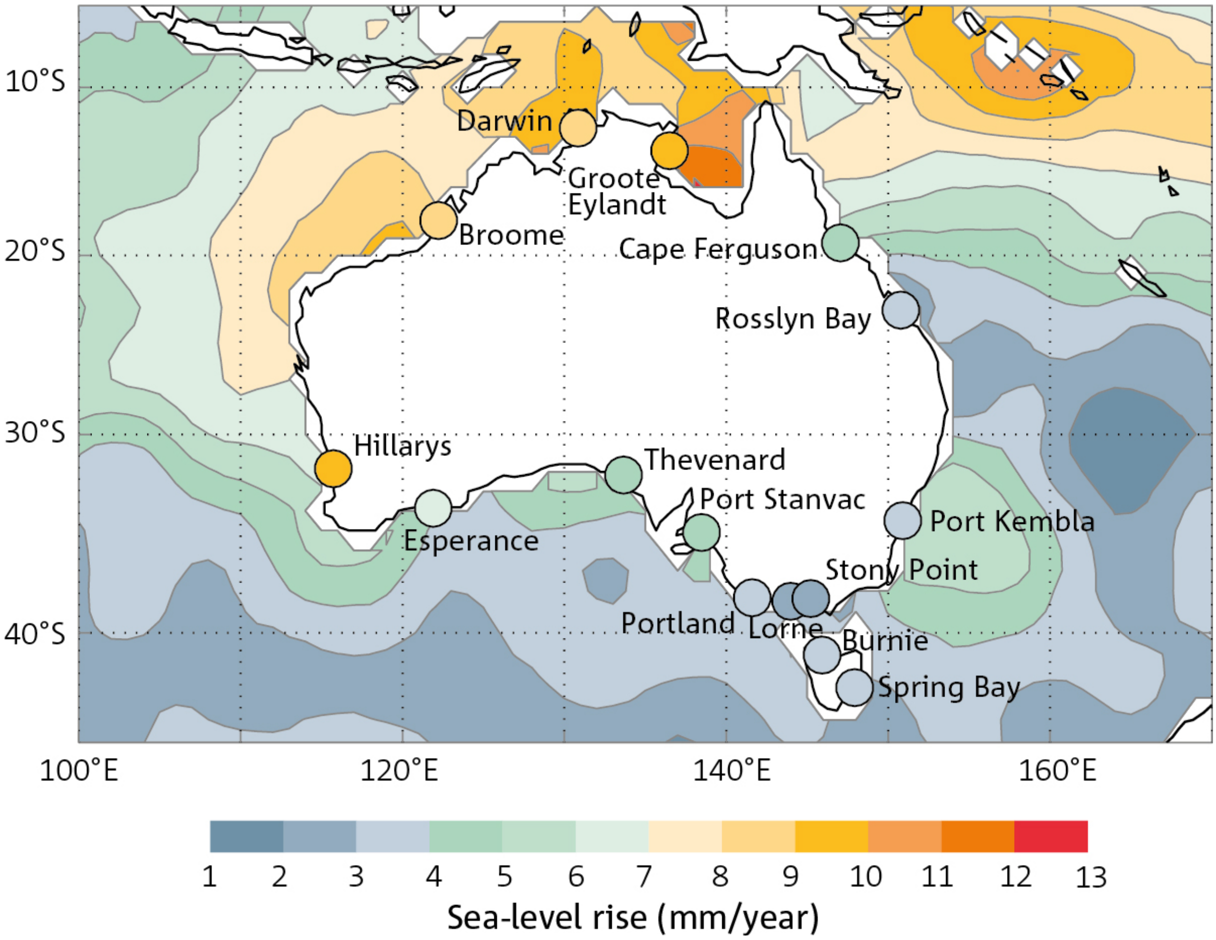

Figure 11: *The rate of sea-level rise around Australia as measured by coastal tide gauges (circles) and satellite observations (contours) from January 1993 to December 2011. Source: Bureau of Meteorology and CSIRO.*[10]

Global warming is projected to produce a further average global sea level rise of between 18 and 59 cm by the end of this century (compared to 1980-1999), with the eventual rise depending upon the future emissions[28] (Figure 12). Possible rapid melting of the Greenland and West Antarctic ice sheets could add a further 10 to 20 cm of sea-level rise by the end of the century, and even further increases are possible should some potential glacier instabilities eventuate[12].

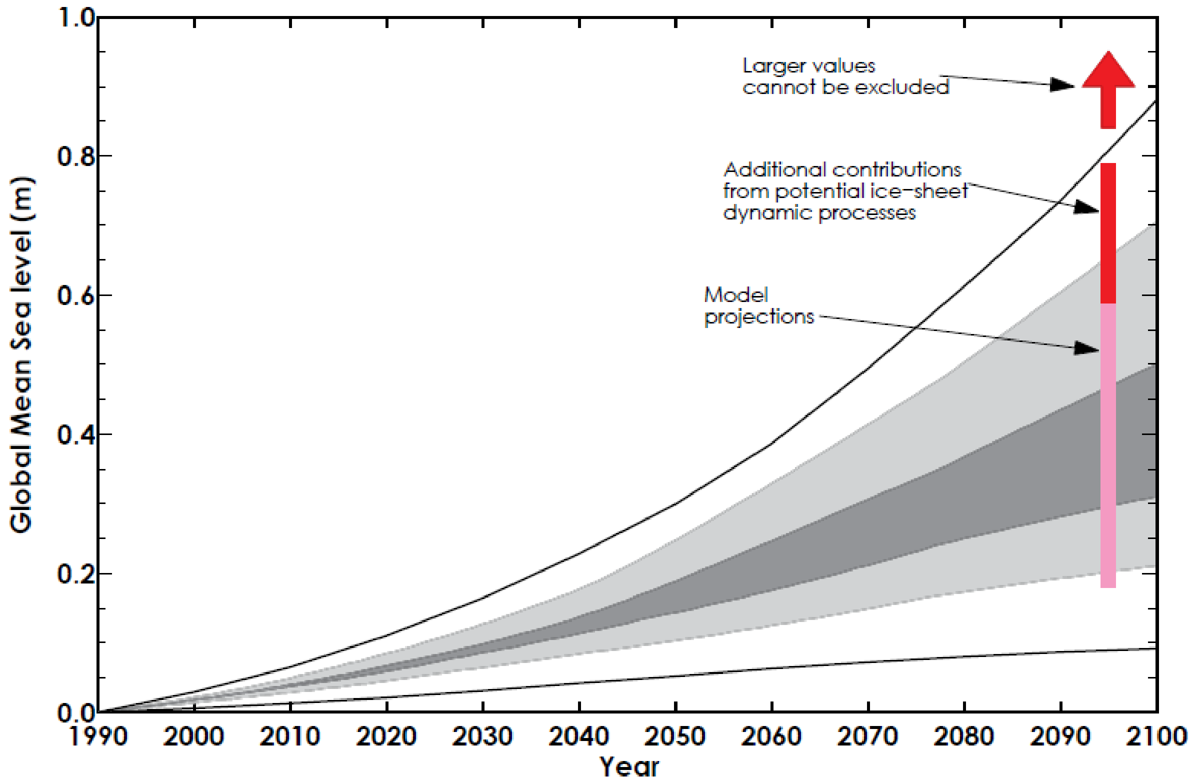

Figure 12: *Projected range of global-averaged sea-level rise from IPCC's Third and Fourth Assessment Reports relative to 1990. Lines and shading show projections from the Third Assessment Report (dark shading is model average envelope for all emission scenarios; light shading is envelope for all models and all emission scenarios; outer lines include additional uncertainty for changes in land ice and sediment deposition). Bars plotted at 2095 show projections from the Fourth Assessment Report. The magenta bar is the range (at 90% confidence) of model projections and the red bar is the extended range, allowing for a potential additional contribution from Greenland and Antarctic ice sheets. The red arrow indicates that the upper bound is poorly quantified. Source: Antarctic Climate and Ecosystems CRC Report Card*[12, 26]..

Associated with the rise in average sea level is the consequent increased frequency of coastal inundation from storm surges. It has been estimated that an average sea-level rise of 50 cm will result in a 10–1000 times increase in the frequency of coastal flooding, depending on the particular location around the Australian coastline[25] (Figure 13).

Figure 13: *Projected increase in frequency of flooding events from the sea for a sea-level rise of 0.5 m[23]. Source: Antarctic Climate and Ecosystems CRC Report Card[26].*

In the future, weak to moderate strength tropical cyclones will be likely to generate more coastal flooding than at present, and severe cyclones are more likely to result in very serious damage to coastlines through flooding and erosion associated with storm surges.

Outside the tropics, storm surge threat is driven by sustained extreme wind and low pressure events, and it is strongly influenced by sea-level rise. While we cannot as yet determine whether an individual storm surge event leading to coastal inundation (e.g. as observed in Perth and Hobart in 2012) would have occurred without global warming, higher global sea-levels will, on average, increase the height of water levels during storm surge events and increase the risk of coastal inundation.

The Bureau is not commenting on the following Terms of Reference:

(ii) The costs of extreme weather events and impacts on natural ecosystems, social and economic infrastructure and human health.

(iii) The availability and affordability of private insurance, impacts on availability and affordability under different global warming scenarios, and regional social and economical impacts.

(c) Assessment of the preparedness of key sectors for extreme weather events, including major infrastructure (electricity, water, transport, telecommunications), health, construction and property, and agriculture and forestry.

The Bureau of Meteorology is not commenting on this Term of Reference.

(d) An assessment of the preparedness and the adequacy of resources in the emergency sector to prevent and respond to extreme weather events.

The Bureau of Meteorology's level of preparedness to respond to severe weather events was recently assessed by an independent review commissioned by the Australian Government[36]. The government is currently giving consideration to the recommendations of this review.

(e) The current roles and effectiveness of the division of responsibilities between different levels of government (Australian, state and local) to manage extreme weather events

The Bureau issues the overwhelming majority of warnings for natural hazards in Australia. Warnings, watches and advices are disseminated via the broadcast media and directly to the public via the Internet. The Bureau directly informs emergency management agencies via a range of digital channels, phone calls and face-to-face briefings. Warnings issued by the Bureau are also the basis for most of the warning messages that State and Territory Governments, emergency management agencies and the broadcast media disseminate to the public (Figure 14).

The Bureau has successfully operated as a national agency in the multi-state tapestry of emergency services arrangements across Australia. Minor variations between jurisdictions have made our task more difficult at times but these problems are gradually being addressed. Overall, the Bureau enjoys a very positive and productive working alliance with the emergency services apparatus of each State and Territory.

Figure 14: *Focus of the Bureau's role and interaction within the emergency management community - police, emergency service organisations, all levels of government, media and the general public. Source: Bureau of Meteorology*.

One area where the Bureau has concerns relates to the arrangements in place for flood monitoring, forecasting and warning.

When discussing flooding, it is customary to distinguish between 'flash flooding' and 'riverine flooding'. Flash flooding refers to rapid onset flooding, where the response time from rainfall to flood peak is less than six hours. Flash flooding is common in urban areas dominated by impervious surfaces and in steep upland catchments where heavy rainfall is common. Riverine flooding is much slower to occur, with response times between rainfall and flood peaks being greater than six hours. Riverine flooding mainly occurs on floodplains at the bottom of large catchments and may occur some distance away from where the heaviest rainfall occurs.

Formally, *per* the *Meteorology Act 1955*, the Bureau was required to issue warnings on weather conditions likely to give rise to flooding. Over the last few decades, it has widened its remit to issue riverine flood warnings, site-specific forecasts of river levels and to publish online in real-time the observed river levels as measured by a range of other agencies. These arrangements have been negotiated informally between the Commonwealth and the States, and never codified or ratified, nor supported by explicit service level agreements and funding commitments. Under those same arrangements it has been agreed that local governments are responsible for issuing flash flood warnings.

There are two key areas of concern for the Bureau which require attention. The first issue relates to flood river level monitoring. For the Bureau to forecast the timing and magnitude of flooding and to issue warnings, it requires real-time access to rainfall and river level information. Under current arrangements the Bureau is responsible for measuring rainfall, and over 100 state agencies and councils across Australia are responsible for monitoring river levels. These agencies supply, free of charge, their river level observations to the Bureau for use in flood forecasting and for online publication of real-time river levels. The Bureau's flood products are heavily utilised, vital to community safety and pivotal in emergency services response during flood events. The Bureau thoroughly values the generous cooperation it receives from these many data-supplying agencies, noting that many are struggling with network maintenance costs and that very few are explicitly resourced to monitor river levels for flood management purposes. Nonetheless, we see the need to voice concern about several issues that are limiting the overall extent and quality of flood warning and forecasting services to the community. The problems being experienced today will be magnified with projected climate change and more severe flooding, and are thus salient to climate change adaptation policy.

River level observations made by non-Bureau parties are usually gathered for purposes other than flood monitoring and suffer from a range of problems, including:

- monitoring network designs that are often ill-suited to flood forecasting and warning requirements;
- an inability of most agencies to service monitoring equipment on a 24/7 basis;
- a lack of funds or expertise to maintain monitoring stations to an adequate standard or to upgrade them readily;
- an inability to supply data at the temporal currency that the Bureau needs; and
- the absence of an enduring funding model to extend networks into new areas as circumstances require.

These problems are not due to any lack of goodwill or effort on behalf of the data collecting agencies involved. They almost always arise from either agency funding constraints or misaligned agency business imperatives. In our view, there are simply too many players with varied responsibilities and capacities, for an adequate, let alone future-ready, national flood monitoring network to eventuate.

The second issue relates to responsibilities for flash flood warning. As noted earlier, this is the responsibility of local government authorities. Given the sheer number of these authorities and the great variation in their size and resource base, there is little consistency in approach and level of service provided to citizens around Australia. Many local governments lack the resources and technical expertise to deliver effective flash flood warning services. Even for an agency with the scale and expertise of the Bureau, flash flood warning is a challenge due to the short response times involved. Nonetheless, with realigned responsibilities and appropriate funding arrangements we believe that far better outcomes can be attained, with communities better prepared to adapt to future climate change-driven increases in flash flood frequency and magnitude.

(f) Progress in developing effective national coordination of climate change response and risk management, including legislative and regulatory reform, standards and codes, taxation arrangements and economic instruments

The Bureau of Meteorology is not commenting on this Term of Reference.

(g) Any gaps in Australia’s Climate Change Adaptation Framework and the steps required for effective national coordination of climate change response and risk management.

The Bureau recently made a submission to the *Productivity Commission Inquiry into the Barriers to Effective Climate Change Adaptation*. A copy of that submission is provided in Attachment A. In this the Bureau argues that investments in early warning systems and associated high performance computing capacity and environmental monitoring are a particularly cost effective option for climate change adaptation.

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Attachment A

Productivity Commission Inquiry into the Barriers to Effective Climate Change Adaptation

Submission by the Bureau of Meteorology

26 July 2012

Enquiries should be addressed to:

Dr Rob Vertessy
Acting Director of Meteorology

Introduction

The Bureau of Meteorology welcomes the opportunity to make this submission to the 2012 Productivity Commission Inquiry into the Barriers to Effective Climate Change Adaptation. We are confining our submission to the matters traversed in Part 6 (Information Provision) of the Productivity Commission's Draft Report dated April 2012. We support in the broad the observations made in Part 6 of the Draft Report. We would however encourage a stronger focus on the merits of enduring environmental intelligence services as a pillar of climate change adaptation, and that is the thrust of our submission to follow.

We define environmental intelligence as *"conclusions drawn from environmental observations and models to guide decisions and actions by governments, businesses and individuals"*.

In a recent presentation given at the Australian Academy of Sciences, Dr Jane Lubchenco, Under-Secretary of Commerce for Oceans and Atmosphere and Administrator of the National Oceanic and Atmospheric Administration in the United States described the essence of the climate change challenge. She aptly characterized it as "avoiding the unmanageable and managing the unavoidable", highlighting the tandem requirement for mitigation and adaptation strategies.

There are multiple lines of robust evidence to show that earth's atmosphere and oceans are warming as a result of greenhouse gas emissions from the burning of fossil fuels. Significant changes have been recorded already, and further change is now locked in for centuries, whether or not emissions are reduced or even halted in the near term. The rate and magnitude of future changes will be determined by the level of future emissions, and a series of complex environmental feedbacks, but it is now likely that the average temperature of the atmosphere will rise by more than 2°C relative to pre-industrial revolution conditions (ie. beyond the ~1°C rise recorded to date). A rise of 2°C would exceed the commonly quoted "guardrail" level, deemed by experts to be the threshold beyond which dangerous impacts may arise. In this sense, Australia needs to prepare itself to "manage the unavoidable".

Climate change is driving changes in sea levels, ocean chemistry, marine, terrestrial and aquatic ecosystems, agricultural production, water security and the frequency and magnitude of severe weather events. These have the potential to impact profoundly on society, so effective adaptation strategies are vital. All of these changes present particular adaptation challenges for various nations and the many stakeholders within them. Effective climate change adaptation depends strongly on systematic monitoring of such changes and good foresight regarding likely future change. Good foresight implies knowledge of the timing, magnitude and potential impacts. Such knowledge is necessary for effective climate change adaptation, but also vital for informing the design and timing of mitigation strategies aimed at "avoiding the unmanageable".

The better utilisation of currently available environmental intelligence assets, and investments in new ones, could help to identify the most essential and cost effective adaptation options and thus significantly improve the ability of governments, businesses and individuals to reduce the manifold risks posed by climate change.

The role of the Bureau of Meteorology

The Bureau of Meteorology provides Australians with environmental intelligence for their safety, sustainability, well-being and prosperity. In practical terms, this entails providing Australians with the information and related support they need to manage and live within their natural environment, encompassing the atmosphere, oceans, water and land.

Some of the key functions of the Bureau of Meteorology are:

- monitoring and reporting on current environmental conditions
- analysing and explaining historic trends in environmental conditions
- providing forecasts, warnings and long-term outlooks on environmental phenomena that affect the safety, prosperity and resilience of Australians, and
- encouraging the use of of environmental intelligence for social benefit.

Below we elaborate on the different ways in which environmental intelligence provided by the Bureau is of value to Australians, and can support effective climate change adaptation.

Environmental intelligence that keeps us safe

On a 24/7 basis, we provide alerts, warnings and forecasts for cyclones, fire weather, floods, high winds, thunderstorms, hail, tsunami, ocean waves, tidal surges, air turbulence, visibility, volcanic ash, solar disturbances and ultraviolet radiation. In so doing, the Bureau helps protect people on the land, at sea and in the air, across Australia's territory and, in some cases, beyond. As we improve the speed, accuracy and dissemination of our alerts, warnings and forecasts, we reduce the risk of injury and loss of life and contribute to the resilience of Australian communities. In other words, the Bureau is already active in helping the community to adapt to and manage risks to safety and security arising from weather and climate. As noted earlier, an increase in severe weather events is a likely consequence of climate change. Early warning systems have proven time and time again to be the most effective and cost efficient approach to mitigating economic losses and loss of life arising from severe weather.

Environmental intelligence for sustainability

We monitor how our environment is changing over time, providing insight into possible impacts on our climate, food and water security, natural ecosystems and human health. Subtle changes in these parameters can have profound consequences for ecosystems, biodiversity and our food production systems. The Bureau is a 'listening post' for changes in rainfall and temperature, the chemical composition of our atmosphere, surface and groundwater availability, land cover and soil condition, the temperature and chemical balance of our oceans, and pollutants in our air, water, soil and oceans. In the context of this inquiry, such intelligence provides the reference frame. For instance, the Australian Climate Observations Reference Network for Surface Air Temperature (ACORN-SAT), managed by the Bureau, is the definitive data set chronicling the rate and pattern of climate change in Australia.

Environmental intelligence to secure our prosperity

The Bureau provides governments and businesses with environmental intelligence that underpins vital economic decisions. We provide insights into future climate conditions and water availability, trends in water utilisation and trade, ocean temperatures and currents, and changes in Australia's natural capital. These insights inform important investment and planning decisions, adaptation strategies, markets for environmental services, and regulatory and compliance regimes. Ongoing changes in our climate will demand periodic adjustments to planning and regulatory regimes and markets and such adjustments are best founded on sound environmental intelligence.

What more could be done to support climate change adaptation?

Whilst, by international standards, the Australian public is well served by quality environmental intelligence issued by the Bureau and other agencies, the efficacy of climate change adaptation strategies could be enhanced with better information.

The Bureau recognises that it is a matter for Governments to determine funding and resource allocation decisions amongst competing priorities. Noting that there are likely to be many productive investments that government could contemplate as part of a climate change adaptation strategy, we see two key areas of new investment where significant benefits could be captured, these being:

1. Improving early warning systems
2. Improving environmental monitoring and analysis

Below, we elaborate on these two areas.

1. Improving early warning systems

Climate change studies indicate that we can expect a higher incidence of severe weather events, particularly heavy rainfalls and very hot days. This increases the odds of more serious flooding, heatwaves and bushfires. These studies also indicate an intensification of our already significant interannual climate variability. This increases the odds of more severe droughts, particularly in southern Australia, and more severe wet seasons, particularly in the north. As noted earlier, early warning systems are an effective and cost-efficient means of mitigating the impacts of such changes.

With respect to severe weather events, the underlying message is that our communities face greater risk, both from the increasing likelihood of weather extremes and from increasing vulnerability arising from population growth and development. This heightened risk profile can be cost-effectively mitigated by improved early warning capability provided by numerical weather prediction systems. These models, already operational within the Bureau, provide forecasts for up to 10 days ahead and are now a mainstay of emergency response systems. There are clear pathways to extract further value from such systems, contingent on increased investment.

Appendix A to this submission outlines how numerical weather prediction systems, such as the ACCESS-based system operated by the Bureau of Meteorology, can be advanced to improve our ability to cope with severe weather events. Key messages in this document are:

1. Scientific knowledge has advanced to the point where we are able to model severe weather events with increasing fidelity.
2. Access to high performance computing capacity is the key to improving weather forecast timeliness, lead time, resolution and certainty.

We would add here that access to high quality observational data from satellites is particularly critical to the quality of severe weather forecasts. Over the last three decades, Bureau forecasts have improved each time new and higher resolution forms of satellite data became available for use in the models. Future improvements in forecast skill will depend heavily on continuing access to better observational data from satellites. For this reason, the Bureau supports the development of a national policy on earth observations from space.

Looking out further in time, benefits can also accrue from early warning systems capable of predicting interannual climate variability arising from medium-term variations in the heat balance of the atmosphere and the oceans. Our initial estimates indicate that about 5% of the variability in Australia's national gross domestic product (GDP) can be attributed to interannual climate variability. This equates to about $58 billion dollars variation in economic activity per year when averaged over the last 10 years (2001-2010). It is anticipated that this sensitivity will increase with further development and climate change. Some of this economic risk can be mitigated by the uptake of forecasts from seasonal climate forecasting systems, even if only slight changes in sectoral behaviour occur.

Seasonal climate forecasting systems look out from 1 to 3 months ahead, and potentially as far as 9 months. Traditional users of the Bureau's monthly-updated seasonal forecasts include farmers making decisions about annual production strategies and emergency management services preparing for fire or flood seasons. The Bureau has recently started to issue seasonal streamflow forecasts, providing guidance on the likely availability of water in major water supply systems across eastern Australia. Many others are now starting to utilize seasonal forecasts to mitigate risks posed by climate variability, including the energy, health, insurance and finance sectors. It appears as though the uptake of seasonal forecasts has been stimulated by the strong interannual climate variability we have experienced over the last decade, indicating that climate change is likely to stimulate further uptake.

Around the world, advanced coupled dynamic modelling approaches that consider interactions of atmosphere-ocean-land-ice processes are now being developed to forecast climate conditions at timeframes from a few weeks to a few seasons ahead. The science and technical capabilities of these advanced coupled dynamic models are maturing rapidly and offer great promise for helping us manage better with interannual climate variability. These new models have many advantages over our current statistical climate forecasting methodologies, not least of which they can account for changes in oceans and the atmosphere that are occurring as a consequence of global warming.

The Bureau of Meteorology is scheduled to implement its first operational climate forecasting service based on a version of a coupled dynamic climate model for Australia later this year. This model, known as the Predictive Ocean Atmosphere Model for Australia (POAMA), has been under development for more than a decade. While this model currently has only low spatial resolution and moderate skill, it will be a modest step forward from the current statistically-based system operated by the Bureau. It is likely to improve the skill of the Bureau's seasonal streamflow forecasting system also. In parallel with the release of POAMA, the Bureau is placing greater emphasis on the utilization of the forecasts by end-users. Based on extensive end-user requirements analysis, we are improving how we deliver seasonal forecasting information to different sectors.

Whilst we envisage improved utilization of seasonal forecasts in the near future, significant skill improvements will be slow to eventuate at the current rate of POAMA development. As a consequence, so too will be the realization of societal benefits. Accelerated development of POAMA could bring significant benefits forward in time. It is noteworthy that our major international trading competitors, in the US, UK, Europe, and Asia, are presently making significant investments in improved seasonal forecasting services.

As with severe weather prediction, access to high performance computing capability is a key to improvements in seasonal forecasting skill. However, in this case there is also a greater requirement for research and development as the science is less advanced.

2. Improving environmental monitoring and analysis

Some reference has been made already to the importance of environmental observations as a vital underpinning to early warning systems, namely numerical weather prediction systems for severe weather and seasonal forecasting systems for interannual climate variability. Beyond these requirements, we see three key areas where improvements in monitoring and data analysis are desirable to support effective climate change adaptation.

2.1 Rainfall intensity, frequency and duration

Accurate estimates of the intensity/frequency/duration characteristics of rainfall are critical to the task of designing structures affected by rainfall and flooding, such as gutters, culverts, drains and bridges. These estimates are also a critical input to hydrologic models used for the assessment of flood risk. Current estimates of design rainfall published in the Engineers Australia handbook Australian Rainfall and Runoff are based on data available up to 1983. Since then the availability of additional rainfall data has increased markedly and new techniques in frequency analysis have been developed. The Bureau is working with Engineers Australia to revise design rainfall estimates for the nation, using a much larger rainfall database and the latest analysis methods. Much of the new data being used was collected by the Bureau from a large number of contributing agencies under the aegis of the *Water Act 2007*, highlighting the value of this important data sharing reform policy.

A new body of IFD design rainfall estimates will be released later this year and should significantly enhance confidence in hydrologic design for the current climate regime. However, noting that most structures have long life cycles and that our climate is changing, the challenge remains on how to estimate what future IFD patterns may be. Maintaining continuous, high frequency rainfall measurements will be important for future revisions of rainfall IFD statistics, but so too will be the development of analysis methods for estimating future ones using currently available data. Under-design and over-design can both be costly.

Although different organizations have provided advice on the consideration of climate change in flood studies and investigations have been undertaken for specific areas of Australia, there does not exist a consistent approach on the consideration of climate change in flood studies. The Bureau of Meteorology is working closely with Engineers Australia and a variety of practitioners and academics involved in design flood studies, to develop a robust and consistent national approach.

2.2 River height monitoring for floods

For the Bureau to forecast the timing and magnitude of flooding and to issue warnings, it requires real-time access to rainfall and river height information. Under the current arrangements the Bureau is responsible for measuring rainfall and over 100 State agencies and Councils across Australia are responsible for monitoring river heights. These agencies supply, free of charge, their river height observations to the Bureau so that we are able to use them in our flood forecasting process and to publish real-time river levels online. These products are vital to community safety and pivotal in emergency services response to flood events.

The Bureau is most appreciative of the cooperation it receives from these many data-supplying agencies, noting that they are virtually all struggling with network maintenance costs and that very few are explicitly resourced to monitor river heights for flood management purposes. Nonetheless, we see the need to voice concern about several issues that are limiting the overall extent and quality of flood warning and forecasting services to the community. The problems being experienced today will be magnified in a climate-changed world with more severe flooding, and are thus salient to climate change adaptation policy.

River height observations made by non-Bureau parties are usually gathered for purposes other than flood monitoring and suffer from a range of problems, including:

i. Monitoring network designs that are sometimes ill-suited to flood forecasting and warning requirements;
ii. An inability of most agencies to service monitoring equipment on a 24/7 basis;
iii. A lack funds or expertise to maintain stations to an adequate standard or to upgrade them readily;
iv. An inability to supply data at the temporal currency that the Bureau needs; and
v. The absence of an enduring funding model to extend networks into new areas as circumstances require.

We stress that these problems rarely arise from any lack of goodwill or effort on behalf of the data collecting agencies involved. They almost always arise from either agency funding constraints or institutional arrangements that do not provide for the maintenance of sufficient professional expertise and data management and communication systems. In our view, there are simply too many players with varied responsibilities and capacities, for an adequate, let alone future-ready, national flood monitoring network to eventuate.

Ensuring that citizens receive timely and accurate flood warnings and forecasts should be an important facet of Australia's future climate change adaptation strategy. Noting the criticality of river height observations for flood warning and forecasting services, we recommend government consideration of alternative institutional arrangements and funding models for this important function.

2.3 Monitoring environmental change

In recent years the Bureau has built upon its traditional weather and climate monitoring and forecasting roles to assess a variety of environmental processes and ecosystems that are sensitive to climate change. A range of new Bureau products and services are emerging that can help to support effective climate change adaptation.

In 2007, the Bureau was assigned a new water information function under the *Water for the Future Initiative* and the *Water Act 2007*. As part of this new function, the Bureau is now making regular assessments of water balances for the nation, complementing our climate analysis function. This entails reporting on water availability, water quality, water entitlements and water use, providing a firm foundation upon which to make assessments of the role of climate change in affecting water security. An important aspect of this role is collecting and standardising the diverse primary water data collected by more than 215 agencies involved in this space. Another important aspect is the free dissemination of the harmonised data and derived products generated by the Bureau, providing governments, businesses and individuals with vastly superior insight into water resources than existed prior to the recent severe droughts.

In 2010, the Bureau was assigned a new environmental information function under the *National Plan for Environmental Information Initiative*. This entails establishing plans, standards, relationships, legislation, infrastructure and institutional arrangements to affect a step change in the availability and utility value of environmental information. Whilst we are only in the early stages of this program, the Bureau is already making good headway with several Federal, State and private partners to develop monitoring systems for the Great Barrier Reef (GBR), an ecosystem known to be very sensitive to climate change.

The eReefs project is a $25 million, five-year collaboration that brings together corporate Australia (through the Great Barrier Reef Foundation and its partner BHP Billiton Mitsubishi Alliance), Australia's leading operational and research agencies (the Bureau of Meteorology, CSIRO, and the Australian Institute of Marine Science), the Science and Industry Endowment Fund and Reef Managers (Great Barrier Reef Marine Park Authority). Contributions are also being made by the Australian Government, through Caring for our Country's Reef Rescue Program.

Managers of the GBR face ongoing challenges in the context of water quality, shipping, fishing, coastal development and particularly climate change. eReefs will help decision-makers manage the GBR by providing integrated and interactive information at both a scale and detail that has hitherto been lacking. Operational services scheduled to be launched by the Bureau include a Reef water temperature product and a Reef water quality product, developed by the eReefs research partners. Coupled hydrodynamic and ecologic forecasting systems for the GBR lagoon are also under development and expected to be launched in later phases of the program. A critical complement to this work are the primary coastal observations being made by the Integrated Marine Observing System (IMOS) initiative and the Australian Institute of Marine Sciences (AIMS). Without these observations, reporting and forecasting systems such as eReefs could not operate. We note that many marine and coastal zone observation programs underway in Australia are supported by short-term research programs.

eReefs is emblematic of the kind of environmental monitoring services that the Bureau is aspiring to host under the auspices of the *National Plan for Environmental Information Initiative*. These need to be supported by observation programs that are stable and enduring and this will necessitate arrangements to transition research programs into operational ones. We see merit in directing initial focus to iconic ecosystems that are sensitive to climate change and the prime focus of climate adaptation planning. What is lacking is appropriate institutional arrangements and an investment model to bring such monitoring services to fruition at the pace required by climate change and other environmental pressures. Redressing this deficiency is one of the primary aims of the proposed *National Plan for Environmental Information*.

Appendix A

Australian Government

Bureau of Meteorology

HIGH-PERFORMANCE COMPUTING FOR NUMERICAL WEATHER PREDICTION

AN ESSENTIAL REQUIREMENT FOR THE FORECASTING OF SEVERE WEATHER EVENTS AND THEIR IMPACT ON THE COMMUNITY

10 April, 2012

1. Forecasting severe weather events

1.1. The demand

The 2010/11 and 2011/12 summers were extraordinary for their extremes of weather and climate, going from a period of unparalleled drought in the southern and south-eastern regions of Australia, to one characterised by floods and extremes of weather. Just as the previous decade introduced new records in temperature and low rainfall, this recent period saw extraordinary downpours and extreme flooding through Queensland and the south-eastern States.

The loss of life and enormous damage to property highlighted the vulnerability of modern society, its infrastructure and communities, as did the drought, heatwaves and bushfires in the preceding few years.

Climate change studies suggest we may expect more extreme patterns of weather and climate variability. Likely early impacts of climate change on communities are the increased frequency and magnitude of extreme rainfall and associated flash flooding and riverine flooding, coastal flooding from storm surges, heatwaves and bushfires. The underlying message is that our communities face greater risk, from the increasing likelihood of extremes, from increasing vulnerability, or from a combination of both.

This heightened risk profile can be mitigated to some extent by improved early warning capability for the onset of severe weather events. This is achieved by the use of numerical weather prediction systems such as the ACCESS-based system operated by the Bureau of Meteorology.

Scientific knowledge has advanced to the point where we are able to model such phenomena with increasing fidelity. Over the last thirty years weather prediction has moved from an uncertain science where prediction at 1-2 days lead time over large regions was a challenge, to the point where 7-10 day forecasts are considered very skilful and local forecasts are routine. Forecast skill is measured by comparing model predictions of temperature, humidity, pressure, wind and rainfall fields with observations of these phenomena. The Bureau systematically collects such verification statistics for every forecast so that it can demonstrate improvements in model accuracy over time.

There are at least three reasons for the increases of forecast skill. First and foremost is the advance in scientific knowledge and that representation of that in the models. Second is the ability to observe and assimilate data into models, particularly from satellites. Third is the enormous growth in computer power which now allows the best global models to run at 10-30 km resolution, and regional models at scales down to 1-4 km. For extreme weather, where the scales of action are often in the 10-30 km range and the complexity of weather is at its most intense, the ability to run models at high resolution with the complexity of the atmosphere addressed in detail is vital.

Most developed countries and an increasing number of developing nations consider numerical weather prediction (that is, numerical computer models of the atmosphere and its evolution in time) as a core capability of their National Meteorological and Hydrological Services. While not every service runs global prediction models, most recognize that timely and accurate forecasts for their region offer distinct social and economic benefits, particularly in terms of timeliness and local relevance.

Timing matters. Every hour of additional lead-time provides further opportunity to reduce vulnerability and exposure to severe weather, saving lives and injuries, and reducing property loss. Seasonal outlooks provide advantage for primary industries and an ability to prepare for possible enhanced extreme weather activity.

There are other natural and man-made disasters that also benefit from high performance computing. For the Australian Tsunami Warning System, an outstanding requirement is the need to generate inundation predictions in real-time, noting that time is again of the essence (minutes matter). For disasters such as the Montara oil spill, ocean prediction systems that forecast surface and subsurface currents come into play.

High performance computing systems enable such outcomes.

1.2. Benefits and impact

The utility value of severe weather forecasting (and related forecast systems mentioned above) essentially increases as the power of high performance computing systems increase. This is because the models improve in terms of:

- *timeliness* – the models can be run more frequently, providing more ‘current’ results
- *lead time* – the models can be run for longer time windows, providing earlier warning
- *resolution* – the models can be run at finer scale, providing greater relevance to local decision making
- *certainty* – the models can be run many times over (referred to as ensembles), providing probabilities for a range of outcomes.

Six case studies are provided below, each illustrating how these benefits are unlocked when high performance computing constraints are reduced. In each case resolution is shown to be a key determinant in the skill and usefulness/relevance of the forecasts. It is important to note that, since regional and fine scale models are nested in other models of larger domain, there is an interdependence flowing from the global models down to the specialist models such as for tropical cyclones.

These case studies also demonstrate the potential for applications in specific areas. For example, skilful forecasts of extreme heat allow for the development of sophisticated heatwave response strategies. The bushfire model allows for interaction with emergency services, at scales that are relevant for operations. Improved resolution of topography will reduce the need for forecasters to make corrections in these regions. The detailed wind forecasts for TC Yasi open up the possibility of generating impact forecasts ahead of the tropical cyclone.

Seasonal forecasting lags weather prediction in maturity, and faces even more complexity because of the need to consider the ocean and land and their interaction with the atmosphere. Models of seasonal climate variability do not attempt to capture the details of weather since it is unpredictable beyond around 14 days, but instead try to capture the pattern and evolution of “average” weather (climate). This is possible because the coupling of the ocean and atmosphere in the tropics generates joint effects that appear to be predictable on seasonal time scales, perhaps even out to a year and more.

Advanced warning of shifts in climate (for example drier or wetter seasons) provides valuable intelligence for managers in climate-sensitive industries (such as agriculture and energy), for emergency management (as highlighted in the QLD Floods Commission of

Inquiry), and for water management. The utility of forecasts varies with lead-time, region and sector. There is significant value in simply understanding how climate has varied in the past (so-called hind-casts). In some sectors this is on weekly to monthly time scales, and in others it is on seasonal to yearly time scales. For models, both atmospheric and oceanographic information must be taken into account. It is thought that predictability mainly derives from knowledge of the ocean state, but the atmospheric and land states are also important.

1.3. Operational change

A primary motivation for increased computer power is the potential to generate estimates of the uncertainty (error growth) in weather forecasts. The “butterfly effect” says that miniscule differences in the weather state now can manifest as substantial change in the weather days into the future. A similar effect is present for seasonal forecasts. In order to quantify this effect or, equivalently, to provide probabilities for the range of possible climate or weather outcomes, it is usual to generate an ensemble of forecasts, each distinguished by small variations in the initial state and/or minor changes in the model assumptions (the butterfly) but with different weather/climate outcomes as the forecast evolves. These are often run at slightly coarser resolution to allow many ensemble members to be generated. The overall utility value of forecasts is enhanced by such a probabilistic approach allowing informed decision-making and better assessment of risk. These are significant additional computational burdens but the estimates of uncertainty allow informed decision making and better assessment of risk (that is, the likelihood of an event is also forecast).

Errors in forecasts, particularly at fine scales and/or for rapidly evolving storms, can grow significantly over 12 hours (the current default cycle for the Bureau’s weather forecast updates). More frequent updating (say, around every 4 hours) would ensure the most up-to-date information is always available in extreme weather conditions, and allows for event-specific models to be initiated in special circumstances. Examples include for a tropical cyclone approaching landfall, a special high-resolution run to capture fronts for bushfires, or, as in Fukushima, a simulation of the trajectory of a sudden radioactive release.

While empirical models were the mainstay of early seasonal forecasting systems, dynamical models of the ocean and atmosphere are increasingly the norm. Here the challenge is to have sufficient computing power to represent the complex interaction of the ocean and atmosphere, but at relatively coarse scale compared with weather prediction (typically 80-120 km), and to undertake integrations over long periods, typically 9-12 months (compared with 7-10 days for weather prediction.

A unique challenge for seasonal forecasting models is that they still possess systematic errors (biases) that can confound and mask the signal we are trying to predict. The usual treatment is to undertake a number of hind-casts for the recent past (typically from around 1980), and to use these to identify and remove bias. This adds to the computational cost but adds value in terms accuracy and certainty.

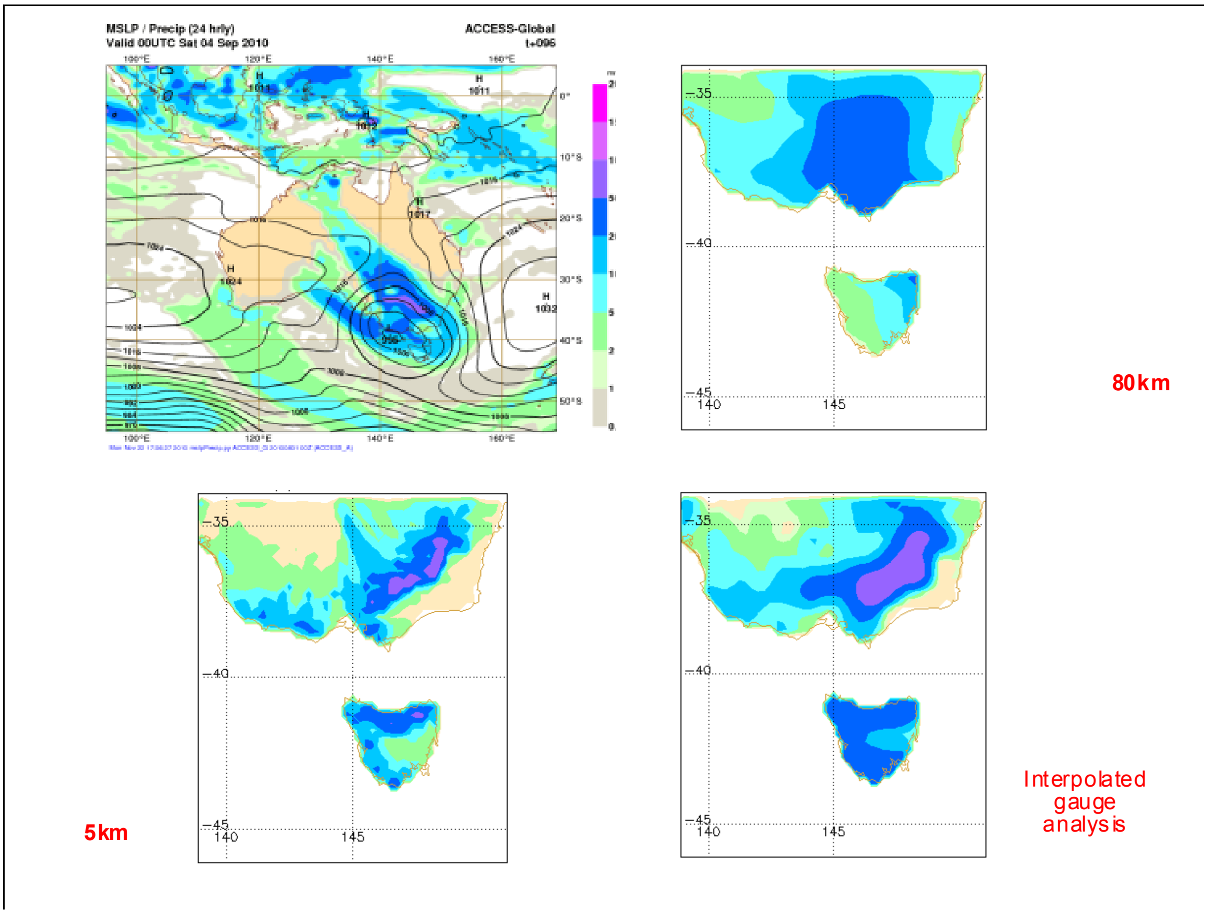
There is also significant value in re-analysing past weather systems. Modern weather prediction systems could be applied to past events such as Cyclone Tracy, to better understand the evolution and spatial structure of the systems, and to generate detailed digital representations of variables such as wind speed and rainfall for planning purposes. For some sectors, such as the re-insurance industry and emergency planning sector, access to detailed statistics of past events, generated through a single modelling system would lead to more accurate assessments of risk.

2. Case Studies

2.1 Case Study 1: Eastern Victoria Flooding September 2010

Severe flooding occurred in eastern Victoria early in September 2010. The ACCESS model is able to forewarn of the likelihood of extreme rainfall several days in advance (Figure 1, top left panel shows the 4 day forecast). Resolution matters. The top right and bottom left panels contrast 80 km and 5 km forecasts, respectively, which can be compared with the independent rain gauge analysis (bottom right).

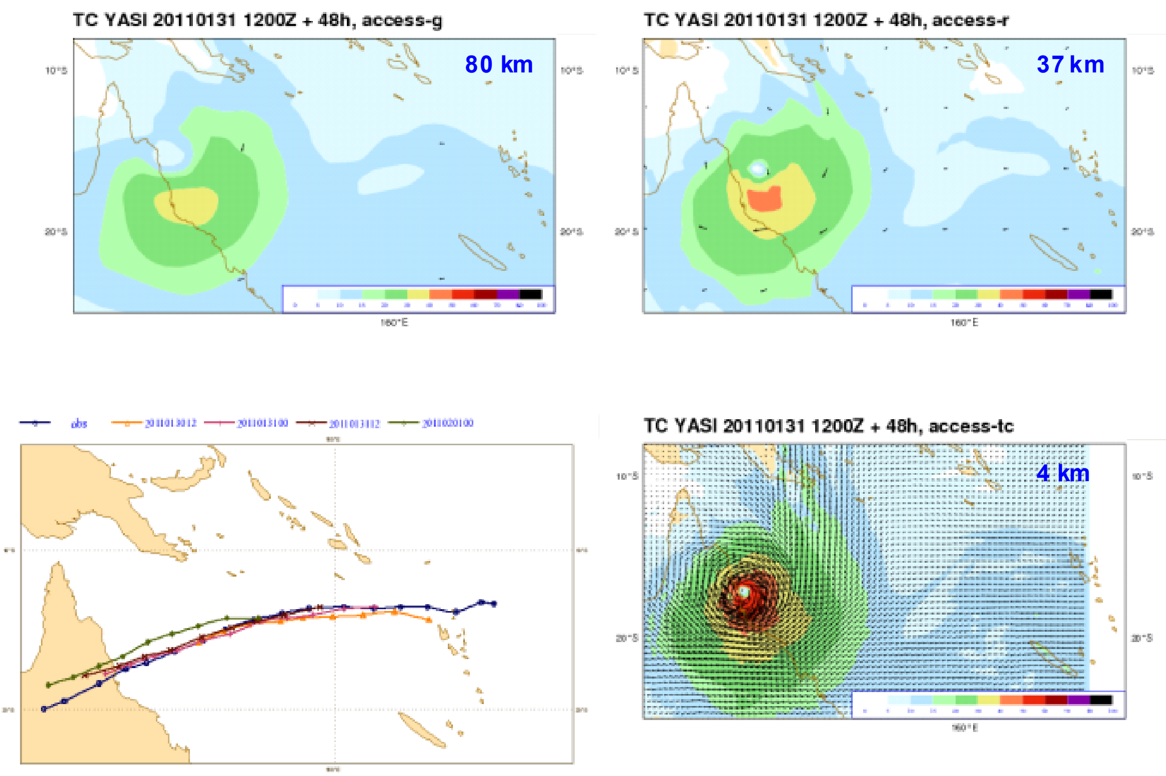
Figure 1. Extreme rainfall September 2010



2.2 Case Study 2: Tropical Cyclone Yasi

The second case study focuses on tropical cyclone Yasi in early February 2011. Again we show the impact of resolution on a 2-day forecast, going from the 80 km global ACCESS model at the time (top left), the regional ACCESS model (top right), to a 4 km resolution model run post the event (bottom panels). The bottom left panel shows forecasts beginning at 1200 on 30 Jan and then every 12 hours until 1 Feb. There is an excellent track forecast with the 4km version of ACCESS and very encouraging skill in the intensity of the forecast (bottom right), with the model getting down to ~950hPa (observed was ~925hPa). At present this model can only run operationally at 12 km. The use of ensembles (running the forecast several times with slightly different initial conditions) gives additional information on the strike probability and opens up the possibility of developing impact scenarios.

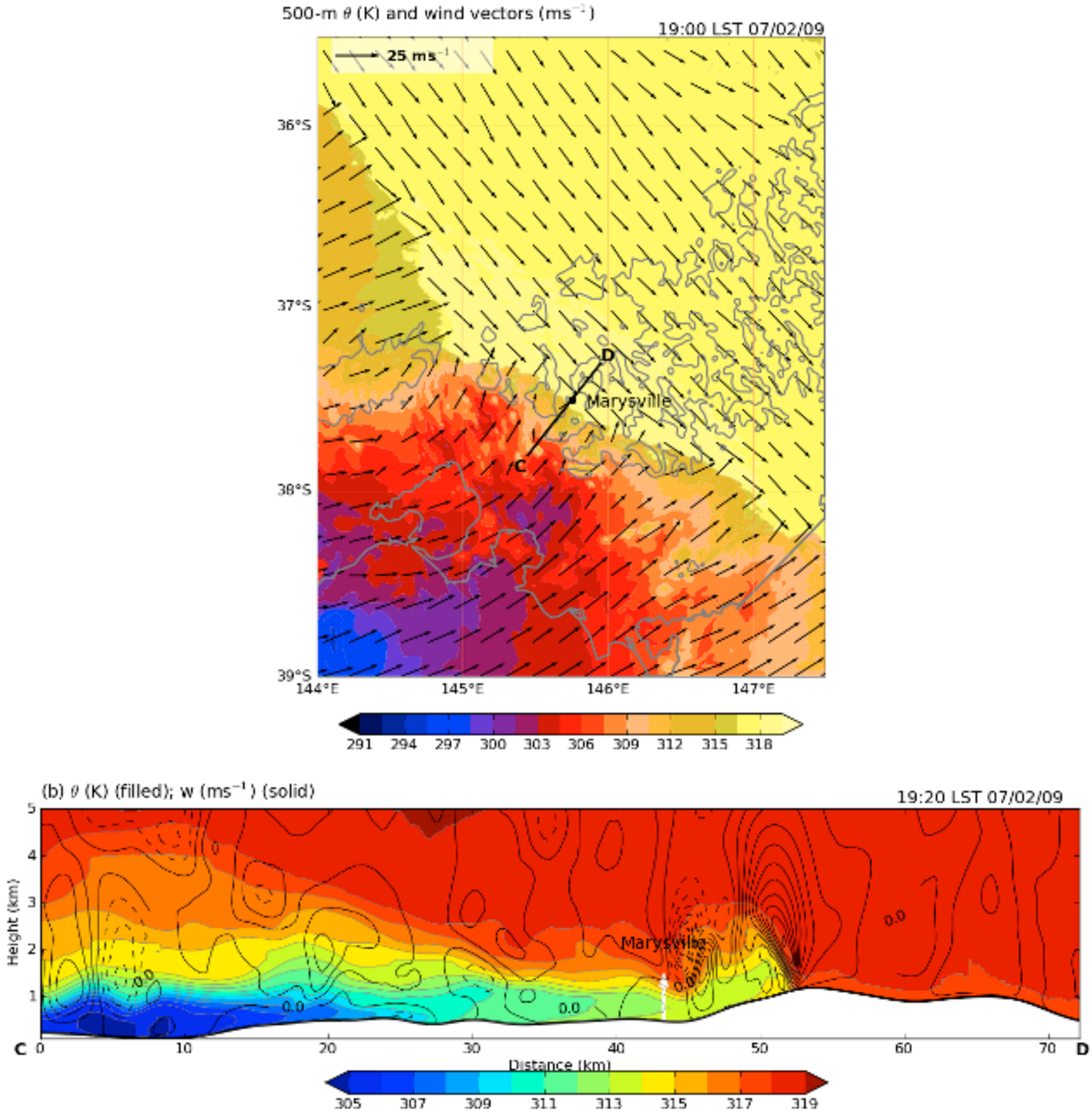
Figure 2. Models of tropical cyclone Yasi.



2.3 Case Study 3: Black Saturday Bushfires February 2009

This case study demonstrates the power of resolution for modelling fire weather and the potential for running special “models on demand”. The model is run at super-fine resolution in order to better represent the evolution of the front through Marysville. This run incorporates detailed topographic information and provides much greater detail in the wind directions, including changes; vital information for fire fighters and emergency services. It provides an accurate prediction of the cool change and major change in wind direction, and a much more accurate depiction of the severity of the event in terms of high temperatures.

Figure 3. High-resolution (0.5 km) forecasts for 7 February 2009 (work with the University of Melbourne).

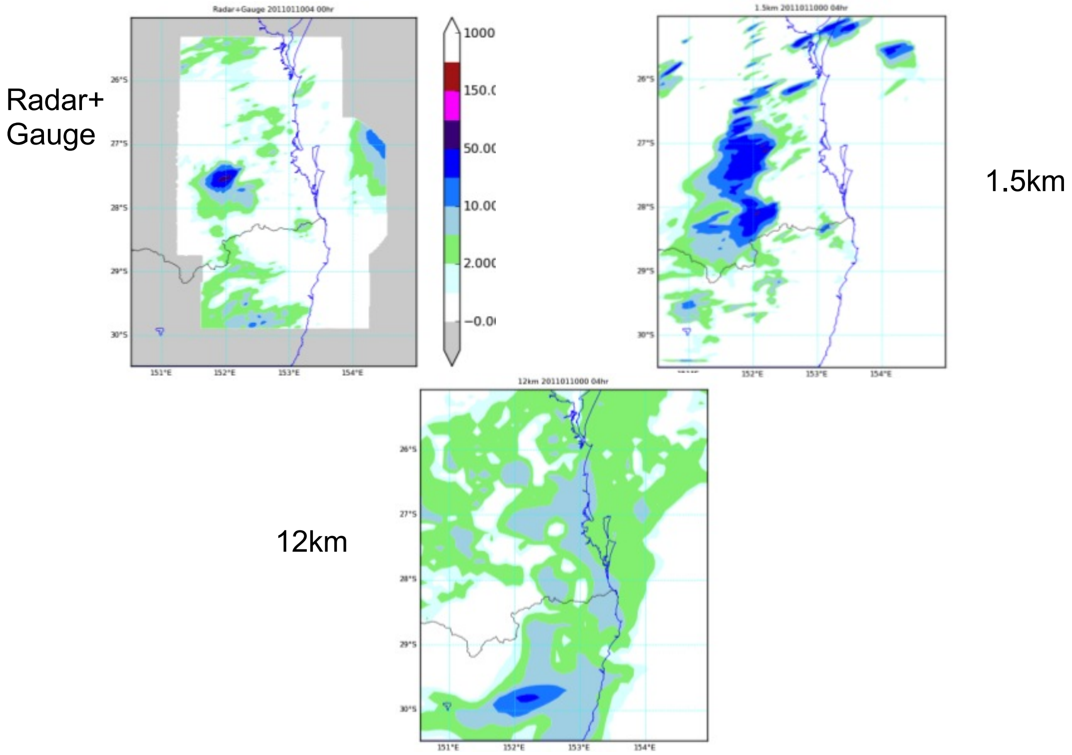


High performance computing for numerical weather prediction

2.4 Case Study 4: Toowoomba Extreme Rainfall Event

This case study shows an experiment with a fine resolution ACCESS model to test the extent to which the detail of intense rainfall events might be captured. Shown are two four-hour forecasts for the severe rainfall in Toowoomba on 10 January, one at the resolution of the regional ACCESS model (12 km, bottom) and one at 1.5 km (top, right). The rainfall inferred from radar measurements is shown top left. Thunderstorms are small-scale and short-duration systems and their predictability is short (few hours), so it is not possible to forecast location or timing of events precisely. The 1.5 km version of ACCESS with latent heat nudging (based on radar-gauge rainfall) and assimilation of radar winds provides an indication of the severe event in the region around Toowoomba. The 12 km operational ACCESS-A provides no such indication. Ensembles have the potential to provide probabilities for severe storms.

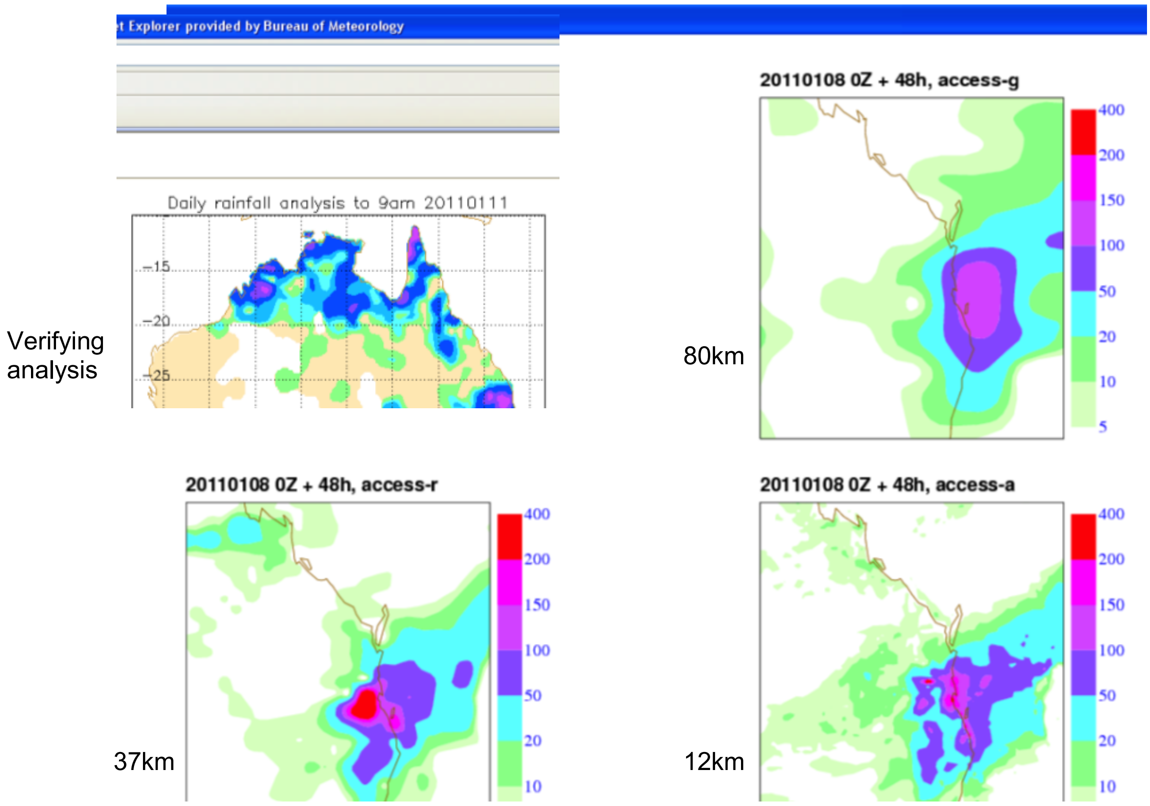
Figure 4. High-resolution experimental forecasts for the Toowoomba rainfall event.



2.5 Case Study 5: Brisbane Floods 2011

Experiments with the ACCESS global and regional models indicate an ability to give warning 6 days ahead of this particular major rain event. Higher resolution runs generate more realistic patterns of rainfall. Higher resolution models with ensembles provide more detailed and specific information, suitable for downstream applications and usable by third parties for integration with other geospatial data to aid decision-making.

Figure 5. Southeast Queensland extreme rainfall as depicted by different resolution models.



2.6 Case Study 6: Ensembles

AGREPS (an ACCESS-based version of the Met Office ensemble technique) has been implemented and is being run in experimental mode in the Bureau. With such technology we can generate likelihood maps for weather impacts. An example of an Extreme Forecast Index (EFI) is shown below. These provide a very powerful visual diagnostic for decision makers in advance of severe weather.

Figure 6. Four of 25 ensembles from an experimental tropical cyclone model run at 37 km grid resolution. The TC Yasi predictions vary in both intensity, track and timing and so provide and indication of the likelihood of particular outcomes.

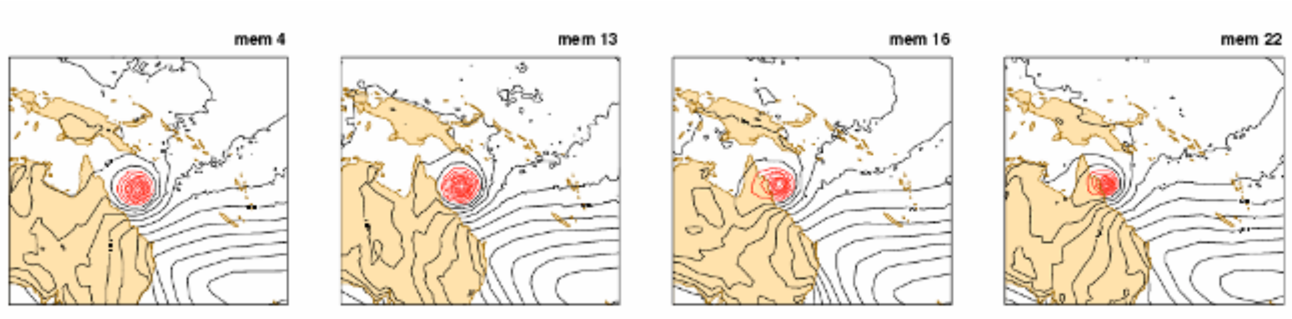


Figure 7. EFI values for 24h total rainfall, 10m wind gust and 2m temperature. EFI identifies areas where the ensemble forecast distribution is significantly different from the climatological distribution.