CSIRO Submission 12/471

Recent trends in and preparedness for extreme weather events

Senate Standing Committee on Environment and Communications

January 2013

Enquiries should be addressed to:

Dr Grant Farrell
CSIRO Ministerial and Parliamentary Liaison
PO Box 225, Dickson ACT 2612

Main Submission Author:

Dr Andrew Ash
Director, Climate Adaptation Flagship
GPO Box 2583 Brisbane QLD

Contents

I. **Executive Summary**

II. **Introduction**

III. **Background - Climate Change: Extreme Weather and Climate Events**

IV. **CSIRO response to 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.***

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

   c. **An 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.**

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

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

I. Executive Summary

CSIRO undertakes a wide range of research on weather and climate, its impacts, and how we can adapt to both current climate and that of the future.

Australia experiences a highly variable climate: our climate includes a range of extreme events which add up to considerable economic, social and environmental impact. Given this large natural variability in weather and climate, it is often difficult to detect a trend in extreme events or it takes a long time for the trend to become statistically significant. However, there is now strong evidence globally that during the past 50 years there has been a change in temperature extremes with fewer cold days and nights and more hot days, hot nights and heatwaves. This warming trend has flow on consequences for other events such as bushfires with an observed tendency towards more days of high forest fire danger in the last few decades. Trends in rainfall extremes are much less certain, though the IPCC reported in 2012 a statistically significant increase in the number of heavy precipitation events in many regions of the world.

Future climate change impacts will increasingly be experienced first through extreme events rather than gradual changes in mean temperature or rainfall. For example, heatwaves: the number of days over 35^{o}C is expected to increase significantly by 2030 for many locations in Australia. Also rainfall: despite the general tendency for decreases, or little change in seasonal-average rainfall in the future for much of Australia, increases in extreme daily rainfall are expected over most of the continent in the future. Likewise, tropical cyclones are likely to become more intense with a decrease in frequency. And dry extremes: drought occurrence is expected to increase over most of southern Australia, especially in south-western Australia.

Extreme events place a huge financial, social and emotional burden on individuals, communities, industry and the government. Better preparing for extreme events through planning, engineering and awareness has proved to be effective in reducing their cost. For example, cyclone building codes in northern Australia are very effective at reducing damage from high intensity wind events. Cost-benefit analyses demonstrate that under a changed climate it is cost effective to put in place stronger engineering codes, especially in sub-tropical regions.

Increased vulnerability to extreme events is not just related to climate change. Planning regulations that place more people in vulnerable areas will lead to greatly increased costs of extreme events. For example, in south-east Queensland, based on current development patterns, the number of residential buildings affected by a 1 in 100 year storm tide inundation event nearly doubles in 2030 compared with today. Sea level rise accounts for only a small amount of this increased exposure in 2030 but by 2070 it is a much more significant contributor to the projected damages.

Human health is an important consideration in the context of extreme events. Heatwaves in particular can lead to considerable loss of life in today’s climate. As the climate warms and heatwaves become frequent the effect on years of life lost increases gradually but then starts to rise rapidly once mean temperatures increase beyond 2^{o}C.

Emergency services agencies can be better equipped through having in place better forecasting and modelling tools and early warning systems for a wide range of extreme events, including heatwaves, bushfires, floods, and inundation events. These forecasting and modelling tools are developing rapidly and with information systems technologies are increasingly able to be deployed in real time.

Finally, it is important to understand the impacts of existing extreme weather and climate events and use these as a window into determining how to respond to future climate change in an enhanced greenhouse world.

II. Introduction

CSIRO welcomes the opportunity to comment on and provide input to the Senate Standing Committee on Environment and Communications inquiry into - *Recent trends in and preparedness for extreme weather events*.

CSIRO provides comprehensive, rigorous science to help Australia understand, respond to and plan for a changing climate. We have significant research activities, nationally and internationally, which have helped us to better understand the causes and impacts of extreme weather events. This information is used to work closely with governments, industry, and the community to develop practical and effective adaptation options. Our response to the inquiry draws on this very broad range of scientific work.

Our comments have been prepared by a team of scientists from across CSIRO with experience and international recognition in many facets of climate research. This submission is focused on sections where CSIRO has undertaken research that is published or in the public domain. We would welcome the opportunity to discuss any areas in more depth with the Committee.

III. Background – Climate Change: Extreme Weather and Climate Events

In 2012, CSIRO and the Bureau of Meteorology released the report entitled *State of the Climate*. Some key highlights include -

- Warming in Australia is consistent with warming observed across the globe in recent decades. Australian annual average daily mean temperatures have increased by 0.9 °C since 1910, and each decade since the 1950s has been warmer than the previous decade.
- Global average mean sea level for 2011 was 210 mm above the level in 1880.
- Sea surface temperatures in the Australian region have increased by about 0.8 °C since 1910.
- Greenhouse concentrations have risen rapidly during the past two centuries. The concentration of carbon dioxide in the atmosphere in 2011 was 390 parts per million – higher than at any time for the past 800,000 years.
- The main cause of the observed increase in carbon dioxide concentration in the atmosphere is the combustion of fossil fuels since the industrial revolution.
- It is very likely that most of the surface global warming observed since the mid-20th century is due to anthropogenic increases in greenhouse gases. This has also influenced ocean warming, sea level rise and temperature extremes. Further increases in greenhouse gases are expected during the 21st century.
- Australian average temperatures are projected to rise by 1.0 to 5.0 °C by 2070 when compared with the climate of recent decades.

A changing climate leads to changes in the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events. Some local climate extremes (e.g. the south-east Australian droughts from 1997-2009) may be the result of an accumulation of weather or climate conditions that are not extreme when considered independently. The natural climate variability that underlies all extreme weather events is now influenced and altered by the effect of human-induced warming of the climate system (IPCC, 2012). It is not relevant to ask whether an individual extreme event is ‘caused’ by climate change (any more than whether a particular warm day in spring is ‘caused’ by the change of season); rather, analysis should focus on whether the *risk* of extreme weather events is changing due to a range of different factors, such as the El Nino Southern Oscillation, land-use change or increases in greenhouse gases.

The Intergovernmental Panel on Climate Change (IPCC, 2012) report on *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* concluded that it is very likely that global warming has caused changes in the frequency of extreme weather events that have been observed since

1950. The report also found that it is very likely that there has been an overall decrease in the number of cold days and nights, and an overall increase in the number of warm days and nights, at the global scale and at the continental scale in North America, Europe, and Australia. There have been statistically significant increases in the number of heavy precipitation events in most regions (IPCC, 2012).

Australia has experienced a number of extreme weather and climate events in recent years, including the 1997-2009 droughts, the Black Saturday bushfires and severe heatwaves in south-east Australia in Jan-Feb 2009, the 2011 Queensland and northern NSW floods and Cyclone Yasi, and 7-8 January 2013 was Australia's hottest 2-day period on record.

Climate change impacts will increasingly be experienced first through extreme events rather than gradual changes in mean temperature or rainfall. Consideration of current vulnerability to extreme events helps to establish the context for assessing changes in vulnerability due to future changes in extremes. Regardless of the cause, it is important to understand the impacts of existing extreme weather and climate events and use these as a window into determining how to respond to future climate change in an enhanced greenhouse world (CSIRO, 2011).

Dealing with uncertainties

Popular narratives about climate change focus strongly on the uncertainties of the future, and it is true that some climate parameters vary greatly, especially at the local scale. Changes in some extremes are hard to project, especially for individual locations: for example, is it very hard to say whether hail storms or extreme winds will hit a specific location in the future. However, there are many climate parameters where the *direction* of change is known with high confidence, and where the changing *risk* of impacts, even at a specific location, can be projected with similar confidence. Thus there is very likely to be increases in maximum temperatures, heatwaves, fire weather conditions, minimum temperatures, ocean temperatures, ocean acidity, and sea level. For these parameters it is possible to specify minimum levels of change for the 21st century and a likely magnitude of change with some uncertainty in timing (Stafford Smith *et al.,* 2011; IPCC, 2012). By contrast, some climate parameters are inherently uncertain: for example, rainfall projections remain highly uncertain in northern Australia (CSIRO and Bureau of Meteorology, 2007). However, even these types of uncertainties can be managed with appropriate risk mitigation approaches.

The implications of uncertainty and extremes for adapting to current and future climate have been canvassed in CSIRO's submissions to the recent Productivity Commission enquiry on barriers to adaptation – the Committee is referred to these public documents for more details: see http://www.pc.gov.au/projects/inquiry/climate-change-adaptation/submissions, submissions 40 and DR136.

Definitions of uncertainty

The IPCC (2012) relies on two metrics for communicating the degree of certainty in key findings, which is based on author teams' evaluations of underlying scientific understanding:

- Confidence in the validity of a finding, based on the type, amount, quality, and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and the degree of agreement. Confidence is expressed qualitatively
- Quantified measures of uncertainty in a finding expressed probabilistically (based on statistical analysis of observations or model results, or expert judgment).

Term*	**Likelihood of the Outcome**
Virtually certain	99–100% probability
Very likely	90–100% probability
Likely	66–100% probability
About as likely as not	33–66% probability
Unlikely	0–33% probability
Very unlikely	0–10% probability
Exceptionally unlikely	0–1% probability

Table 1. Terms used to indicate the assessed likelihood (IPCC, 2012).

IPCC (2012) use the follow summary terms to describe the available evidence: *limited*, *medium*, or *robust*; and for the degree of agreement: *low*, *medium*, or *high*. A level of confidence is expressed using five qualifiers: *very low*, *low*, *medium*, *high*, and *very high* (IPCC, 2012). There is flexibility in this relationship; for a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence (IPCC, 2012).

IV. CSIRO response to 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.

CSIRO's research, conducted with national and international research partners, has improved our understanding of recent trends in extreme climate events.

Extreme temperatures and heatwaves

There is evidence globally that, during the past 50 years, there has been increase in temperatures with a warming of extreme daily minimum and maximum temperatures (IPCC, 2012). Changes include fewer cold days and nights and more hot days, hot nights and heatwaves. It is likely that human influences have already led to warming of extreme daily minimum and maximum temperatures at the global scale (IPCC, 2012). This has occurred against a backdrop of natural, year-to-year climate variability.

In Australia, El Niño and La Niña events have continued to produce the hot droughts and cooler wet periods for which the country is well known. Most notably it has been observed:

- Each decade has been warmer than the previous decade since the 1950s (CSIRO and Bureau of Meteorology, 2012).
- Australian annual average daily maximum temperatures have increased by 0.75 °C since 1910 (CSIRO and Bureau of Meteorology, 2012).
- Australian annual average daily mean temperatures have increased by 0.9°C since 1910 (CSIRO and Bureau of Meteorology, 2012).
- Australian annual average overnight minimum temperatures have warmed by more than 1.1°C since 1910 (CSIRO and Bureau of Meteorology, 2012).
- Australia's hottest year was 2005, with a temperature more than 1°C above the 1961–1990 average (Bureau of Meteorology, 2013a).
- An exceptional heatwave affected south-eastern Australia during late January and early February 2009. The most extreme conditions occurred in northern and eastern Tasmania, most of Victoria and adjacent border areas of New South Wales, and southern South Australia, with many records set both for high day and night time temperatures as well as for the duration of extreme heat (Bureau of Meteorology, 2009).
- 2010 and 2011 were Australia's coolest years recorded since 2001 due to two consecutive La Niña events. (Bureau of Meteorology, 2013a).
- For September to December 2012, the average Australian maximum temperature was the highest on record with a national anomaly of +1.61 °C, slightly ahead of the previous record of 1.60 °C set in 2002 (Bureau of Meteorology, 2013b).
- 7-8 January 2013 was Australia's hottest 2-day period on record, and many other records were broken locally during 4-13 Jan 2013 (Bureau of Meteorology, 2013b).

Droughts and floods

In Australia there has been a trend over recent decades towards increased spring and summer monsoonal rainfall in the north, while the south of the country has experienced decreased late autumn and winter rainfall, and southwest Western Australia has experienced reductions in rainfall since 1970 during the winter half of the year.

Changes in seasonal-average rainfall affect the incidence of drought and floods. Both droughts and floods occur from a combination of biophysical and social phenomena: drought is not just a lack of rainfall but it is influenced by water demand and flood is influenced by urban factors such as development patterns which affect vulnerability of population and infrastructure.

Regarding floods, there have been statistically significant increases in the number of heavy precipitation events in most regions of the world (IPCC, 2012). There is medium confidence that human influences have contributed to intensification of extreme precipitation at the global scale (IPCC, 2012). There is limited to medium evidence available to assess climate-driven observed changes in the magnitude and frequency of floods at regional scales because the available instrumental records of floods at gauge stations are limited in space and time, and because of confounding effects of changes in land use and engineering (IPCC, 2012). Over Australia, trends in heavy rainfall depend on the period of analysis and the metric of interest. For example, the annual number of days with more than 30 mm of rain from 1950-2012 has decreased in much of southern and eastern Australia, but increased in the north (similar to the trend in average rainfall: Bureau of Meteorology, 2013c). Similar results have been found for other metrics (Gallant *et al.,* 2007).

Regarding droughts, there is medium confidence that some regions of the world have experienced more intense and longer droughts, in particular in southern Europe and West Africa, but in some regions droughts have become less frequent, less intense, or shorter, for example, in central North America and north-western Australia (IPCC, 2012). The 14-year period of very low rainfall (or drought) from late 1996 to mid 2010 over parts of Australia has raised questions about how exceptional this period was in the longer-term context.

Based on data available from the Bureau of Meteorology (Bureau of Meteorology, 2013d), there has been a decreasing trend from 1900-2011 in the area of Australia with less than 10% of annual-average rainfall (defined as serious rainfall deficiency). This decrease is apparent in all States and Territories, except Victoria and south-west WA where there has been little change and an increase, respectively.

Trends in the area with serious annual rainfall deficiency do not provide information about whether recent multi-year rainfall deficiencies were exceptional for particular regions. This has been assessed for various multi-year periods and regions.

- For the 7-year period October 2001 to September 2008, Victoria’s area-averaged rainfall (17.6% below the 1961-90 average) fell to the lowest level on record, surpassing the previous record (17.3% below) for a seven-year period set between May 1938 and April 1945 (Bureau of Meteorology, 2010).
- For the 9-year period 2001–2009, annual-average rainfall across the MDB was 406 mm, but the lowest 9-year period on record was 395 mm for 1937–1945 (Leblanc et al., 2012). Despite the similar rainfall deficiencies in both periods, it has been argued that there were much stronger decreases in runoff in the more-recent period partly due to the lower inter-annual rainfall variability and lower autumn and winter rainfall, and other factors such as the impacts of farm dams, groundwater extraction or recent changes in land use (Leblanc et al., 2012).
- For the 12-year period 1997-2008, the area of record low totals covered the majority of southern Victoria from Gippsland westwards, extending into SA and most of the northern and eastern coasts of Tasmania (Bureau of Meteorology, 2010). A separate area of record low totals on the west coast of WA extended from north of Perth south to Busselton, and in parts of the Darling Downs and South Burnett regions between Gayndah and Kingaroy (Bureau of Meteorology, 2010). Around metropolitan Melbourne and to its east, 12-year rainfall totals were around 20% below the 1961-90 average, and 10-13% below the lowest on record for any 12-year period prior to 1996 (Bureau of Meteorology, 2010).

- For the 13-year period 1997 to 2009, rainfall over continental southeastern Australia (south of 33.5°S and east of 135.5 °E) was 11.4% below the long-term average, making it the driest 13-year period on record by a large margin; the previous record is 7.8% below average for the 13-year period 1933–1945 (Timbal and Drosdowsky, 2012). Both the duration and intensity of the 1997–2009 rainfall deficit is without historical precedent in the instrumental record starting from 1900 (Timbal and Drosdowsky, 2012). The spatial signature of the 1997–2009 drought (largest decline observed along the southern coast and near significant orography) and its temporal signature (mostly during autumn–winter–spring) further indicate that the rainfall decline is linked to a weakening of the dominant westerly atmospheric flow as expected in response to a strengthening of the belt of high pressure (Timbal and Drosdowsky, 2012).
- For the 14-year period October 1996 to September 2010, around half of Victoria and half of Tasmania recorded lowest-on-record rainfall, and in south-west WA areas of lowest-on-record rainfall covered western coastal areas between Cape Leeuwin and Kalbarri, and extending inland into the southern wheat belt (Bureau of Meteorology, 2008). The increasing severity of the rainfall deficiencies in south-west Western Australia is significant in the context of a 40-year pattern of drying which has affected the region (Bureau of Meteorology, 2008).

No evidence of significant trends in the total numbers of tropical cyclones or in the occurrence of the most intense tropical cyclones has been found in the Australian region (Kuleshov *et al.,* 2010).

However, sea-surface temperatures, which are important for cyclone formation, have been at or near record high values off the western Australian coast in recent years. These high sea-surface temperatures are a result of a significant warming trend of this part of the Indian Ocean in the past 50 years.

Tropical cyclones

No evidence of significant trends in the total numbers of tropical cyclones or in the occurrence of the most intense tropical cyclones has been found in the Australian region (Kuleshov et al., 2010).

However, sea-surface temperatures, which are important for cyclone formation, have been at or near record high values off the western Australian coast in recent years. These high sea-surface temperatures are a result of a significant warming trend of this part of the Indian Ocean in the past 50 years.

Bushfires

Many parts of Australia are prone to severe bushfires. Peri-urban communities in south-eastern Australia are particularly vulnerable to both forest and grassland fire as experienced through recent devastating bushfires in Canberra (2003), Victoria (2009), and Tasmania (2013).

We have evidence that the fire weather risk has been increasing resulting in a lengthened fire season. Australian fire agencies use a fire danger rating system to reflect the fire behaviour and the difficulty of controlling a particular fire. Analysis of one of these rating systems, the Forest Fire Danger Index (FFDI) showed the annual cumulative FFDI increased significantly at 16 of 38 Australian sites from 1973-2010 (Figure 1: Clarke et al., 2012). The number of significant increases is greatest in the southeast, while the largest trends occurred inland rather than near the coast. The largest increases in seasonal FFDI occurred during spring and autumn, while summer had the fewest significant trends.

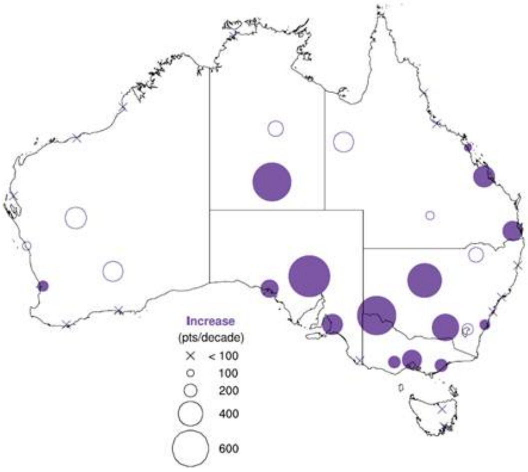

Figure 1: Map of trend in annual cumulative FFDI indicating a lengthened fire season (Clarke *et al.,* 2012).

Sea level and storm surges

Sea levels have increased globally: average mean sea level for 2011 was 210 mm (± 30 mm) above the level in 1880, the earliest year for which robust estimates of global-average mean sea level are available. Global average mean sea level rose faster between 1993 and 2011 (2.8-3.2 mm/year) than during the 20th century as a whole (1.7 mm/year) (Church and White, 2011). The observed global average mean sea-level rise since 1990 is near the high end of projections from the 2007 Intergovernmental Panel on Climate Change Fourth Assessment Report.

Increases in extreme sea level around Australia have been observed to be significant at most sites. Since 1993, the rates of sea-level rise to the north and northwest of Australia have been 7 to 11 mm per year, two to three times the global average, and rates of sea-level rise on the central east and southern coasts of the continent are mostly similar to the global average. These variations are at least in part a result of natural variability of the climate system.

The major reason for the rise in extreme sea level is the mean sea level rise, rather than changes in storm surges. El Niño is one of the most important factors responsible for the interannual variability of extreme sea levels, and this will have played a role in the extreme sea level trends. Tidal contributions to extreme sea levels are especially significant along the Australian coast (Menendez and Woodworth, 2010).

References

- Bureau of Meteorology. 2005. El Niño, La Niña and Australia's Climate. http://www.bom.gov.au/info/leaflets/nino-nina.pdf
- Bureau of Meteorology. 2008. Special Climate Statement 16. http://www.bom.gov.au/climate/current/statements/scs16.pdf
- Bureau of Meteorology. 2009. The exceptional January-February 2009 heatwave in south-eastern Australia. http://www.bom.gov.au/climate/current/statements/scs17d.pdf
- Bureau of Meteorology. 2010. Special Climate Statement 22. http://www.bom.gov.au/climate/current/statements/scs22.pdf
- Bureau of Meteorology. 2013a. Annual Climate Summary. http://www.bom.gov.au/announcements/media_releases/climate/change/20130103.shtml
- Bureau of Meteorology. 2013b. Extreme January heat. Special Climate Statement 43. http://www.bom.gov.au/climate/current/statements/scs43c.pdf
- Bureau of Meteorology. 2013c. Australian Climate Extremes Trend Maps. http://www.bom.gov.au/cgi-bin/climate/change/extremes/trendmaps.cgi?map=R_30&period=1950
- Bureau of Meteorology. 2013d. Australian climate variability & change - Time series graphs. http://www.bom.gov.au/cgi-bin/climate/change/timeseries.cgi?graph=raindecile01&area=aus&season=0112&ave_yr=0
- Church J. A., White N. J., Hunter J. R., and Lambeck, K. 2008. Briefing: a Post IPCC-AR4 Update on Sea-level Rise. The Antarctic Climate and Ecosystems Cooperative Research Centre: Hobart, Tasmania. http://www.cmar.csiro.au/sealevel/downloads/797655_16br01_slr_080911.pdf
- Church J. A. and White N.J. 2011. Sea-level rise from the late 19th to the early 21st Century. *Surveys in Geophysics*, doi:10.1007/s10712-011-9119-1.
- Clarke, H., Lucas, C. and Smith, P. 2012. Changes in Australian fire weather between 1973 and 2010. *International Journal of Climatology*. doi: 10.1002/joc.3480.
- CSIRO. 2008. A summary of probable climate change impacts around Australia. http://www.climatechangeinaustralia.gov.au/documents/resources/Climate_change_poster.pdf
- CSIRO. 2008. Water availability in the Murray-Darling Basin. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia. http://www.csiro.au/partnerships/MDBSY.html

- CSIRO. 2011. Climate Change: Science and Solutions for Australia. http://www.csiro.au/Outcomes/Climate/Climate-Change-Book.aspx
- CSIRO. 2012. Climate and water availability in south-eastern Australia: A synthesis of findings from Phase 2 of the South Eastern Australian Climate Initiative (SEACI), CSIRO, Australia, September 2012, 41 pp. http://www.seaci.org/publications/documents/SEACI-2Reports/SEACI_Phase2_SynthesisReport.pdf
- CSIRO and Bureau of Meteorology 2007. Climate change in Australia. Technical Report. http://www.climatechangeinaustralia.gov.au/technical_report.php
- CSIRO and Bureau of Meteorology. 2012. State of the Climate. http://www.csiro.au/Outcomes/Climate/Understanding/State-of-the-Climate-2012.aspx.
- Gallant A.J.E., Hennessy K.J. and Risbey J.S. 2007. Trends in rainfall indices for six Australian regions: 1910-2005. *Australian Meteorological Magazine*, 56, 223-239.
- IPCC. 2012. Special Report on Extremes – Summary for Policymakers. http://www.ipcc-wg2.gov/SREX/images/uploads/SREX-SPMbrochure_FINAL.pdf
- Kuleshov Y., Fawcett R., Qi L., Trewin B., Jones D., McBride J., and Ramsay H. 2010. Trends in tropical cyclones in the South Indian Ocean and the South Pacific Ocean. *Journal of Geophysical Research*, 115, D01101, doi:10.1029/2009JD012372.
- Leblanc, M., Tweed, S., van Dijk, A. and Timbal, B. 2012. A review of historic and future hydrological changes in the Murray-Darling Basin. *Global and Planetary Change*, 80, p. 226-246. doi: 10.1016/j.gloplacha.2011.10.012.
- Lucas C., Hennessy K.J. and Bathols J.M. 2007. *Bushfire weather in Southeast Australia: recent trends and projected climate change impacts*. Bushfire CRC, Melbourne.
- Menéndez M. and Woodworth P.L. 2010. Changes in extreme high water levels based on a quasi-global tide-gauge 58 data set, *J. Geophys. Res.*, 115, C10011, doi:10.1029/2009JC005997.
- Stafford Smith M., Horrocks L., Harvey A. and Hamilton C. 2011. Rethinking adaptation for a 4°C world. *Philosophical Transactions of the Royal Society A,* 369, 196-216. doi:10.1098/rsta.2010.0277.
- Timbal B. and Drosdowsky W. 2012. The relationship between the decline of South Eastern Australia rainfall and the strengthening of the sub-tropical ridge, *International Journal of Climatology*, doi:10.1002/joc.3492.

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.

CSIRO's research, conducted both at global and national scales, has improved our understanding of projections in extreme climate events, which enable us to explore with increasing confidence the consequences for our climate of various levels of emissions of greenhouse gases from human activities. Two main uncertainties continue to qualify the projections of future climate: the level of humanity's future greenhouse gas and aerosol emissions; and the response of the Earth's climate system to those emissions. These uncertain factors will affect the speed and extent of expected climate change.

Without effective action to mitigate anthropogenic (human-induced) greenhouse gas emissions, it is likely that atmospheric carbon dioxide concentration will double (from pre-industrial levels) sometime this century (IPCC, 2007). Global CO_2 emissions have risen by 1.9% per year in the 1980s, 1.0% per year in the 1990s and 3.1% since 2000 (Peters *et al.,* 2012). These growth rates are at the high end of IPCC emissions scenarios (between SRES A1B and A1FI, and close to the new RCP8.5: Figure 2), which would lead to a global-mean warming of 4.2-5.0°C by the year 2100 (Peters *et al.,* 2012).

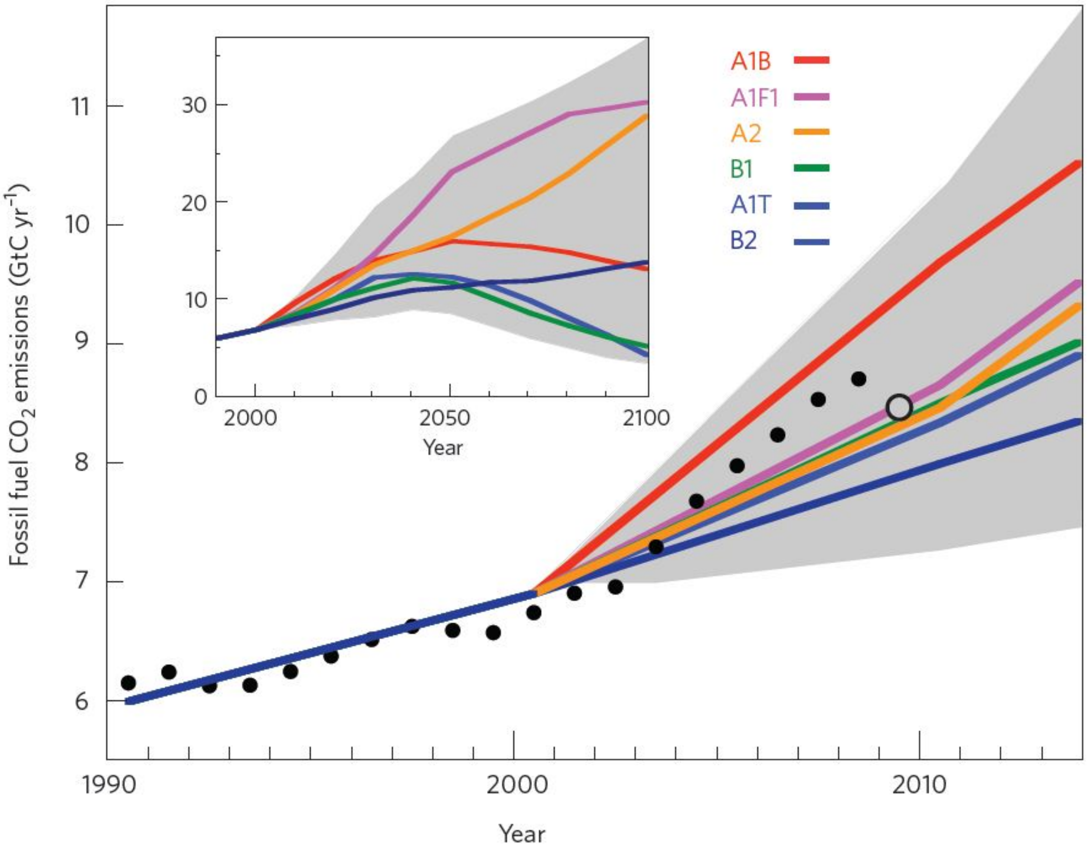

Figure 2: Fossil fuel CO2 emissions. The graph shows that estimates of annual industrial CO2 emissions in gigatons of carbon per year (GtC yr−1) for 1990–2008 (black circles) and for 2009 (open circle) fall within the range of all 40 SRES scenarios (grey shaded area) and of the six SRES illustrative marker scenarios (coloured lines). The inset in the upper left corner shows these scenarios to the year 2100 Source: Manning *et al*., (2010).

A Global Perspective

The IPCC (2012) report entitled *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* concluded that it is virtually certain that increases in the frequency and magnitude of warm daily temperature extremes and decreases in cold extremes will occur in the 21st century at the global scale. The IPCC (2012) also found:

- Warm spells or heat waves are very likely to increase in length, frequency, and/or intensity of warm spells or heat waves over most land areas. Based on medium-high emissions scenarios (A1B and A2), a 1-in-20 year hottest day is likely to become a 1-in-2 year event by the end of the 21st century in most regions. Under a low emissions scenario (B1), a 1-in-20 year event would likely become a 1-in-5 year event.

- The frequency of heavy precipitation or the proportion of total rainfall from heavy falls it is likely to increase in the 21st century over many areas of the globe. Based on a range of emissions scenarios (B1, A1B, A2), a 1-in-20 year maximum daily rainfall event is likely to become a 1-in-5 to 1-in-15 year event by the end of the 21st century in many regions.

- Average tropical cyclone maximum wind speed is likely to increase, although increases may not occur in all ocean basins. For the number of tropical cyclones, the global frequency is likely to either decrease or remain essentially unchanged.

- Mean sea level rise is very likely to contribute to upward trends in extreme coastal high water levels in the future.

- There is medium confidence that droughts will intensify in the 21st century in some seasons and areas, due to reduced precipitation and/or increased evapotranspiration.

Extreme events will have greater impacts on sectors with closer links to climate, such as water, infrastructure, agriculture, forestry, health, and tourism.

Projections for Australia

Extreme temperatures and heatwaves

Under a low emissions scenario (B1), projections for 2070 give an annual mean warming of 1.0-2.5°C over most of Australia (CSIRO and Bureau of Meteorology, 2007). Under a very high (A1FI) emissions scenario, projections for 2070 give an annual mean warming of 2.2-5.0°C over most of Australia (CSIRO and Bureau of Meteorology, 2007). These changes will be felt through an increase in the number of hot days and warm nights, and a decline in cool days and cold nights (CSIRO and Bureau of Meteorology, 2012).

Changes in the annual-average number of days over 35°C have been estimated for 15 sites (CSIRO and Bureau of Meteorology, 2007). Table 2 shows moderate increases for low (B1) emissions, e.g. from 9 days at present to 12-17 days by 2070 in Melbourne, from 17 days at present to 24-31 days by 2070 in Adelaide, and from 28 days at present to 36-46 days by 2070 in Perth. Much larger increases are estimated for very high (A1FI) emissions, e.g. from 9 days at present to 15-26 days by 2070 in Melbourne, from 17 days at present to 29-47 days by 2070 in Adelaide, and from 28 days at present to 44-67 days by 2070 in Perth. Large decreases in extremely cold days are also simulated (CSIRO and Bureau of Meteorology, 2007).

Table 2: Average number of days per year above 35ºC at selected sites for the 'current' climate (average for 1971-2000), and for 2030 and 2070. In each case, the low scenario is the 10th percentile, the median is the 50th percentile and the high scenario is the 90th percentile. For 2030, results are presented for the A1B emission scenario only since there is little difference between warmings for this and other emission scenarios. For 2070, results are presented for the A1FI and B1 emission scenarios. Source: CSIRO and Bureau of Meteorology (2007).

	Current	2030 A1B low	2030 A1B median	2030 A1B high	2070 B1 low	2070 B1 median	2070 B1 high	2070 A1F1 low	2070 A1F1 median	2070 A1F1 high
Adelaide	17	21	23	26	24	26	31	29	36	47
Alice Springs	90	102	109	118	112	122	138	132	155	182
Brisbane airport	1.0	1.5	2.0	2.5	2.1	3.0	4.6	4.0	7.6	20.6
Broome	54	71	86	107	89	119	173	147	220	281
Cairns	3.8	5	7	9	8	12	22	19	44	96
Canberra	5	7	8	10	8	10	14	12	18	26
Darwin	11	28	44	69	49	89	153	141	227	308
Dubbo	25	31	35	39	35	40	51	44	61	87
Hobart	1.4	1.6	1.7	1.8	1.7	1.8	2.0	2.0	2.4	3.4
Melbourne	9	11	12	13	12	14	17	15	20	26
Mildura	32	36	39	43	39	45	51	48	60	76
Perth airport	28	33	35	39	36	41	46	44	54	67
St George	47	56	63	72	64	74	91	80	103	135
Sydney	3.5	4.1	4.4	5.1	4.5	5.3	6.6	6	8	12
Wilcannia	63	71	77	82	79	85	96	92	106	129

Extreme Rainfall

In Australia, despite the general tendency for decreases or little change in seasonal-average rainfall, increases in extreme daily rainfall are expected over most of the continent in future (CSIRO and Bureau of Meteorology, 2007). Changes in extreme daily rainfall, with return periods of 10-50 years, have been estimated by Rafter and Abbs (2009) for 11 Australian regions for 2050 and 2090, based on 12 climate models driven by the high (A2) emissions scenario. The global warming by 2090 in these models ranges from 2.5-3.7°C. By 2090 most models simulate increases in the intensity of the 1-in-20-year event in most regions, e.g. changes of -1.4 to +30.2% in Victoria, -9.1 to 51.2% in eastern NSW, and -28.8 to +66.8% in south-east Qld.

Drought

Drought occurrence is projected to increase over most of southern Australia, especially in south-western Australia (Hennessy *et al.,* 2008). Global climate models provide projections of the future frequency and areal extent of high temperature, low rainfall and low soil moisture conditions (Kirono et al., 2011). These data have been used to characterise future drought conditions across twelve different geographical regions of Australia to the year 2100. A method called the Reconnaissance Drought Index (RDI) was used to define drought conditions, which is the ratio between rainfall and potential evapotranspiration (Kirono *et al.,* 2011). These results show that by 2030, it is likely (greater than 66% probability) that a 1-in-20 year drought during the 20th century may become a 1-in-10 year drought over south west Western Australia. By 2050, this could include the Murray-Darling Basin, South Australia and Victoria, and by 2070 this could extend to eastern New South Wales and Tasmania. No significant increases in drought frequency are projected for the northwest WA or northern and central Queensland (Kirono *et al.,* 2011).

Based on modelling undertaken in the CSIRO Murray-Darling Sustainable Yields Project (MDBSY; 2007-2009), Kirby et al. (2013) analysed projections for drought frequency and severity under climate change scenarios for 2030, in which the warming is about 0.5-2.0°C.

The Murray-Darling Basin experiences frequent droughts and in recent year parts of the region experienced the worst drought in the 110 years of comparatively high-quality records. Climate change projections suggest that the Murray-Darling Basin will be on average drier in the future (CSIRO and Bureau of Meteorology, 2007). The 1997-2009 drought period saw lower autumn and winter rain and higher temperatures than past droughts, resulting in the lowest runoff totals on record in recent years. While these features may be associated with climate change, they may equally be a result of large, long-term climate variability.

Given general expectations of a drier future for the south of the Murray-Darling Basin, the 1997-2009 drought raises the question: what may be expected of droughts in the future?

Kirby *et al*. (2013) focussed on drought in the river system: that is, it mainly considered runs of years with low runoff and river flow (relevant to irrigation diversions and environmental flows in the river system). However, runs of years of low rainfall (relevant to rain-fed agriculture) were also considered.

While the overall trend in projected rainfall for the Murray Darling Basin is one of decline, the uncertainties associated with modelled rainfall projections span small increases in rainfall to significant decreases so the study of Kirby *et al*. (2013) considered this range of possibilities. They concluded that:

- A decline in rainfall leads to a proportionally greater decline in runoff and an even greater proportional decline in river flows. Thus water available in the river system for irrigation or environmental water flows is reduced by far more than the reduction in rainfall.
- Under the dry extreme and median rainfall projections, droughts are longer, more frequent and more severe – that is, with greater rainfall, runoff and river flow reductions – than those in the past, strongly so in the case of the dry extreme scenario. As an example, focussing only on long droughts of five years or more, the Goulburn region experiences four long droughts in runoff under the median scenario, and six under the dry extreme scenario, compared to two such droughts historically. During these long droughts under the median scenario runoff is 62% of the historic median runoff, while under the dry extreme scenario runoff is 52% of the historic median runoff. Under historical long droughts runoff was 70% of the historic median runoff.
- The projected changes to the longer and more severe droughts are greatest in the south of the Murray-Darling Basin. For example, under the dry extreme scenario the Goulburn region is, in most years, in a state that is currently considered to be drought. Under the dry extreme scenario, flows

in the Goulburn River are below the historic median for five years or more sequentially for 87 out of 111 years. The average flow during those 87 years is 37% of the historic median flow. Similarly, under the dry extreme scenario, surface water diversions are below historic median diversions for five or more years sequentially for 108 of the 111 years. Average diversions during those 108 years are 67 % of the historic median diversions.

- Under the wet extreme scenario, where rainfall is higher than the long-term historical average, droughts are generally of the same length as, and slightly less severe than, those that have been experienced historically.

Bushfires

Over southern and eastern Australia, warmer and drier conditions are expected in future (CSIRO and Bureau of Meteorology, 2007). Consequently, an increase in fire weather risk is likely, with more days of extreme risk and a longer fire season.

The annual average number of extreme fire weather days at 26 climate stations in south-eastern Australia was estimated by Lucas et al (2007) for the current climate (1973-2007), using the Forest Fire Danger index (FFDI). Projected changes in daily temperature, humidity, wind and rainfall and daily weather observations were used to recalculate FFDI values for 2020 and 2050. By 2020, a 5-25% increase in the annual-average the number of extreme fire danger days was estimates for low (B1) emissions, and 15-65% for very high (A1FI) emissions. By 2050, the increase is 10-50% for low (B1) emissions and 100-300% for very high (A1FI) emissions.

Cyclones

For the Australian region, projections show a general trend towards a decrease in frequency but increase in intensity for tropical cyclones in northern and north-western Australia.

Global climate models have been downscaled to a 65 km grid using CSIRO's CCAM model (Cotton *et al.,* 2001; Katzfey *et al.,* 2009) for a high (A2) emissions scenario for a period centred on 2070, when the global warming is 1.35-3.60°C (CSIRO and Bureau of Meteorology, 2007). The CCAM projections show a strong tendency for a decrease in cyclone numbers in the Australian region (Abbs, 2010). On average, for the period 2051-2090 relative to 1971-2000, the simulations show an approximately 50% decrease in frequency, a small decrease (0.3 days) in the duration of a given cyclone and a southward movement of 100 km in the genesis and decay regions. On average, the southward movement in the decay region (the region into which weakened tropical cyclones migrate) is greater off the Queensland coast than off the coast of Western Australia.

The Regional Atmospheric Modelling System (Cotton *et al.,* 2001) was used to further downscale to a grid-spacing of 15 km for 40-year time slices centred on 1980, 2030 and 2070 (Abbs, 2010). For each time slice 100 cyclone events were modelled. These simulations show a distinct shift towards deeper atmospheric pressures (stronger cyclones) with a larger percentage of cyclones producing high wind speeds (exceeding 25 m/s) in the 2070 climate.

In Western Australia, Abbs (2012) found there could be a 50 per cent reduction in the number of storms from 2051–2090 compared to the period 1971–2000. These cyclones are also moving southward by one degree of latitude, or a hundred kilometres, meaning they are decaying closer to Perth (Abbs, 2012).

Sea Level and storm surge

Projected changes in extreme sea levels around southern Australia are likely to be dominated by the mean sea level rise, rather than changes in storm surges (Colberg and McInnes, 2012). For the high (A2) emission scenario, the range of mean sea-level rise by 2090-2100 is 23-51 cm. Figure 3 shows the estimated increase in the frequency of extreme sea-level events caused by a 50 cm mean sea-level rise for 29 Australian locations where good tidal records longer than 30 years exist (DCCEE, 2009). Extreme events that now happen every 10 years, on average, would happen about every 10 days in 2100, and become even more frequent around Sydney, with smaller increases around Adelaide and along parts of the Western Australian coast (DCCEE, 2009).

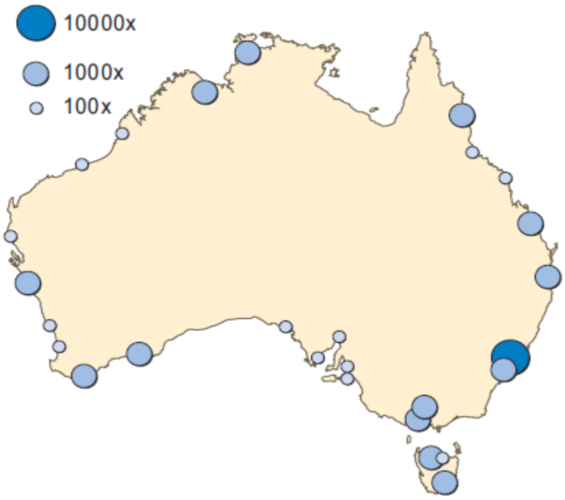

Figure 3 - Estimated increases in the frequency of extreme sea-level events (indicated by the diameters of the circles) caused by a mean sea-level rise of 50 cm. Source: DCCEE (2009).

References

- Abbs, D. 2012. The Impact of Climate Change on the Climatology of Tropical Cyclones in the Australian Region. CSIRO Climate Adaptation Flagship Working paper No.11. http://www.csiro.au/en/Organisation-Structure/Flagships/Climate-Adaptation-Flagship/CAF-working-papers.aspx
- Bates B.C., Hope P., Ryan B., Smith I. and Charles S. 2008. Key findings from the Indian Ocean Climate Initiative and their impact on policy development in Australia. *Climatic Change,* 89:339–354
- Colberg F. and McInnes, K. 2012. The impact of future changes in weather patterns on extreme sea levels over southern Australia. *Journal of Geophysical Research,* 117, C08001, doi:10.1029/2012JC007919
- Cotton W. R., Pielke R.A. Sr., Walko R.L., Liston G.E., Tremback C.J., Jiang H., McAnelly R.L., Harrington J.Y., Nicholls M.E., Carrio G.G., and McFadden J.P. 2003. RAMS 2001: Current status and future directions. *Meteorology and Atmospheric Physics*, 82, 5–29.
- CSIRO and Bureau of Meteorology 2007. Climate change in Australia. Technical Report. http://www.climatechangeinaustralia.gov.au/technical_report.php
- CSIRO. 2008. The Murray-Darling Basin Sustainable Yields Project. Overview and reports available at http://www.csiro.au/partnerships/MDBSY.html
- CSIRO and the Bureau of Meteorology. 2012. State of the Climate. http://www.csiro.au/Outcomes/Climate/Understanding/State-of-the-Climate-2012.aspx.
- Department of Climate Change and Energy Efficiency. 2009. Climate Change Risks to Australia's Coast: a first pass national assessment. Department of Climate Change, 172 pp. http://www.climatechange.gov.au/publications/coastline/climate-change-risks-to-australias-coasts.aspx
- Hennessy K.J., Fawcett R., Kirono D.G.C., Mpelasoka F.S., Jones D., Bathols J., Whetton P., Stafford Smith M., Howden M., Mitchell C., and Plummer N. 2008. An assessment of the impact of climate change on the nature and frequency of exceptional climatic events. Drought exceptional circumstances. July 2008. Canberra: Australian Government Bureau of Meteorology. http://www.daff.gov.au/__data/assets/pdf_file/0007/721285/csiro-bom-report-future-droughts.pdf
- IPCC. 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. www.ipcc.ch

- IPCC. 2012.Summary for Policymakers. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 1-19. http://www.ipcc-wg2.gov/SREX/images/uploads/SREX-SPMbrochure_FINAL.pdf
- Katzfey, J.J., McGregor, J. Nguyen K. and Thatcher. M. 2009. Dynamical downscaling techniques: Impacts on regional climate change signals. 18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009. http://mssanz.org.au/modsim09
- Kirby M., Chiew F.H.S., Mainuddin M., Young W.J., Podger G. and Close A. Forthcoming. Drought and climate change in the Murray-Darling Basin: a hydrological perspective. In: Schwabe K, Albiac J, Connor J, Hassan R, Meza-Gonzalez L (Eds). Drought in Arid and Semi-Arid Environments: A Multi-Disciplinary and Cross-Country Perspective. Springer.
- Kirono D.G.C., Kent D.M., Hennessy, K.J. and Mpelasoka, F. 2011). Characteristics of Australian droughts under enhanced greenhouse conditions: Results from 14 global climate models. *Journal of arid environments* 75(6): 566-575. doi:10.1016/j.jaridenv.2010.12.012.
- Leslie L.M., Leplastrier M. and Buckley B.W. 2008. Estimating future trends in severe hailstorms over the Sydney Basin: A climate modelling study. *Atmospheric Research*. 87: 37–51.
- Lucas, C., Hennessy, K.J,, Mills, G., and Bathols, J. 2007. Bushfire Weather in Southeast Australia: Recent trends and projected climate change impacts: consultancy report prepared for the Climate Institute of Australia. Bushfire Cooperative Research Centre, Melbourne. http://www.bushfirecrc.com/research/downloads/climate-institute-report-september-2007.pdf
- Manning M.R., Edmonds J., Emori S., Grubler A., Hibbard K., Joos F., Kainuma M., Keeling R.F., Kram T., Manning A.C., Meinshausen M., Moss R., Nakicenovic N., Riahi K., Rose S.K., Smith S., Swart R.,.van Vuuren D.P. 2010. Misrepresentation of the IPCC CO_2 emission scenarios. *Nature Geoscience*, 3(6):376–377. doi:10.1038/ngeo880
- McInnes K., Erwin T., and Bathols J. 2011. Global Climate Model projected changes in 10 m wind speed and direction due to anthropogenic climate change. *Atmospheric Science Letters*. doi: 10.1002/asl.341.
- Peters G.P., Andrew R.M., Boden T., Canadell J.G., Ciais P., Le Quere C., Marland G., Raupach M.R. and Wilson, C. 2012. The challenge to keep global warming below 2°C. *Nature Climate Change*. doi:10.1038/nclimate1783.
- Rafter T. and Abbs, D. 2009. An analysis of future changes in extreme rainfall over Australian regions based on GCM simulations and Extreme Value Analysis. http://www.cawcr.gov.au/publications/researchletters/CAWCR_Research_Letters_3.pdf
- Whetton P., Karoly D. Watterson I., Drost F., Webb L. and Kirono D. (2011). Australian climate at four degrees or more of global warming. Draft paper for Four Degrees conference, 12-13 July, 2011, Melbourne.

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

Extreme weather events, interacting with exposed and vulnerable systems, can lead to disasters (IPCC, 2012). In Australia, vulnerability to extreme weather events has been recently highlighted by:

- the south-east Australian heat wave in late January 2009, which resulted in 374 excess deaths in Victoria over what would be expected (Vic DHS, 2009);
- the Victorian bushfires in early February 2009, which killed 173 people and more than 1 million animals, destroyed more than 2000 homes, burnt about 430,000 hectares, and cost about $4.4 billion (Victorian Bushfires Royal Commission, 2010);
- the floods in Queensland in 2010-2011, which killed 33 people and affected more than 78 per cent of the state and over 2.5 million people, with 29,000 homes and businesses suffering some form of inundation, and a cost in excess of $5 billion (Queensland Floods Commission of Inquiry, 2011).

Two issues arise here: one is the level of impacts and costs of extreme events from the historical record; the second is how these costs may change in the future and to what extent adaptation actions may reduce these costs (i.e. the value of proactive disaster preparedness allowing for climate change). There is relatively little analysis of the latter in Australia, but CSIRO is undertaking a growing body of work presented here.

Risks and costs on settlements and infrastructure

CSIRO has investigated the current and projected costs of extreme events on some individual sectors or material, and in some specific locations. Our goal has been to provide these sectors and regions with information on which to base adaptation strategies.

Costs and benefits of planned adaptation to sea level rise in South East Queensland

CSIRO undertook a preliminary assessment of the costs and benefits of proactive, planned adaptation on built infrastructure in South East Queensland (SEQ) in 2009, a region recognised by both the insurance industry and governments to face a high risk of inundation. Costs and benefits have been investigated by estimating the population and economic effects of an historical 1-in-100-year inundation event and then exploring how these may change under different scenarios of settlement patterns in 2030 and 2070.

At present, an estimated 227,000 people in SEQ are at risk of inundation from a 1-in-100-year storm tide. If the population in SEQ does not change, sea level rise could see this number increase to rise to about 245,000 people by 2030 and 273,000 people by 2070. However the population is expected to increase from today's 2.69 million to 4.4 million by 2030, greatly compounding the impact of climate change if the population remains at its current pattern of settlement. Indeed the exposure to inundation is more strongly influenced by the current settlement patterns projected into the future than by the additional impact of sea level rise.

The value of adaptation in reducing these risks has also been assessed. Currently in SEQ 35,200 residential buildings are exposed to a 2.5 m storm tide (approximately a 1-in-100-year event), risking structure and content damage of about $1.1 billion. By 2030, with projected population increase and using the same planning and building regulations as today coupled with an additional 0.2m sea level rise over 1990 levels, the number of residential buildings at risk from a 2.5 m storm tide will increase to about 61,500 and the costs will increase to about $2.0 billion, while the exact number will be affected by the discount rate applied in the estimation. In 2070 this will affect approximately 121,000 residential buildings and cost about $3.9 billion (Wang *et al.,* 2010). Altering future development patterns and planning regulations to reduce exposure will greatly reduce the costs of a 1 in 100 year inundation event.

Risk assessment of extreme wind events in Queensland

Economic analysis of the likely changes in wind extremes in areas of Queensland shows a 'no regrets' benefit of adapting houses or changing building codes sooner rather than later. Assuming 'business as usual' (no adaptation measures), a changing climate can increase mean cumulative wind damage direct losses (house and contents damage) for Cairns, Townsville, Rockhampton and South East Queensland by up to $3.8, $9.7 and $20.0 billion by 2030, 2050 and 2100, respectively, assuming a 4% discount rate. If indirect losses are considered, then mean cumulative wind damage losses for Cairns, Townsville, Rockhampton and South East Queensland can increase by up to $3.9, $9.9 and $20.5 billion by 2030, 2050 and 2100, respectively. There is a high likelihood of large potential economic losses if there is no change to building standards, and suggests that climate adaptation strategies are needed to ameliorate these losses (Stewart and Wang 2011; Stewart and Wang 2012; Stewart *et al.,* 2012) .

Assessment of potential inundation on coastal settlements and transport infrastructures of selected hotspots in Queensland

Using 100-year ARI storm tides (with wave setups) of each hotspot (at current sea level) as the basis for comparison, the hotspots with the highest percentages of affected factors in QLD are shown in Table 3 (together with the projected sea level rises of 0.3m and 0.8m for years 2050 and 2100), respectively. The applied projected sea level rises followed the Queensland Coastal Plan (2011).The results indicate that Maroochy/Caloundra may be the most significantly affected hotspot in terms of geographic area, population, and streets. The other hotspots that may warrant further investigations are Brisbane, Gold Coast, Mackay, Moreton Bay, and Townsville due to the high percentage/amount of affected factors (Khoo *et al.,* 2011).

Table 3: Hotspots with the highest percentages/amounts of affected factors at current 100-year ARI storm tides with wave setups (as well as projected sea level rises of 0.3 and 0.8 m for years 2050 and 2100, respectively, in these hotspots). Damage costs are given in terms of 2010 dollar values Source: Khoo and Wang (2011).

Factor	**Hotspot**	**Percentage/amount affected**		
		Current	**2050**	**2100**
Geographic area	Maroochy/Caloundra	33.4%	37.5%	41.4%
Population	Maroochy/Caloundra	23.6%	31.6%	39.6%
Residential buildings	Mackay	12.9%	16.5%	24.4%
Commercial buildings	Townsville	29.3%	36.3%	52.7%
Airports	Brisbane, Cairns, Mackay, Maroochy/Caloundra, and Townsville	100.0%	100.0%	100.0%
Railway stations	Moreton Bay	14.3%	14.3%	14.3%
Railway lines	Gold Coast	17.1%	21.4%	23.4%
Streets	Maroochy/Caloundra	26.5%	34.4%	40.9%

Impacts of climate change on concrete

The impact of extreme events on Australia's infrastructure will further be exacerbated by the likelihood that the long-term structural reliability would be compromised by accelerated deterioration due to changing climate and increasing carbon concentration, for example, concrete, timber and steel structures.

Concrete deterioration is caused by a range of physical, mechanical and/or chemical factors. Two major threats are: 1) carbonation, which occurs when atmospheric CO_2 penetrates into the structure to expose steel reinforcements to corrosion and 2) corrosion caused by chloride penetration causing cracking, delamination, or spalling, of the concrete especially in marine and coastal areas. Both corrosion mechanisms are influenced by climate change – in particular increasing temperatures and sea level rise. The time it will take for climate change to exacerbate carbonation and chloride-induced corrosion of concrete structures will depend on their location and level of exposure to the elements.

Impacts of heatwaves on the performance of building and infrastructure

Heatwaves which last for several days have significant impacts on how building and infrastructure perform; specifically how they maintain temperature for human comfort and safety, fire hazards or utility failures. Using historical temperature data from 548 temperature stations across Australia it was shown that heatwave events at many stations are increasing – not just in terms of numbers of hot days but also in numbers of hot spells longer than two days (Nguyen *et al.,* 2011).

These hot spells affect buildings and urban infrastructure and preliminary work highlights some of these effects. For a typical house – one story brick veneer three bedroom home –the longer the hot spell the warmer the house interior (without air-conditioning) and more energy is used to cool the building. For power transmission in an electricity network the amount of power lost during the transmission process increases by more than 50% due to increased power demand. The study (Nguyen et *al.,* 2011) also contained an assessment of the thermal load and buckling of railways during the heatwave in Melbourne in January 2009 to better understand extreme heat impacts on the tracks (Nguyen *et al.,* 2012).

Heatwave can significantly deteriorate the indoor thermal environment of buildings. This may particularly lead to significant consequences of low-incoming households, who normally have no air-condition to abate the impact of heat (Barnett *et al.,* 2012).

Another study (Wang *et al.,* 2010) showed how the extra energy load for heating and cooling would change with climate change in different cities across Australia. Although this study was not primarily concerned with extremes, it found that the meaningfulness of different energy star ratings will change with global warming.

Impacts of extreme events on human health

Extreme events such as heatwaves, storms and floods are likely to have a direct impact on the health of Australians, such as causing an increase in heat-related deaths. Indirect impacts of climate change will be through effects on biological processes such as infectious diseases and physical processes such as air pollution or altering insect activity increasing vector borne diseases.

Impacts of heatwaves on years of life lost in Brisbane

While it is often relatively easy to determine the human cost of extreme events such as bushfires or floods, deaths due to heat waves are less obvious. Researchers investigated an indicator used by the health sector as a novel measure of mortality in Brisbane. 'Years of life lost' is an indicator of premature mortality that accounts for the age at which deaths occur by giving greater weight to deaths at younger ages. Years of life lost were estimated by matching each death by age and sex to the Australian national life tables for the years 2002-2004.

It was found that the association between temperature and years of life lost is U-shaped, with increased years of life lost for cold and hot temperatures. This pattern occurs because the increased heat-related years of life lost are somewhat offset by the decreased cold-related years of life lost. For a 2 °C increase, we projected a total increase of 381 temperature-related years of life lost, as the decreases in cold-related years of life lost will not fully offset the increases in heat-related years of life lost. Assuming a 4 °C increase, the health consequences become very significant, with a projected net increase of 3,242 temperature related years of life lost in 2050 relative to 2000 (Huang *et al.,* 2012).The temperature-related years of life lost will worsen greatly if future climate change goes beyond a 2 °C increase and without any adaptation to higher temperatures. This study highlights that public health adaptation to climate change is essential.

Impacts of heatwaves on years of life lost through cardiovascular deaths

Extreme temperatures are associated with cardiovascular disease deaths. Previous studies have investigated the relative cardiovascular disease mortality risk of temperature, but this risk is heavily influenced by deaths in frail elderly people. To better estimate the burden of extreme temperatures, years of life lost due to cardiovascular disease were estimated. It was found that the association between temperature and years of life lost due to cardiovascular disease was U-shaped, with increased years of life lost attributable to cold and hot temperatures. A significant added effect of heat waves implies that an extra risk arises when the exposure to extreme heat is sustained for two days or more (Huang *et al.,* 2012).

Health impacts of climate change due to vector borne diseases

Health is also affected by climate change indirectly, principally through biological processes such as vector-borne and other infectious diseases and physical processes such as air pollution. For example, Australia can expect an increase in disease due to the spread of insect vectors, with 0.6 to 1.4 million more people exposed to dengue fever by 2050, as well as a rise in waterborne and food-borne diseases. Higher temperatures are likely to cause an increase in the concentrations of volatile organic compounds and ozone in the atmosphere. An analysis of future climate found that under an SRES A2 (relatively high emission) scenario, increased ozone pollution is projected to cause a 40% increase in the projected number of hospital admissions by the period 2020–2030, relative to 1996–2005, and a 200% increase by the period 2050–2060.

References

- Barnett G. 2012. Pathways to climate adapted and healthy low incoming housing. NCCARF report.
- Beebe N.W., Cooper R.D., Mottram P., and Sweeney A.W. 2009. Australia's Dengue Risk Driven by Human Adaptation to Climate Change. *Plos Neglected Tropical Diseases* 3(5).
- Huang C., Barnett A.G., Wang X., and Tong S. 2012. Years of Life Loss due to Cold and Hot Climates in Brisbane, Australia. *Nature Climate Change*, 2: 265-270. doi:10.1038/nclimate1369.
- Huang C., Barnett A.G., Wang, X. and Tong S. 2012. Effects of extreme temperatures on years of life lost for cardiovascular deaths: a time series study in Brisbane, Australia. *Circulation: Cardiovascular Quality and Outcomes,* 5: 609-614. doi:10.1161/circoutcomes.112.965707.
- Huang C, Barnett A.G., Xu Z., Chu C., Wang X., Turner L.R., and Tong S. Under review. Managing the Health Effects of Temperature in Response to Climate Change: Challenges Ahead. Submitted to *Environmental Health Perspectives*.
- Khoo Y. B. and Wang X. 2011. Assessment of Potential Inundation on Coastal Settlements and Transport Infrastructures of Selected Hotspots in Queensland. Published by CSIRO, Canberra. May, 2011. ISBN 978 0 643 10478 5.
- Nguyen M., Wang X. and Chen D. 2011. An investigation of extreme heatwave events and their effects on building and infrastructure. CSIRO Climate Adaptation Flagship Working paper No. 9. CSIRO, Brisbane. ISBN: 978-0-643-10633-8. http://www.csiro.au/en/Organisation-Structure/Flagships/Climate-Adaptation-Flagship/CAF-working-papers/CAF-working-paper-9.aspx
- Nguyen M.*,* Wang X. and Wang C-H. 2012. Reliability Assessment of Railway Track Buckling under Extreme Heatwaves. Proceedings of the Institution of Mechanical Engineers, Part F. *Journal of Rail and Rapid Transit*. 226(5): 513-17. doi:10.1177/0954409712441743.
- Nguyen M., Wang X. and Leicester B. Under review. An Assessment of Climate Change Effects on Atmospheric Corrosion Rates of Steel Structures*.* Submitted to *Corrosion Engineering Science and Technology*.
- Queensland Floods Commission of Inquiry. 2011. Interim Report, 262 pp. http://www.floodcommission.qld.gov.au/__data/assets/pdf_file/0007/8791/QFCI-Interim-Report-Preface,-Introduction.pdf
- Stewart M.G. and Wang X. 2011. Risk Assessment of Climate Adaptation Strategies for Extreme Wind Events in Queensland. Published by CSIRO, Canberra. ISBN 978 0 643 10431 0.
- Stewart M.G. and Wang X. 2012. Risk Assessment of Climate Adaptation Strategies for Australian Housing Subject to Extreme Wind Events. *Climatic Change*. (Revised)
- Stewart M. G., Wang X. and Willgoose G.R. 2012. Indirect Cost and Benefit Assessment of Climate Adaptation Strategies for Extreme Wind Events in Queensland. Published by CSIRO, Canberra, May 2012. ISBN 978 0 643 10854 7.
- Victorian Bushfires Royal Commission. 2010. *Final Report, Volume 1*. Government Printer for the State of Victoria, Melbourne, 361 pp. http://www.royalcommission.vic.gov.au
- Victorian Department of Health Services. 2009. *January 2009 Heatwave in Victoria: an Assessment of Health Impacts*. http://www.health.vic.gov.au/chiefhealthofficer/downloads/heat_impact_rpt.pdf
- Wang C-H and Wang X. 2012. Vulnerability of Timber in Ground Contact to Fungal Decay under Climate Change. *Climatic Change*, 115:777-794. doi: 10.1007/s10584-012-0454-0.
- Wang X., Syme M., Nguyen M. and Stewart M.G. 2010. Analysis of Climate Change Impacts on the Deterioration of Concrete Infrastructure. CSIRO, Australia. http://www.csiro.au/Portals/Publications/Research--Reports/concrete-durability-report.aspx#a1
- Wang X., Stewart M., and Nguyen M. 2012. Impact of Climate Change on Corrosion and Damage to Concrete Infrastructure in Australia. *Climatic Change*, 110(3-4): 941-957. doi:10.1007/s10584-011-0124-7.

- Wang X., Chen D. and Ren Z. 2010. Assessment of climate change impact on residential building heating and cooling energy requirement in Australia. *Building and Environment,* 45(7):1663-1682.
- Wang X., Stafford Smith M., McAllister R., Leitch A., McFallan S. and Meharg S. 2010. Coastal inundation under climate change: a case study in South East Queensland. Report prepared for the South East Queensland Climate Adaptation Research Initiative. CSIRO Climate Adaptation Working paper 6, Canberra. http://www.csiro.au/en/Organisation-Structure/Flagships/Climate-Adaptation-Flagship/CAF-working-papers/CAF-working-paper-6.aspx

c. An 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.

CSIRO has investigated various sectors. In addition to those described in more detail below, this includes the mining sector (Hodgkinson et al., 2010), some aspects of the electricity sector (Wang et al., 2012),

Agricultural sector preparedness

The agricultural sector in Australia is highly affected by climate variability and climate extremes. Over two hundred years it has developed a wide range of innovative risk management strategies to cope with Australia's highly variable climate (Stokes and Howden, 2009). These are technological (such as drought-resistant crop varieties and zero-tillage), managerial (such as improved crop rotations or irrigation), financial (such as forward selling) and social (such as support networks). Notwithstanding this risk-management capacity, the scale of extreme climate events means that there are often substantial impacts such as reduced productivity and quality of product, damage to the natural resource base, and social and psychological disruption. Significant droughts can halve national wheat production, and significantly reduce production of other crops and livestock. The impacts flow through to the national economy with reductions in national GDP of 1-2% in years of severe drought (Leblanc *et al.,* 2012). In 2007-08, 23 per cent of Australia's 143,000 farms received drought assistance, totalling over $1 billion, with some on income support continuously since 2002 (Productivity Commission, 2009). The seriousness of such impacts has resulted in a range of institutional responses such as establishment of Landcare groups, various drought policies, water resource policies and training each of which has enhanced preparedness and capacity.

As the climate changes and with potential increases in frequency and severity of climate extremes (as noted above), these risk management and institutional approaches will likely need to change (Howden et al., 2010). New approaches to drought preparedness are being trialled that factor in added dimensions of climate change (e.g. DAFF's WA pilot of farm planning). These new approaches to planning and preparedness are necessary but they may not be sufficient to deal with the more systemic and transformative changes that will increasingly be needed under climate change (Howden *et al.,* 2010). CSIRO has initiated research into these bigger change processes, understanding them, how they are triggered and what helps or hinders them so that we can help design support systems for the agricultural sector (Park *et al.,* 2012). There is also ongoing research that will provide the technological options for farmers of the future to equip themselves for the climate they face such as climate-change-ready crops (Chapman *et al.,* 2012) and livestock that are adapted to heat stress extremes (Nidumolu *et al.,* 2011).

Property sector preparedness

Property prices in areas prone to inundation

For flood-prone urban areas, the prospect of increasing population densities and more frequent extreme weather associated with climate change is alarming. Proactive adaptation can reduce potential flood risks in theory however there is little research available to support such decisions making. Despite the vital important of the family home there have been few studies that have considered the loss in value of land, as a key asset, due to inundation. Yet in many urban areas the family home represents individuals' major asset, and with population growth land values are increasing as a proportion of value in residential housing.

For instance, in Australia the family home makes up over 40% of individual's total net assets and land values have increased as a proportion of value in urban residential housing from ~25% in 1990 to over 60% in 2010. Moreover, land values appreciate over time, so implementing adaptations now to protect against damage due to inundation in the future protects an ever more valuable asset. Within the residential sector, the financial impact of inundation on land values due to changing coastal inundation regimes under future sea level rise scenarios is expected to be of a similar magnitude to infrastructure damage by 2050. As such, including appreciating lost land values as well as infrastructure damage is important to accurately assess the potential benefits of adapting coastal residential communities to coastal inundation. Correctly accounting for these potential benefits will strengthen the case for greater investment in adaptation, sooner.

Closely related to the property sector is the insurance sector. This sector is particularly sensitive to a change in exposure of populations to extreme events (e.g. more people residing in vulnerable areas and to changes in frequency or intensity of extreme events.

Water sector preparedness

Floods, droughts, and climate change are the three most important influences of climate on Australia's water resources. Water resources are vulnerable to both climate variability and change; for example, runoff into Perth's reservoirs has declined by 55% since the 1970s and the 1997 to 2009 drought resulted in unprecedented decline in runoff and water use in the southern Murray–Darling Basin and Victoria. Climate change has played a part in recent reductions in rainfall and water resources, however its specific contribution is difficult to quantify. Climate change by 2030 is likely to reduce average river flows by 10% to 25% in some regions of southern Australia but further climate change could produce even more profound reductions of water resources in southern Australia. Climate and water scientists in CSIRO, the Bureau of Meteorology, and elsewhere continually work to improve projections of future water availability and streamflow characteristics, and these are used to inform the water reforms and water adaptation strategies across Australia (CSIRO, 2011).

The Bureau of Meteorology has been issuing seasonal weather outlooks since the 1990s, and in 2010 it launched a new service on seasonal river flow forecasting. This forecasting system is based on models developed by CSIRO that give probabilistic forecasts of river flow several months ahead, in particular flows to major water storages (CSIRO, 2011).

The Bureau of Meteorology is also responsible for issuing flood warnings and is planning to extend its current flood warning service to forecast river flows continuously up to 10 days ahead. The Bureau of Meteorology and CSIRO are jointly developing and testing a modelling system for this purpose combining hydrological and weather prediction models that use real-time data from climate stations, river flow gauging sites, and satellite data (CSIRO, 2011).

References

- Chapman S. C., Sukumar C., Fernanda D.M., and Howden M.S. 2012. Plant adaptation to climate change—opportunities and priorities in breeding. *Crop and Pasture Science* 63, 251–268.
- CSIRO. 2011. Water, Science and Solutions for Australia. Chapter 3. CSIRO Publishing. http://www.csiro.au/en/Outcomes/Water/Water-Book/Chapter-3-Water-and-climate.aspx
- Fletcher C.S., McAllister R.R.J., Collins K., and Rambaldi A.N. Under review. Costs and benefits of adaptation to coastal inundation to protect appreciating assets, Submitted to *Climatic Change.*
- Fletcher C.S., Taylor B.M., Rambaldi A.N., Harman B.P., Heyenga S., Ganegodage K., Lipkin F., McAllister R.R.J. Under review. Costs and coasts: an empirical assessment of physical and institutional climate adaptation pathways. Submitted to *National Climate Change Adaptation Research Facility Gold Coast*.
- Hodgkinson J.H., Littleboy A., Howden M., Moffat K. and Loechel B. 2010. Climate adaptation in the Australian mining and exploration industries. CSIRO Climate Adaptation Flagship Working paper No. 5. http://www.csiro.au/resources/CAF-working-papers.html

- Howden S.M., Crimp S.J., and Nelson R.N. 2010. Australian agriculture in a climate of change. Managing Climate Change: Papers from the GREENHOUSE 2009 Conference, eds. Jubb I., Holper P., and Cai W. CSIRO Publishing, Melbourne, pp 101-111.
- Leblanc, M., Tweed, S., van Dijk, A. and Timbal B. 2012. A review of historic and future hydrological changes in the Murray-Darling Basin. *Global and Planetary Change*, 80, p. 226-246. doi: 10.1016/j.gloplacha.2011.10.012
- Marshall N.A. 2010. Understanding social resilience to climate variability in primary enterprises and industries. *Global Environmental Change,* 20, 36-43.
- Marshall N., Gordon I. and Ash A. 2011. The reluctance of resource-users to adopt seasonal climate forecasts to enhance resilience to climate variability on the rangelands. *Climatic Change,* 107, 511-529.
- Nidumolu U., Crimp S., Gobbett D., Laing A., Howden M., and Little S. 2011. Heat stress in dairy cattle in northern Victoria: responses to a changing climate. CSIRO Climate Adaptation Flagship Working paper No. 10. ISBN: 978-0-643-10634-5. http://www.csiro.au/Organisation-Structure/Flagships/Climate-Adaptation-Flagship/CAF-working-papers/CAF-working-paper-10.aspx
- Park S. E., Marshall N. A., Jakku E., Dowd A-M., Howden M., Mendham E. and Fleming, A. 2012. Informing adaptation responses to climate change through theories of transformation. Global Environmental Change, 22, 115-126. doi:10.1016/j.gloenvcha.2011.10.003.
- Productivity Commission. 2009. Government Drought Support. Productivity Commission Inquiry Report number 46. 431 pp. http://www.pc.gov.au/projects/inquiry/drought/report
- Rambaldi A.N., McAllister R.R.J., Collins K., and Fletcher C.S. 2011. An unobserved components approach to separating land from structure in property prices: A case study for the city of Brisbane. School of Economics Discussion Paper. University of Queensland, Brisbane.
- Rambaldi, A.N, Fletcher C.S., Collins K., and McAllister R.R.J. 2012. Housing Shadow Prices in an Inundation Prone Suburb. *Urban Studies.* doi:10.1177/0042098012465904.
- Stokes C. and Howden M. 2010. Adapting agriculture to climate change: preparing Australian agriculture, forestry and fisheries for the future. CSIRO Publishing, Melbourne. ISBN: 9780643095953.
- Wang X., Stafford Smith M., McAllister R., Leitch A., McFallan S. and Meharg S. 2010. Coastal inundation under climate change: a case study in South East Queensland. Report prepared for the South East Queensland Climate Adaptation Research Initiative. CSIRO Climate Adaptation Working paper 6, Canberra. http://www.csiro.au/en/Organisation-Structure/Flagships/Climate-Adaptation-Flagship/CAF-working-papers/CAF-working-paper-6.aspx
- Wang C-H., Grozev G. and Seo, S. 2012. Decomposition and statistical analysis for regional electricity demand forecasting. *Energy,* 41, 313-325.

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

CSIRO cannot present any assessment of the preparedness of emergency services as such, but we are undertaking a number of research projects to support more effective response to extreme events by the emergency services sector. They include improving better prediction of how extreme events ‘behave’, and better information and communications systems. These aim to contribute to improved efficiency or efficacy in some areas of operations.

Predicting bushfire behaviour

Understanding the factors—and the interactions between these factors— that influence the behaviour of bushfires is essential to the development of robust tools for predicting the behaviour and spread of bushfires across the landscape. While the existing systems for predicting the likelihood of the occurrence, spread and impact of bushfires in Australia, developed in the 1960s, are adequate for determining the mean behaviour of bushfires over a number of hours, the highly chaotic nature of bushfires means instantaneous behaviour of bushfires can be more unpredictable than the mean value. This can result in short-lived, but extremely hazardous, conditions that can imperil the safety of not only the general public threatened by a raging bushfire but also the firefighters tasked with protecting them and their property.

CSIRO research focuses on the science and tools needed by rural fire authorities and land management agencies to better prepare for and respond to bushfire emergencies. This includes: the development of improved tools for predicting the behaviour of bushfires burning in forest fuels under dry summer conditions; development of tools for the prediction of behaviour of fires burning in mallee-heath scrub; assessment of the effectiveness of video-based fire detection technology; reconstruction of the behaviour and spread of the Kilmore East Black Saturday fire that claimed 119 lives; development of models for predicting the maximum potential spotting distance from a crown fire in eucalypt forest and pine plantation; development of firefighting resource deployment tools; and the construction of a large combustion wind tunnel to enable the study of fire propagation mechanisms through bushfire fuel.

Better understanding flood and tsunamis through modelling

Improved flood modelling can support governments, planning groups, rescue and recovery agencies, municipal councils, insurance companies and communities to better cope with flood disaster events; from prevention, preparation, response to recovery.

New computational modelling techniques have been developed to better understand and prepare for flood disasters. Importantly, emergency services will be able to use this information to make sound decisions based on accurate data from real-life disaster scenarios. Geophysical flow events are difficult to study because solids and fluids move in large volumes over large areas, many physical processes are at work including erosion, sedimentation and deposition and they occur over an expanse of time and space.

CSIRO uses a combination of shallow water for large scale fluid flows, smoothed particle hydrodynamics for fluid-structure interaction and discrete element models for land and mudslides, to accurately model geophysical events using real 3D digital models of the surrounding landscape. The powerful modelling technique gives realistic water simulations that include difficult-to-model behaviours such as wave motion, fragmentation and splashing including fluid structure interaction. As well as being immensely important for disaster management and new infrastructure planning, the work could help Australian coastal councils and stakeholders prepare for extreme weather. This work has been applied to several prediction projects for the local government/councils in Australia and for various dam break scenarios in China.

Monitoring social media to alert authorities sooner

The 'sooner the better' for alerts to emergency services of natural disasters and CSIRO's Emergency Situation Awareness tool provides valuable intelligence to disaster coordinators and emergency managers about the impact of natural disasters on communities. We apply capabilities in statistical modelling, text mining and streaming data analysis to the challenges of extracting early signals, high-value messages and topics from Twitter during crises and emergencies.

The Emergency Situational Awareness Project (or ESA, http://www.csiro.au/en/Outcomes/ICT-and-Services/Early-Adopters-Social-Media.aspx) has been deployed and in use by various emergency management authorities in Australia including – several federal agencies and at least one department responsible for Emergencies in each state and territory in Australia.

References:

- Albini F.A., Alexander M.E. and Cruz M.G. 2012. A mathematical model for predicting the maximum potential spotting distance from a crown fire. *International Journal of Wildland Fire,* 21, 609–627.
- Box P. 2012. Building Information Communities: Spatially Enabled Social Protection in Indonesia. Invited presentation at *Information and Innovation in Service Delivery Conference* 26-27 November 2012, Canberra.
- Cheney N.P., Gould J.S., McCaw W.L., and Anderson W.R. 2012. Prediction fire behaviour in dry eucalypt forest in southern Australia. *Forest Ecology and Management*, 280: 120-131.

- Cleary P. W. and Prakash M. 2004. Discrete element modelling and smoothed particle hydrodynamics: potential in the environmental sciences, *Philosophical Transactions of the Royal Society A*, 362, 2003-2030. doi:10.1098/rsta.2004.1428.
- Cleary P. W., Prakash M. and Rothauge K. 2010. Combining digital terrain and surface textures with large-scale particle-based computational models to predict dam collapse and landslide events. *International Journal of Image and Data Fusion*, 1(4), 337-357.
- Cruz M.G., Sullivan A.L., Gould J.S., Sims M.C., Bannister A.J., Hollis J.J., and Hurley R.J. 2012. Anatomy of a catastrophic wildfire: The Black Saturday Kilmore East fire in Victoria, Australia. *Forest Ecology and Management,* 284, 269-285.
- Ellis P.F.M. 2011. Fuelbed ignition potential and bark morphology explain the notoriety of the eucalypt messmate 'stringybark' for intense spotting. *International Journal of Wildland Fire,* 20, 897-907.
- Kostanski L., Atkinson A., Box P. and Watt, B. 2012. Feature Types for Global Gazetteers, paper submitted to the *10th United Nations Conference on the Standardisation of Geographic Names***,** New York, August 2012. http://unstats.un.org/unsd/geoinfo/ungegn/docs/10th-uncsgn-docs/econf/E_Conf.101_56_Add1_Feature%20Types%20for%20Global%20Gazetteers.pdf
- Matthews S., Sullivan A.L., Gould J., Hurley R., Ellis P. and Larmour J. 2012. Field evaluation of two image-based wildland fire detection systems. *Fire Safety Journal,* 47, 54-61.
- McCarthy G.J., Plucinski M.P. and Gould J.S. 2012. Analysis of the resourcing and containment of multiple remote fires: The Great Divide Complex of fires, Victoria, December 2006. *Australian Forestry,* 75:1, 54-63.
- McCaw W.L., Gould J.S., Cheney N.P., Ellis P.F. and Anderson W.R. 2012. Changes in behaviour of fire in dry eucalypt forest as fuel increases with age. *Forest Ecology and Management,* 271:170-181.
- Cameron M.A., Power R., Robinson B. and Yin J. 2012. Emergency situation awareness from twitter for crisis management. *WWW* (Companion Volume) : 695-698.
- Yin J., Lampert A., Cameron M., Robinson B. and Power R. 2012 Using Social Media to Enhance Emergency Situation Awareness. *IEEE Intelligent Systems*, 27(6), 52-59.
- Prakash M., Debroux F. and Cleary P. 2001. Three dimensional modelling of dam break induced flows using Smoothed Particle Hydrodynamics. 14th *Australasian Fluid Mechanics Conference*, Adelaide, Australia, 10-14th Dec 2001, 379-382.
- Prakash M. And Cleary P.W. 2011. Three dimensional modelling of lava flow using smoothed particle hydrodynamics. *Applied Mathematical Modelling*, 35(6), 3021-3035.
- Prakash M, Cleary P.W., Mead S., Bolger M., Tang X., Wang H., Ye F., Ouyang S. and LI S. 2011. Environmental Informatics for the Development of Landscape Scale Monitoring and Modelling Extension — Field trip report, *ACEDP Technical Report No*: EP116571, 84 pages.
- Prakash M., Mead S., Cleary P.W., Lemiale V., Ye F., Ouyang S., Li Z., Wang H., and Tang X. 2011. Environmental Informatics for the Development of Landscape Scale Monitoring and Modelling Extension — A risk framework for determining consequences of failure of earth dams, *ACEDP Technical Report No*: EP121485, 73 pages.
- Prakash M., Woolard F. and Mead S. 2012. Modelling and visualisation of inundation due to a potential storm surge in Townsville. 21st *NSW coastal conference*, Kiama, NSW, 6-9 November 2012.
- Ye, F., Prakash M., Wang H., Ouyang S., Tang X. and Li Z. 2012. Spatio- temporal analysis and visualization using SPH for dam-break and flood disasters in a GIS environment. *Geomatics for Integrated Water Resources Management*, 19-21 Oct., Lanzhou, Gansu, China.
- Yin J., Karimi S., Robinson B. And Cameron M. 2012. ESA: Emergency Situation Awareness via Microbloggers ACM International Conference on Information and Knowledge Management, 2701-2703.
- Watt W., Kostanski L., Atkinson A. and Box P. 2012. Four Faces of Toponymic Gazetteers. Paper submitted to the 10th United Nations Conference on the Standardisation of Geographic Names, New York, August 2012. http://unstats.un.org/unsd/geoinfo/ungegn/docs/10th-uncsgn-docs/econf/E_CONF.101_57_The%20Four%20Faces%20of%20Toponymic%20Gazetteers.pdf

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

CSIRO's research has particularly focused on responses to extreme weather in the context of allowing for future change. In general terms, a survey of diverse sectoral representatives (both in government and outside) found that adaptation planning and implementation has to date been largely thematic, sectoral in nature or industry-based (Park *et al.,* 2011). Taking such a narrow perspective potentially overlooks many complex economic, social and ecological issues and interactions, and may lead to unintended and maladaptive consequences. This includes clarification of roles and responsibilities, which have been the subject of studies in more specific contexts.

Integration between tiers of government over climate change

Abel *et al.* (2012) and Gorrdard *et al.* (2011) show how complex the institutional arrangements among tiers of government and of other players can be in Australia. Roles and responsibilities associated with planning for and managing the impacts of events such as storm surge and coastal inundation for instance need to be clearly articulated. While this is occurring to some degree between levels of government, it is restricted by current formal arrangements and therefore of imperfect effectiveness.

A key issue is that the ability of one tier of government to make a decision (within its respective responsibility) is constrained or even compromised by decisions at another level of government. For instance where local governments have statutory responsibilities for local planning and development controls, they do not generally have the capabilities to manage many of the legal and financial risks generated from those decisions. This is particularly the case in implementing planning controls on private property for storm surge events and coastal inundation where local governments have repeatedly looked to State Government to provide adequate legislative protection, regulatory clarity and or financial support to guard against legal action arising from local decisions made in the public good to limit risk **(**Inman *et al.,* 2012; Harman *et al.,* forthcoming).

In a similar vein, there have been high profile recent changes to coastal management policies (including the management of coastal flooding hazards) in the States of Queensland and NSW. Significant changes in state-level policy create considerable uncertainty and ambiguity for local government level decision-makers, compromising their ability to develop clear rules and practices that persist over time and are accepted and understood by their communities. This is significant as it is the local tier of government that private property developers have the highest level of interaction with, including on strategies to limit risks from natural hazards associated with development projects (Taylor *et al.,* 2012).

Government responsibilities in the coastal zone

The coastal zone is subject to particularly complex governance arrangements which make it difficult to manage for a changing climate. The nature of climate change in coastal systems means that no single policy, process or insight will result in effective coastal adaptation. The attribution of impacts and responsibilities and therefore investment in adaptation options needs coordinating across all levels of government and private actors to ensure that important but often unintended and indirect consequences of decisions are accounted for.

Existing decision-making and policy processes only consider a subset of possible futures and possible adaptation options and pathways because they do not adequately account for:

1. Changing values and preferences – that values and preferences of individuals and groups for the balance between nature and development will be different in the future to those currently held.
2. Small-probability high-impact events (i.e. extreme events), which, if seriously and appropriately considered in economic analyses, can lead to entirely different options being assessed as

preferable. These options may lead a community to delay or avoid defence and instead adopt a strategy of planned retreat.

3. Constraints on existing decision and policy spaces, and entrenched institutions and organisational arrangements (e.g. existing budgetary and short-term planning cycles) can unintentionally lock development into unwanted trajectories.
4. Diverse and changing cross-scale effects that can require problems and decision processes to be reframed.

References

- Abel, N., Gorddard, R., Harman, B., Leitch, A., Langridge, J., Ryan, A., and Heyenga, S. 2011. Sea level rise, coastal development and planned retreat: analytical framework, governance principles and an Australian case study. *Environmental Science & Policy,* 14, 279-288.
- Gorddard R., Wise R.M., Alexander K., Langston A., Leitch A., Dunlop M., Ryan A., and Langridge J. 2012. Striking the balance: Coastal development and ecosystem values. Report prepared for the Australian Department of Climate Change and Energy Efficiency and the CSIRO Climate Adaptation National Research Flagship. ISBN: 978-1-922003-38-6.
- Harman, B., Taylor, B. and Inman, M. Under review. Scaling-up, scaling-down, scaling-out: Local planning responses to sea level rise, Submitted to *Geographical Research*, November 2012.
- Inman M., Taylor, B., and Harman, B. 2012. Incorporating coastal inundation and SLR considerations into local and regional planning responses: A guideline to support good planning practice in the Sydney Coastal Councils Area, Prepared by CSIRO and the Sydney Coastal Councils Group, October 2012.
- Park S.E., Crimp S., Dowd A-M., Ashworth P. and Mendham E. 2011. Understanding climate change adaptation as a national challenge. CSIRO Climate Adaptation Flagship Working paper No. 8. http://www.csiro.au/Organisation-Structure/Flagships/Climate-Adaptation-Flagship/CAF-working-papers/CAF-working-paper-8.aspx
- Productivity Commission, 2012, Barriers to effective climate change adaptation, Productivity Commission Draft Report, April 2012.
- Taylor B.M., Harman B., Heyenga S. and McAllister R.R.J. 2012. Property Developers and Urban Adaptation: Conceptual and Empirical Perspectives on Governance. *Urban Policy and Research*, 30(1) 5-24.
- Wise R.M., Fazey I., Stafford Smith M., Parke S., Eakin H., Campbell B. and Maru Y. Under review. Reframing adaptation as pathways for managing change. Submitted to *Global Environmental Change*.