The Centre for Australian Weather and Climate Research
A partnership between CSIRO and the Bureau of Meteorology

Australian Government
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Climate Science Update: A Report to the 2011 Garnaut Review

Keenan, T.D. and Cleugh, H.A. (Editors)

CAWCR Technical Report No. 036

March 2011

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Contents

INTRODUCTION

In November 2010, Professor Ross Garnaut was commissioned by the Australian Government to provide an update of his 2008 Climate Change Review (http://www.garnautreview.org.au/2008-review.html).
This review (see http://www.garnautreview.org.au/update-2011/terms-of-reference.html) was to consider developments in climate change mitigation, climate change science, proposals to develop a carbon price in Australia, trends in domestic and international emissions, changes in low emission technology, the potential for abatement within the land sector and developments in the Australian electricity market. A series of papers related to the above are being released during the period November 2010 to March 2011 with the final report due May 2011.

The Centre for Australian Weather and Climate Research (CAWCR - see http://www.cawcr.gov.au/) received a request from the Department of Climate Change and Energy Efficiency (DCCEE) to provide input to this process. This technical report was developed in response to the request. The rationale was to provide from CAWCR a summary of the science of climate change, especially since the 2008 Garnaut Report, and associated national developments in climate change programs.

This report was one part of the process that informed Professor Garnaut during the development of his Climate Change Science Report. Essentially this science update is a rapid assessment of material published from 2008 to 2010, designed specifically for consideration by Professor Garnaut in his climate science update.

This technical report is based on scientific contributions from both CSIRO[1] and the Bureau of Meteorology. It is not intended to be comprehensive in terms of depth or breadth. Rather it is a snapshot of the "state of the science" mainly from the perspective of CAWCR scientific expertise based on peer-reviewed literature. The issues covered relate mainly (but not exclusively) to the scope of Working Group One (WGI) of the Intergovernmental Panel on Climate Change (http://www.ipcc.ch/); i.e. an assessment of the physical and scientific aspects of the climate system and climate change. We are particularly grateful to these contributors for undertaking this significant effort within a very tight timeline.

Thanks are also extended to the reviewers, who played important roles in assessing the content. For the technical production we extend our thanks to others who assisted, especially Paul Holper (CSIRO), Andrew Hollis (Bureau of Meteorology) and Keith Day (Bureau of Meteorology).

Finally we would also like to thank DCCEE and the Garnaut Secretariat for the opportunity to contribute to this important process.

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CAWCR	CSIRO Marine and Atmospheric Research

[1] Primarily from CSIRO Marine and Atmospheric Research Division (http://www.cmar.csiro.au/) with additional contributions from the CSIRO National Research Flagships (http://www.csiro.au/partnerships/NRF.html) including: Wealth from Oceans Flagship, Water for a Healthy Country Flagship, and the Climate Adaptation Flagship.

1. UPDATE ON THE STATE OF THE CLIMATE, LONG-TERM TRENDS AND ASSOCIATED CAUSES

Karl Braganza, Scott Power, Blair Trewin, Julie Arblaster, Bertrand Timbal, Pandora Hope, Carsten Frederiksen and John McBride
The Centre for Australian Weather and Climate Research – A partnership between the Bureau of Meteorology and CSIRO

David Jones and Neil Plummer
Bureau of Meteorology

This section provides a brief update on Australian climate variability and change since 2008. We also discuss recent observations and longer-term changes in global temperature, and severe tropical cyclones making land-fall over eastern Australia. The causes of the observed changes are discussed in some cases.

Three appendices on popular questions are also provided: i) did global warming stop in 1998? (Appendix A1), ii) was climate change responsible for Black Saturday? (Appendix A2), and iii) how are the heavy rains in eastern Australia during late 2010 and early 2011 related to La Niña and climate change? (Appendix A3).

1.1 Temperature

The decade ending in 2010 has easily been Australia's warmest decade since record keeping began and continues a trend of each decade being warmer than the previous that extends back 70 years (Figs 1.1 and 1.2). 2009 was the second warmest year on record based on the mean annual temperature across Australia. 2010 was +0.19 °C above the 1961 to 1990 average of 21.81°C. This is milder than the previous eight years, underscoring the fact that individual years can still be relatively cool even as the warming of Australia's climate continues (see Appendix A1 for further discussion of related issues).

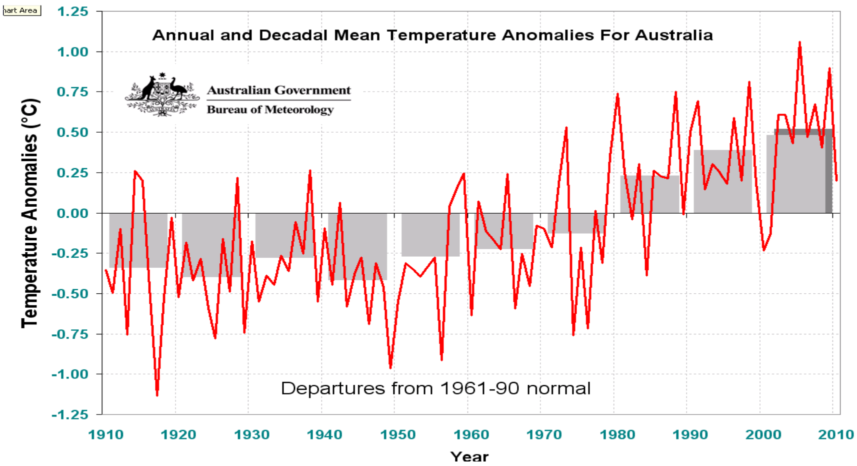

Fig. 1.1 Annual (red line) and decadal mean (light grey bars) temperature deviations from the 1961 to 1990 average for Australia. This reference period is used throughout this Section unless stated otherwise. The average for the last ten years is shown in the dark grey bar. Temperature (and rainfall data appearing later) are quality controlled using multiple analyses to estimate the robustness of broad-scale trends and variability. Such analyses show that changes in Australia's climate over the last 60 years are robust and unlikely to be greatly affected by issues such as urbanisation, uncertainties, and occasional errors in the observational data. Source: Australian Bureau of Meteorology.

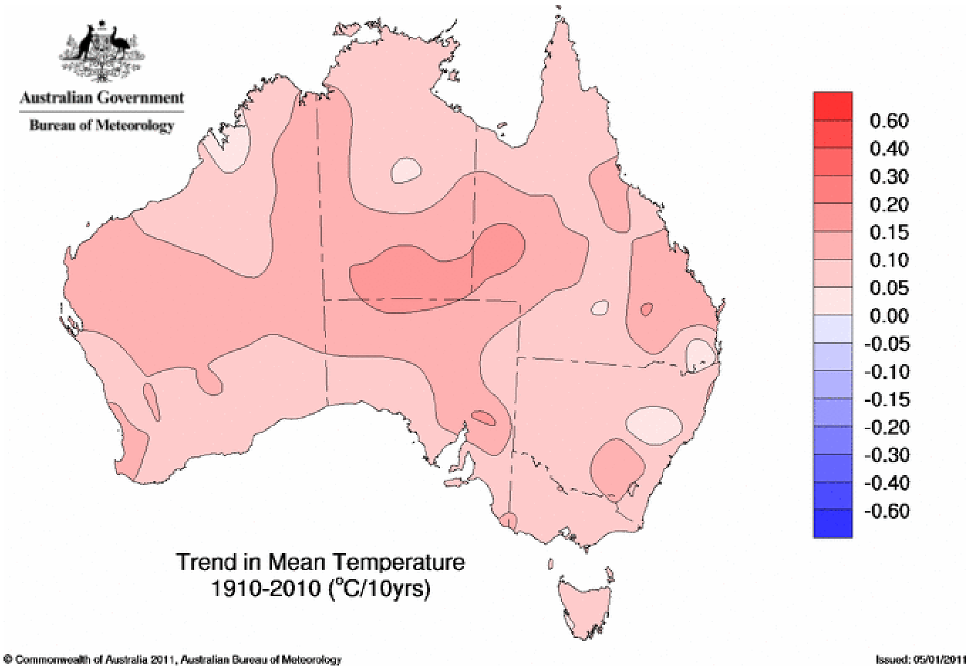

Fig. 1.2 Trends in annual mean temperature across Australia during 1910-2010. All regions show a warming (positive) trend, with values up to approximately 0.2˚C/decade. Source: Australian Bureau of Meteorology.

Global temperature data for the period 1950-2010 have been compiled by the UK Hadley Centre and Climatic Research Unit, the National Aeronautics and Space Administration (NASA), and the US National Climatic Data Centre. These observed data led the World Meteorological Organization to conclude that "the year 2010 ranked as the warmest year on record, together with 1998 and 2005. Data received by the WMO show no statistically significant difference between global temperatures in 2010, 2005 and 1998" (see Fig. 1.3). Globally, the current decade is the warmest on record.

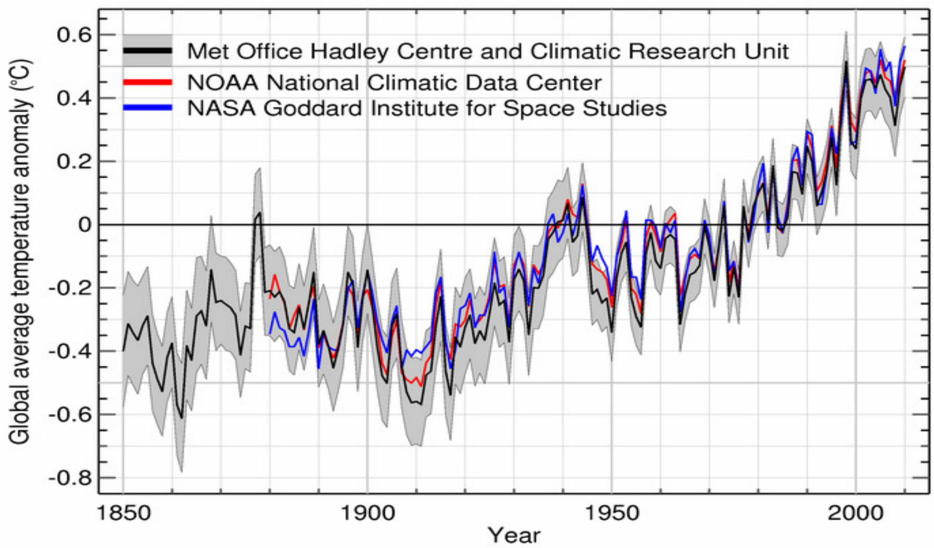

Fig. 1.3 Global average annual surface temperature deviations from the 1961-1990 average for the period 1850-2010. Data sources: UK Hadley Centre/Climatic Research Unit, NASA Goddard Institute for Space Studies, US National Climatic Data Centre.
Reference: http://www.wmo.int/pages/mediacentre/press_releases/pr_906_en.html.

The IPCC Fourth Assessment Report (2007) concluded that "most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations". This is a more definite statement than in the preceding IPCC Third Assessment Report which concluded that "most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations".

The IPCC (2007) conclusion was based on information available up to 2005 and part way through 2006 only. Global average temperatures since that time have continued to be anomalously high (Fig. 1.3). On this basis the IPCC (2007) statement is adequate, and perhaps underestimates, the degree of confidence in the extent to which humans have influenced global temperature. The factors leading to the high temperature in 1998 are likely to be a combination of natural variability (e.g. El Niño - Southern Oscillation) and (very likely) human-caused greenhouse gas emissions. See Appendix A1 for further details.

1.2 Australian rainfall, sea-surface temperature and the SOI

La Niña events historically have been linked to heavy rainfall and flooding across eastern Australia and the same was true in 2010 and early 2011. Data collected by the Bureau of Meteorology show that most areas of Australia experienced very much above average rainfall during 2010 (Fig. 1.4).

The Australian mean rainfall total for 2010 was 701 mm, well above the long-term average of 465 mm and making 2010 Australia's second-wettest year since records commenced in 1900. Only 1974 (760 mm), itself a La Niña year, was wetter. The second half (July to December) of 2010 was Australia's wettest on record.

Record rainfall fell in spring 2010 across Queensland, New South Wales and the Northern Territory. The Murray-Darling Basin received its highest annual rainfall total on record and the most significant rainfall in over a decade, which effectively overcame the severe and prolonged rainfall deficits across the Basin. Queensland also had its wettest year on record. Seasonal rainfall records were broken in south-east Queensland. Victoria experienced its wettest summer on record and 2010 was the first year since 1996 to experience above average rainfall for some parts of the southeast of the continent.

Not all areas were very wet during 2010. For example, south-west Western Australia had its driest year on record and the Perth region experienced record low inflows to water storages as a result. The high (positive) phase of the Southern Annular Mode (SAM) during winter is associated with dry conditions across the south-west (Hendon *et al*. 2007). The dry conditions are therefore consistent with the fact that from mid-May until the end of August 2010 – when most of south-west Western Australia's rain falls - the US Climate Prediction Centre's SAM index persisted in its positive phase for a longer period than has been observed previously (102 days compared to the next longest of 84 days).

Dry conditions also occurred in central and eastern Gippsland during 2010, continuing the pattern of long-term drying observed in this region.

Very high rainfalls in Victoria during 2010 were concentrated in the state's north, and principally in the second half of the year. Melbourne's water storages, whose catchments received rainfall which was only slightly above average, received a fourteenth consecutive year of below-average inflows. The seasons experiencing the most acute rainfall decline in south-eastern Australia were autumn and early winter, and 2010 rainfall in those seasons was still only close to normal even though it was substantially higher than in recent years.

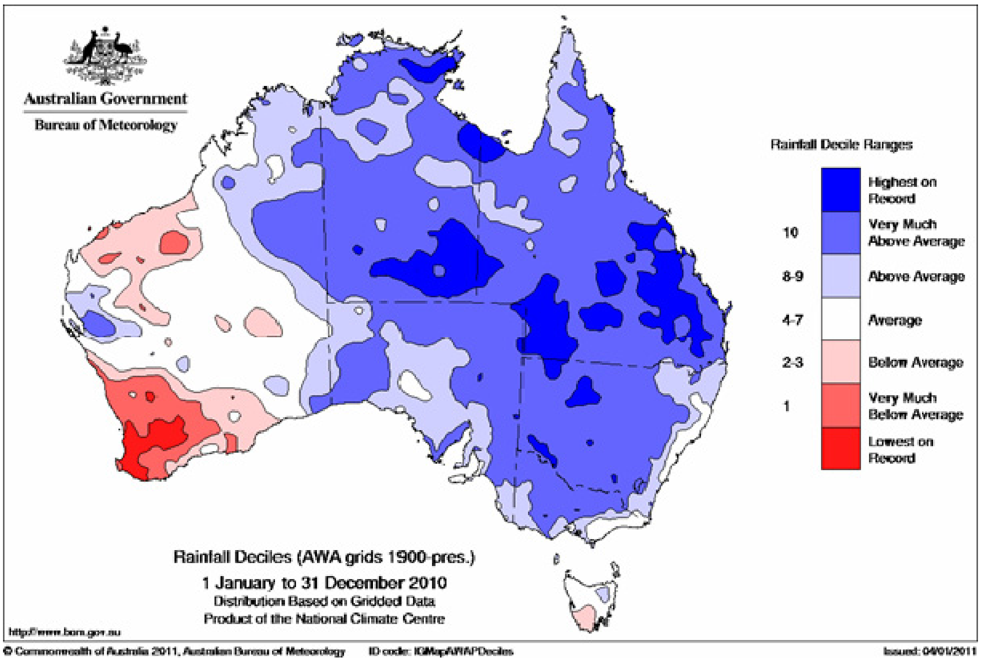

Fig. 1.4 2010 annual rainfall compared with historical rainfall records (deciles) from 1900 to the present. Source: Australian Bureau of Meteorology.

Late November and December 2010 were extremely wet through much of eastern Australia. Four major rain events affected large parts of the eastern states during this period, resulting in widespread flooding on many rivers, especially in Queensland and New South Wales. The most severe flooding of 2010 occurred in Queensland and far northern and central western New South Wales in the last week of December, with downstream impacts continuing into January. These floods were the most significant in Australia since at least the 1970s in terms of extent and impact. There was also substantial flooding in various parts of the eastern states earlier in December 2010, especially in the Murrumbidgee and Lachlan catchments of inland New South Wales. There was further severe flooding in January 2011 in south-eastern Queensland, along with record-breaking floods in western and north-western Victoria. December 2010 was the wettest December on record for Queensland and for eastern Australia as a whole and the second-wettest for the Murray-Darling Basin. The heavy rainfall in late November and December 2010 followed a very wet July to October for Australia, meaning many catchments were already wet before the flooding rain.

The rains of late 2010 took place during a very strong La Niña event in the Pacific Ocean. The December Southern Oscillation Index (SOI) was +27.1, the highest December value on record and the highest monthly value since 1973 (Fig. 1.5). Previous strong La Niña events, such as those of 1955 and 1974, were also associated with widespread and severe flooding in eastern Australia. The June-December SOI is sometimes used to track El Niño-Southern Oscillation (ENSO) activity (e.g. Power *et al*. 2006; CSIRO-BoM 2007). The 2010 June-December SOI was the third highest on record. Records for the SOI extend back to 1876.

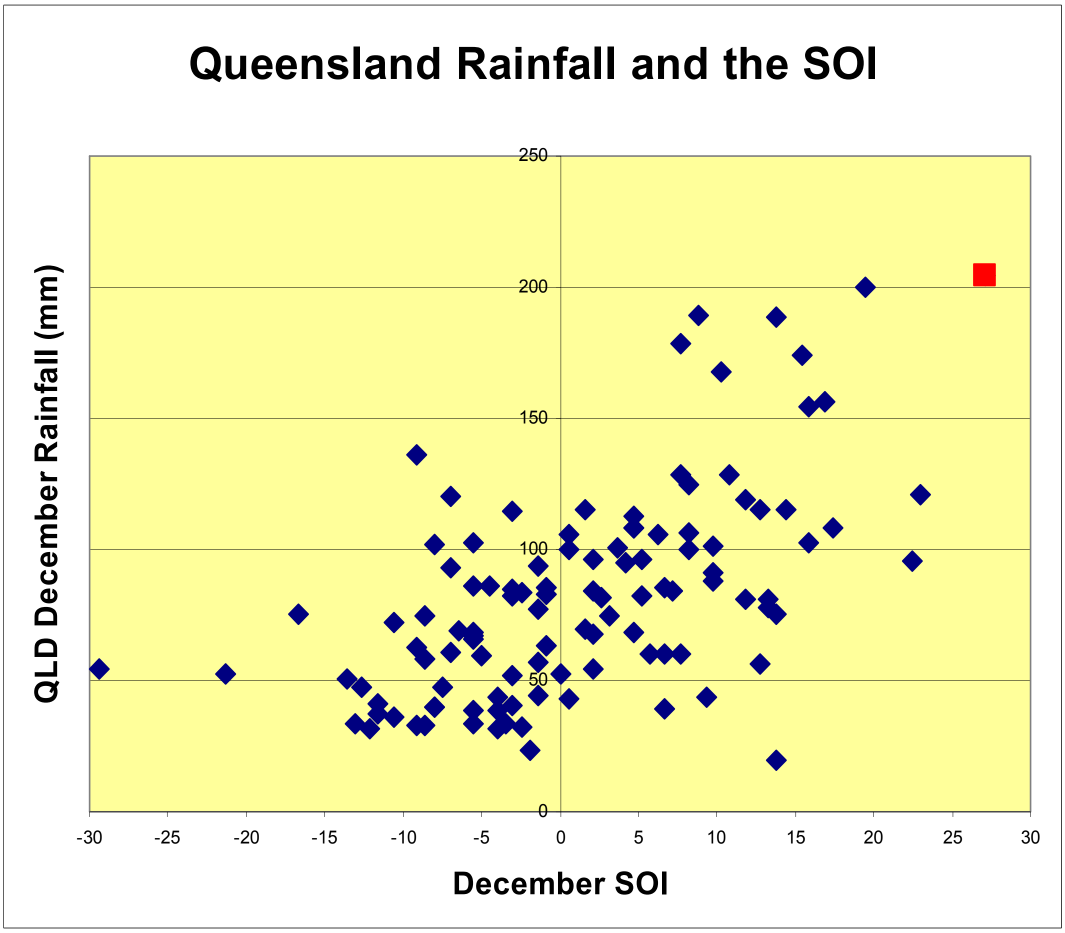

Fig. 1.5 Queensland rainfall (area average) and the Southern Oscillation Index during December, for the period from 1900 - 2010. Both reached record values in December 2010 (red square). Source: Australian Bureau of Meteorology.

Rainfall in Australia is strongly influenced by sea surface temperatures (SSTs) in the tropics around northern Australia. Ocean temperatures in this region were the highest on record during spring 2010 and SSTs to the north of Australia during September-December in 2010 were either the highest on record or very much above average for those months (Fig. 1.6). However, the gridded and interpolated SST data sets available, including the one used here, have extensive gaps prior to the satellite era. Confidence in the SST records consequently is less than that for the temperature and rainfall records described earlier which derived from weather stations across the Australian continent.

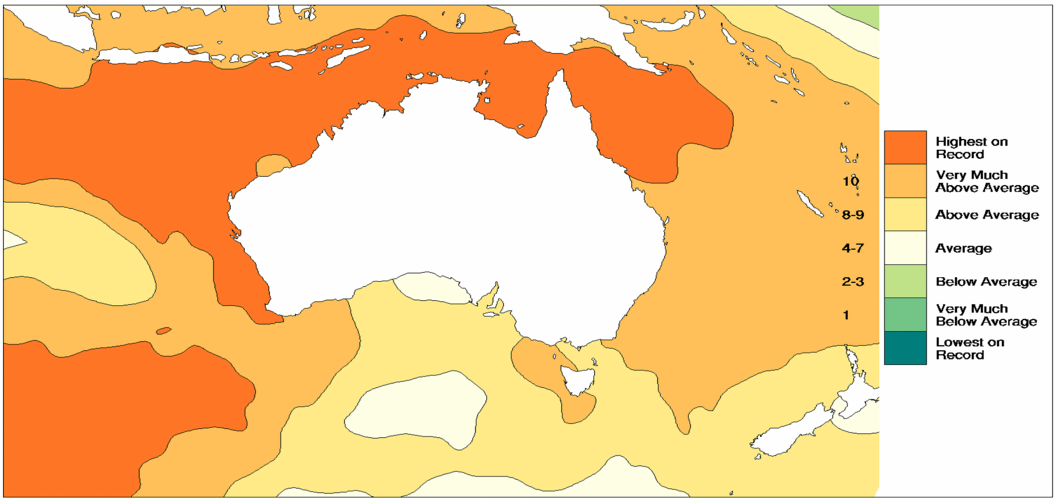

Fig. 1.6 Sea-surface temperature deciles for the period September-December 2010 using data for 1900-2010. Data Source: Reynolds SST data set: ERSST.v3b.

Sea surface temperatures in the Australian region also appeared to be the highest on record during 2010 (Fig. 1.7), but again note the limitations in SST data available.

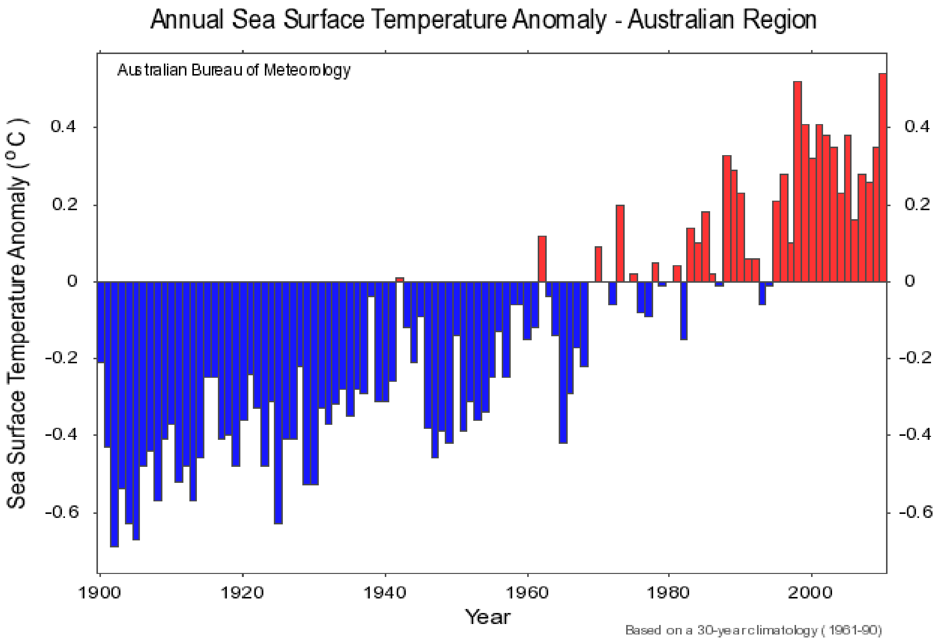

Fig. 1.7 Annual sea surface temperature anomalies in the Australian region relative to the 1961-1990 average of 21.9˚C. Source: Australian Bureau of Meteorology.

The average to above average rainfall in the south-east and southern Queensland came after a very dry period extending back to late 1996 (Fig. 1.8). The south-east of the continent experienced similar rainfall declines to the south-west during this period. The rainfall declines in both regions have been characterised by both recurrent drought and systematic declines in autumn and winter rainfall. These longer-term declines have been linked, in part, to anthropogenic climate change (CSIRO-BoM 2007; Timbal *et al*. 2010) and might not be due to natural variability in tropical SST (Smith and Timbal 2010).

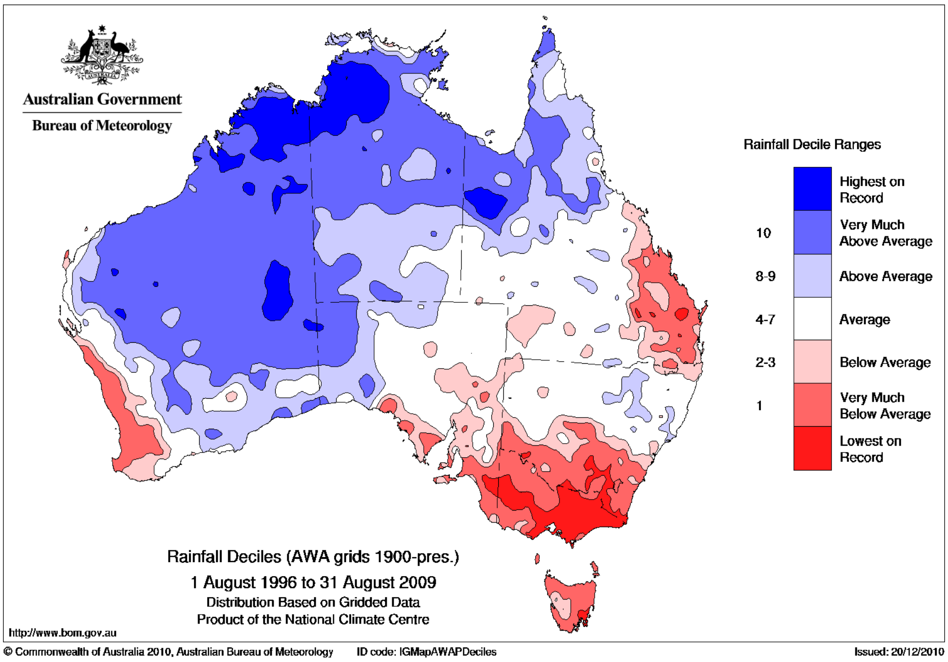

Fig. 1.8 Rainfall deciles for the period August 1996-August 2009. Statistically significant changes in rainfall have occurred in the south-west, where a 10-20% step change (decline) in autumn and winter rainfall occurred around 1970 and again in 2000 and in the south-east, where a similar decline occurred around 1996. Drying also has occurred in south-east Queensland but this is less noteworthy given high local rainfall variability. The baseline, as indicated on the graph, is from 1900 to the present. Source: Australian Bureau of Meteorology.

Trends in annual mean rainfall during 1900-2010 are presented in Fig. 1.9. Monsoonal rainfall has increased in the Top End and the north-west of the continent since 1900, while rainfall declined in parts of the south-west, north-east and south-east.

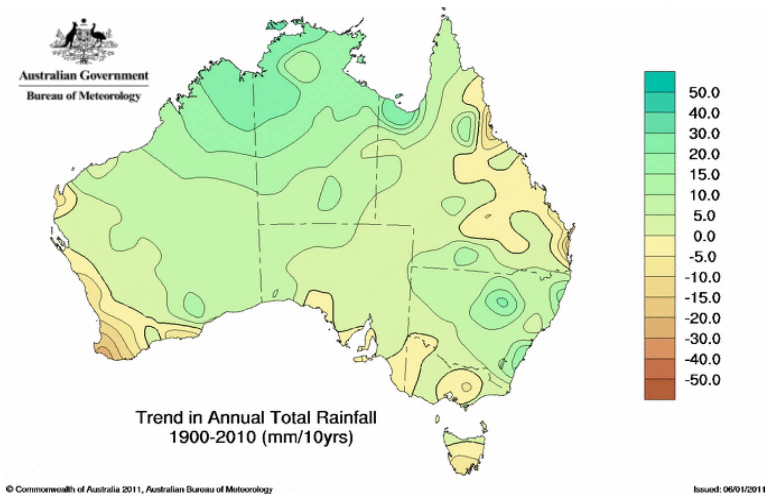

Fig. 1.9 Linear trends in annual rainfall from 1900 to present (mm/decade). Source: Australian Bureau of Meteorology.

The long-term drying trends in the southern part of the continent are related to a systematic and continuing reduction in the strength of the sub-tropical jet stream, the weaker growth of mid-latitude storms and a southward deflection of some storms (Frederiksen and Frederiksen 2007; Frederiksen *et al*. 2010, 2011). Studies have shown that the observed drying over south-west Western Australia is likely to be linked to anthropogenic climate change (Timbal *et al.* 2006; Power *et al*. 2005; Bates *et al*. 2008) and might also be linked to anthropogenic changes in the land surface (Timbal *et al*. 2006).

1.3 Tropical cyclones

Determination of trends in tropical cyclone frequency or tropical cyclone intensity is a difficult exercise due to a) the large fluctuations in cyclone activity that exist on interannual and inter-decadal time scales, and b) the dependence of the cyclone record on technology that is rapidly changing including radar systems, satellite instrumentation and advanced computing display and analysis methods. A recent World Meteorological Expert Team global synthesis concluded: “It remains uncertain whether past changes in tropical cyclone activity have exceeded the variability expected from natural causes”. It went on to say, “there was no significant change in global tropical storm or hurricane numbers from 1970 to 2004, nor any significant change in hurricane numbers for any individual (cyclone) basin over that period, except for the Atlantic”. (Knutson *et al*. 2010).

Scientists from the Australian National Climate Centre at the Bureau of Meteorology and CAWCR carried out a major study of trends in the Southern Hemisphere and Australian region tropical cyclone data sets (Kuleshov *et al*. 2010). That study concluded “In the Australian region, no significant trends in the total numbers of tropical cyclones, or in the proportion of the most intense tropical cyclones, have been found.”

The time series of all tropical cyclones and of severe tropical cyclones in the Australian region in the era of satellite observations is shown in Fig. 1.10. There is an apparent decrease in the total number of cyclones during this period. However, given the large inter-annual fluctuations, this trend is not significant when subjected to Monte-Carlo type statistical tests. This apparent decrease may partly be due to an improved discrimination between tropical cyclones and sub-cyclone intensity tropical lows. If weak cyclones are excluded from the analysis, the trend is more gradual and follows the downward trend in the Southern Oscillation Index suggesting that the decrease in cyclone numbers may be related to the greater number of El Niño events since

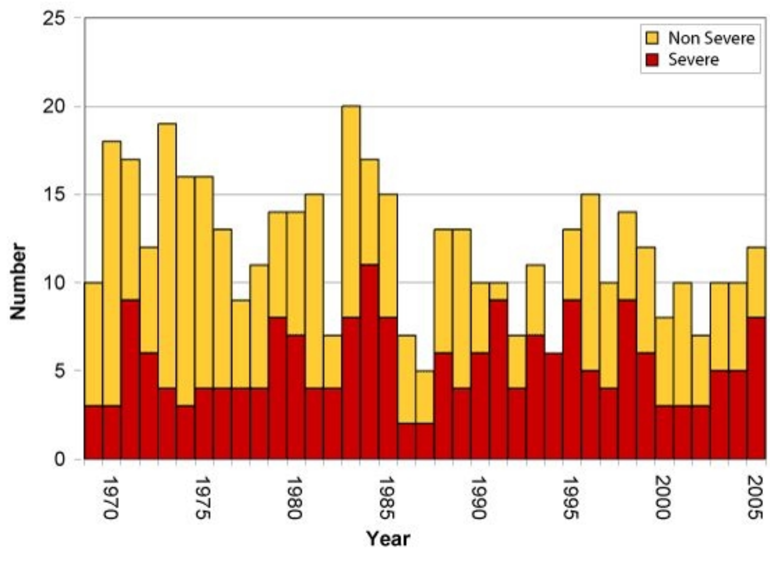

Fig. 1.10 Number of severe and non-severe tropical cyclones occurring in the Australian region from 1969 to 2005. Source: Australian Bureau of Meteorology (2011).

the mid-1970s. This does not appear to be due to improved discrimination between cyclones or trends in the Southern Oscillation Index. The actual cause of this is unknown (see also Bureau of Meteorology http://reg.bom.gov.au/cyclone/climatology/trends.shtml). Harper et al (2008) in an industry-funded study used satellite-based techniques to reanalyse the intensities of cyclones occurring in northwestern Australian.

Hassim and Walsh (2008) studied recent trends in tropical cyclone occurrence in the Australian region, considering the east and west separately and also differentiating between severe tropical cyclones frequencies including category 3 (A3 - central pressure in the range 956-970 hPa) and category 4-5 (A45 - central pressure < 956hPa). They found differences in trends in the proportion of severe intensity cyclones in the two regions. Kuleshov *et al*. (2010) also found differences in the trends of severe tropical cyclones in the two regions. Kuleshov *et al.* (2010) state the overall trend in the proportion of severe intensity tropical cyclones was positive, but not significant at the five per cent level, across a range of thresholds in the western region and the Australian region. Due to the larger number of cyclones, the Australian region mirrors the western region. Over different periods, both positive and negative trends in occurrence of tropical cyclones were identified but these trends were not statistically significant (see discussion above).

More recently Callaghan and Power (2010) used historic resources to develop a data set of severe tropical cyclones crossing a 1600 km stretch of coastline from Cairns southwards. Their time series (Fig. 1.11) shows that there is a very large variability in coastal crossing on a time scale of several decades. Their analysis indicates that the most recent 20-year period contains a historically low number of severe tropical cyclone crossings. The inference is that a return to a greater number of tropical cyclone events along the eastern coastline may occur in future decades. The role of global warming in the observed recent decline is not known at this stage (Callaghan and Powers 2010). Section 10 provides further details on projected changes to tropical cyclone activity in Australia.

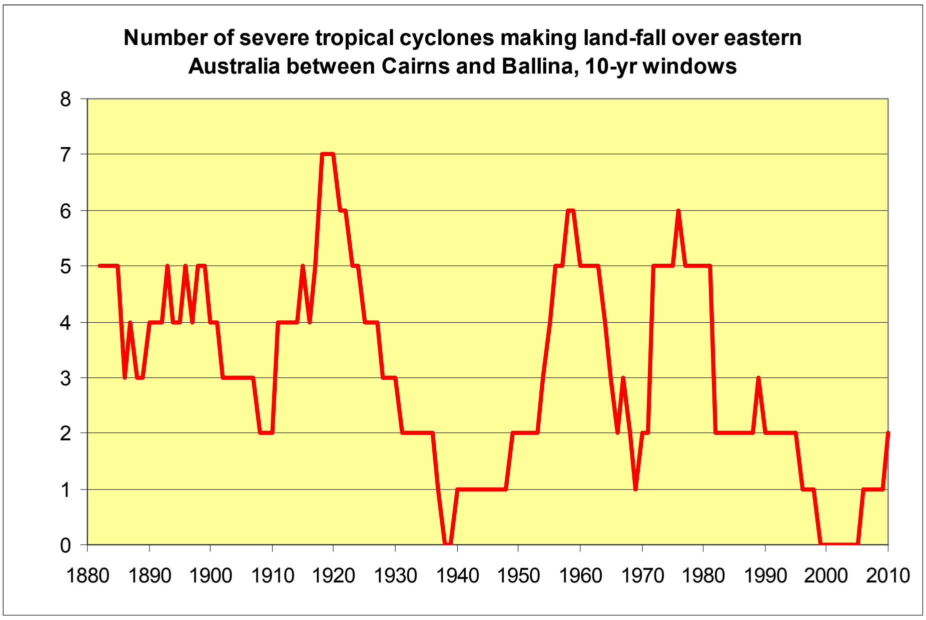

Fig. 1.11 Decadal variability (10-year running totals) in the number of severe tropical cyclones making land-fall over eastern Australia between Cairns (Queensland) and Ballina (NSW). Source Callaghan and Power (2010).

1.4 Appendices

A1. Did global warming stop in 1998?

The assertion that global warming ended in 1998 is inconsistent with the range of observational evidence available. The assertion is made due to the very warm year that occurred in 1998 and most subsequent years with temperatures cooler than in 1998.

The World Meteorological Organization concluded that "the year 2010 ranked as the warmest year on record, together with 1998 and 2005. Data received by the WMO show no statistically significant difference between global temperatures in 2010, 2005 and 1998" (see Fig. 1.3). Furthermore, the last two decades have been the warmest decades on record (Fig. 1.3). Year-to-year, decadal, and longer variability arising from natural processes (e.g. ENSO, changes in volcanic activity) is expected even in the absence of climate change but climate change is expected to alter some characteristics of that variability. It is necessary to analyse statistically the observed record to discriminate between the effects of short-term temperature changes due to global climate variability and any underlying longer-term trends. There is a range of methods for performing such corrections. Studies (see, for example, Easterling and Wehner 2009; Fawcett 2008) using these methods have consistently shown that the underlying trend in global mean temperature is an increasing one that has continued over the last ten years.

A "hot topic" article has been prepared on this issue for the Department of Climate Change and Energy Efficiency and is accessible at: http://www.climatechange.gov.au/en/climate-change/myths/~/media/publications/science/hot-topics-globalwarming-v2.ashx.

One of the most important points in relation to measuring climate change is that global warming has not been measured using the global mean temperature alone. There are multiple lines of observational evidence, from the oceans, atmosphere and land surface, that strongly indicate a warming climate system. This evidence is extensively documented, and synthesised in various reports, such as the global State of the Climate Report for 2009, available at: http://www.ncdc.noaa.gov/bams-state-of-the-climate/2009.php.

A2. Was climate change responsible for the weather conditions of Black Saturday?

It is not possible to attribute single weather events to climate change in a deterministic sense. This means it is not physically correct to state that "global warming caused the weather conditions of Black Saturday", since such conditions are the confluence of both climatological conditions, as well as antecedent weather conditions.

It is possible to look at the probability of such an event, or of the physical components of such an event, however, and make probabilistic statements about likely causality. In other words, one may ask, "How likely would this event have been if no global warming has taken place?" Individual events may be assessed for their consistency with expectations in a warmer world and compared with the analogous expectations if the underlying climate conditions had not been changing. It is important to recognise that such comparisons generally do not allow us to state categorically that "such an event could only have occurred with climate change".

Multiple aspects of the extreme weather conditions associated with Black Saturday were consistent with our understanding of conditions that are more likely under anthropogenic climate change.

These include:

1. Prolonged drought: Some aspects of the prolonged drought in the south-east of Australia are consistent with our understanding of changes likely to occur due to anthropogenic climate change. In particular, increases in atmospheric pressure and the strength of the subtropical ridge across southern Australia have been linked with global warming, and are likely to be the strongest influence on systematic rainfall declines in the region. Prolonged drought greatly increases fire potential, and hence fire danger.

2. Longer term higher temperatures: Higher maximum and minimum temperatures have been observed across south-eastern Australia over recent decades and have been attributed to the effects of increasing greenhouse gases in the atmosphere, driven largely by anthropogenic emissions (see e.g. CSIRO-BoM 2007 and references therein). Higher temperatures lead to a greater frequency of extreme heat and hotter extreme days. Record high temperatures have outnumbered record low temperatures in Australia by a ratio of 2-3 to 1 since 1997 (Trewin and Vermont 2010). In general, higher temperatures exacerbate drought conditions in regions such as Victoria. Sequences of very hot days, with increased frequency, also act to dry fuel loads.

Hence, the conditions of Black Saturday were consistent with expectations for a warming world and one would expect an increased frequency of such conditions as warming continues in future.

A3. How are the recent heavy rains in eastern Australia related to La Niña and climate change?

The current La Niña event, as measured by the SOI, is one of the strongest on record (see above).

La Niña events drive an atmospheric circulation that is favourable to heavy rainfall over northern and eastern Australia by intensifying the transfer of moist tropical air over the continent. Past La Niña events have been associated with high rainfall and floods over northern and eastern Australia and these are well documented - for example, see the 1973-76 La Niña event described at http://www.bom.gov.au/climate/enso/lnlist/.

This current La Niña and high rainfalls have coincided with the highest sea surface temperatures around Australia on record (since 1900). Sea surface temperatures around Australia in September, October, November and December 2010 broke previous records by a large margin. Australian sea surface temperatures have risen substantially since 1900, very likely as a result of climate change (http://www.bom.gov.au/cgi-bin/climate/change/timeseries.cgi).

Could global warming have contributed to the heavy and extensive rainfall observed in recent months? Gallant and Karoly (2010) concluded that for Australia as a whole (but not at all locations) there has been an increase in the extent of wet extremes and a decrease in the extent of dry extremes annually and during all seasons from 1911 to 2008 at a rate of between one per cent and two per cent per decade. They also noted that these trends mostly stem from changes in tropical regions during summer and spring. Rainfall averaged over the whole country also has increased, with this increase largely due to increases over northern Australia during the wet season. The reason for this general increase in rainfall over northern Australia is not well-understood.

Gallant and Karoly (2010) also noted relationships between the extent of extreme maximum temperatures, precipitation and soil moisture on inter-annual and decadal time scales that are similar to the relationships exhibited by variations of the means (Nicholls *et al*. 1996; Power *et al*. 1998). However, the long-term trends in temperature and precipitation are both positive, providing evidence that the processes causing the interannual and decadal variations and those causing the longer-term trends are different (Gallant and Karoly 2010).

Projections for the 21st century (IPCC 2007; CSIRO-BoM 2007) suggest an increase in daily precipitation intensity (rain per rain-day) is generally likely though this is not true at all locations (see Section 9 for more details).

The IPCC 2007 report concludes that:

"Available research indicates a tendency for an increase in heavy daily rainfall events in many regions, including some in which the mean rainfall is projected to decrease. In the latter cases, the rainfall decrease is often attributable to a reduction in the number of rain days rather than the intensity of rain when it occurs".

The CSIRO-BoM (2007) examined changes over Australia and concluded that:

"An increase in daily precipitation intensity (rain per rain-day) and the number of dry days is likely. Extreme daily precipitation (highest one per cent) tends to increase in the north and decrease in the south with widespread increases in summer and autumn, but not in the south in winter and spring when there is a strong decrease in mean precipitation".

This conclusion only applies to certain seasons and regions, however, and the effects often appear small. On the other hand, Rafter and Abbs (2009) looked at projected changes in more extreme rainfall events (for 2055 compared to 1980) and found a tendency for much larger percentage changes in the daily rainfall amounts associated with 20-year return periods over most parts of Australia.

In summary, the recent heavy and extensive rain over eastern Australia is consistent with there being a very strong La Niña, but the degree to which global warming may have enhanced heavy rainfall in some parts of eastern Australia remains uncertain.

Finally, the record high value of the SOI during December 2010 begs the question: Could the intensity of the El Niño - Southern Oscillation be increased due to climate change? Research has shown that:

- La Niña is part of the El Niño-Southern Oscillation (ENSO) cycle. ENSO will continue to have a major impact on Australian climate into the future (IPCC 2007; CSIRO-BoM 2007).

- There is no clear guidance from the current generation of climate models as to whether the El Niño-Southern Oscillation (ENSO) will change in response to global warming. Some models have strengthened ENSOs, some weaker, and others exhibit little if any change (see e.g. Collins *et al*. 2010).

- Global warming might have made a small contribution to recent record values in the SOI (Power and Kociuba 2010).

These conclusions are based on climate models in which ENSO simulations have strengths and weaknesses. Hence these issues will continue to be addressed through research using future climate models in which ENSO is simulated in a more realistic way.

1.5 References

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2. HYDROLOGY

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CSIRO Water for a Healthy Country Flagship

2.1 Recent hydroclimatology

Large areas of southern Australia, in particular the southern Murray-Darling Basin, Victoria, south-west Australia and south-east Queensland experienced prolonged drought from 1997 to 2009 (Fig. 2.1). The dry spell in the southern Murray-Darling Basin, Victoria, and south-west Australia was unprecedented over the 110 years of reliable rainfall records (Timbal 2009). The drought resulted in declining storage levels in reservoirs, several years of severe water restrictions in cities, and years of low allocations to irrigators in the southern Murray-Darling Basin and elsewhere in Victoria.

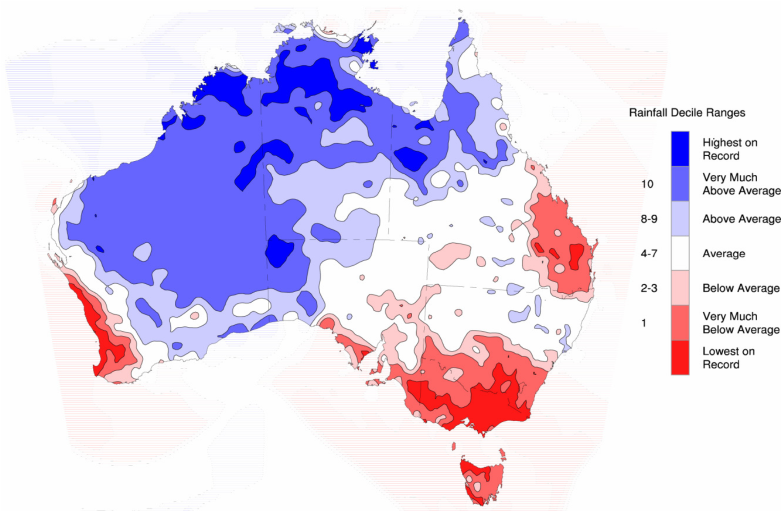

Fig. 2.1 Rainfall deciles across Australia for 1 January 1997 to 31 December 2009 relative to a 1900–2009 climate showing the long dry conditions in the south-east and south-west (CSIRO 2010 using data from the Bureau of Meteorology).

The last decade of very low rainfall in south-west Western Australia has been part of a longer trend of gradually declining rainfall since the mid-1970s (Bates *et al*. 2010) and is also present in trends back to 1900 (Fig. 1.9).

Research in the Indian Ocean Climate Initiative (IOCI 2010), the South-Eastern Australian Climate Initiative (SEACI 2010), and elsewhere has shown that the persistent dry conditions in the south-west and south-east of Australia are at least in part due to climate change (CSIRO 2010; Hope *et al*. 2010; Bates *et al*. 2008; Cai and Cowan 2006; Cai *et al*. 2009). Global mean temperature and ocean temperatures have been rising since the mid-1900s as a result of increases in anthropogenic emissions of greenhouse gases (CSIRO 2011). The dry conditions over parts of Australia are associated with changes to Pacific and Indian Ocean circulation and atmospheric pressure systems, such as the shift of storm tracks towards the South Pole (Nicholls 2009). Climate models indicate that such changes to circulation are likely to intensify and become more persistent in future as climate continues to change. As a result, the majority of climate models project a drier future for southern Australia (Chiew and Prosser 2011) than was experienced last century.

Nicholls (2008) raises the possibility that climate change is increasing the severity of Australian droughts by raising temperatures and hence increasing evaporative demand.

Gallant and Karoly (2010) examined concurrent temperature and rainfall extremes and reported an increase in the extent of hot and wet extremes and a decrease in the extent of cold and dry extremes annually and during all seasons from 1911 to 2008. These trends mostly stem from changes in tropical regions during summer and spring.

Many parts of Australia experienced severe floods in early 2011. The extreme rainfall arose from one of the strongest La-Niña events on record (Section 1). The specific contribution of climate change to such individual events is difficult to assess, as described in Section 1. Greater sea surface temperatures that result from climate change, however, tend to increase the amount of moisture transported from the ocean to the atmosphere. A warmer atmosphere is likely to increase the intensity of extreme rainfall events in general but assessing the extent to which individual extreme rainfall events can be attributed to anthropogenic climate change is very difficult (see Section 1, Appendix A3).

2.2 Impacts of climate change on river flows

Australia has highly variable rainfall, which is amplified into even more unreliable runoff into rivers (Peel *et al*. 2004).

The relationship between rainfall and runoff can change over time. The low rainfall in the southern Murray-Darling Basin and elsewhere in Victoria between 1997 and 2009 led to large declines in runoff and therefore river flows (more than 50 per cent in some areas, Fig. 2.2) (Potter *et al*. 2010). Other factors that have contributed to the large decline in the recent runoff during drought include: the disproportionate rainfall decline in autumn resulting in dry soil conditions at the start of the runoff season; rainfall decline in winter when most of the runoff occurs; the lack of high rainfall years and events in the past decade; and higher temperatures driving greater evaporation (CSIRO 2010).

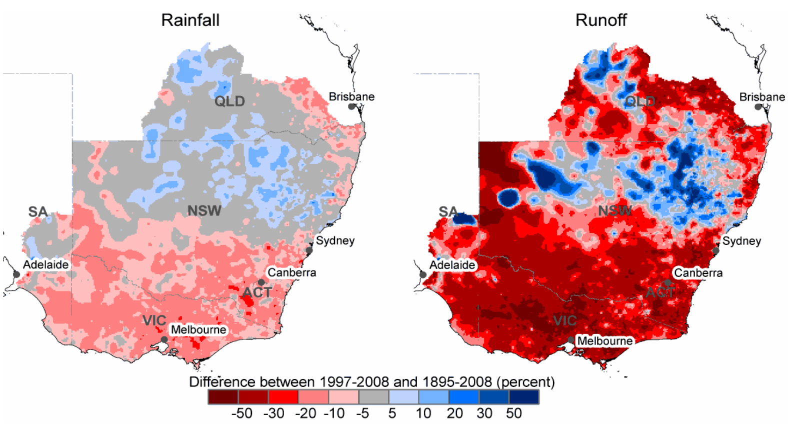

Fig. 2.2 Percentage difference between recent (1997–2008) rainfall (left) and runoff (right) in south-eastern Australia and the long-term (1895–2008) averages (CSIRO, 2010).

This amplification of the rainfall changes into changes in runoff explains why the impact of climate change on water resources is such a concern. It means that small reductions in rainfall lead to much larger reductions in available water resources, as has been experienced in south-western and south-eastern Australia. This amplification also makes the accurate prediction of climate change impacts more difficult because both the extreme and the average hydrologic conditions are important (Chiew and Prosser 2011). Reliability of water supply depends on sequences of reservoir inflows over several consecutive years, while floods and recharge to groundwater systems (Crosbie *et al*. 2010) are dependent on large rainfall events.

Fig. 2.3 shows the modelled range of change in the average annual runoff (and hence river flow) for a 1°C global warming (median warming by 2030 relative to 1990) across Australia. River flows in far south-western and south-eastern Australia are likely to decline in the future by 5-30 per cent or as much as 30-50 per cent under the driest projections.

The median runoff starts to appear similar to the extreme dry conditions of 1997-2009 if the median projections continue to 2070 or if the dry extreme projections to 2050 occur. The experience of the last decade shows that such a reduction would have a significant impact on water use and on river ecosystems, especially if additional droughts are superimposed upon that new median underlying condition (Chiew and Prosser 2011).

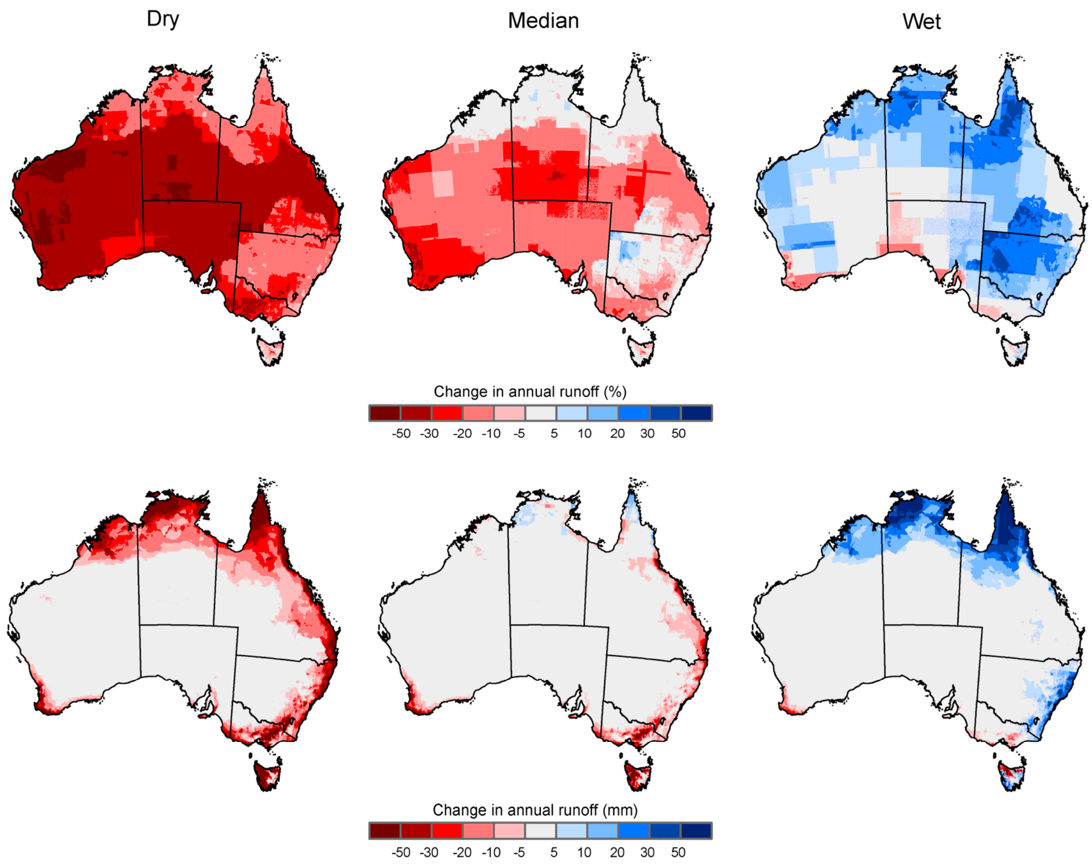

Fig. 2.3 Change in average annual runoff for a 1°C global warming (~2030 relative to ~1990) across Australia. The top row shows percentage change and the bottom row shows change in runoff depth (mm). The 50th percentile is the median estimate and the 10th and 90th percentiles give, respectively, the dry and wet range of estimates (Teng et al. in prep. 2010; CSIRO 2010; Post et al. 2009; Petheram et al. 2009; Silberstein et al. 2010).

2.3 Climate change and water availability

Climate change is likely to reduce the long-term average water availability in southern and eastern Australia where most of the population lives. Long droughts similar to that experienced recently are likely to occur more frequently. A warmer climate will also increase potential evapotranspiration, which will raise the demand for water in irrigated agriculture, cities, and by wetlands and other water-dependent ecosystems. Thus, climate change will not only reduce water availability in these regions but also will increase the gap between supply and demand. Climate change will intensify the water scarcity challenge facing our cities and intensify the often competing needs of water for agriculture and for natural environments in rural catchments (Chiew and Prosser 2011).

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3. BUILDING A NATIONAL CAPABILITY IN CLIMATE AND EARTH SYSTEM SIMULATION

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The need to understand and predict the future state of our planet was highlighted in the recent work of the Australian Academy of Science plan (Gifford *et al*. 2010). The evolution of our planet under a number of human and natural pressures is far from clear. A coherent approach covering the physical sciences, socio-economics, and humanities is required to first understand these pressures and their interconnected nature — including those associated with human induced changes — and to develop a sustainable and resilient way forward. This is known as Earth system science (see Reid *et al*. 2010, Nobre *et al*. 2010).

Climate modelling forms an important component of an Earth system approach. It is the basis for the development of climate projections. At the most basic level, a global climate model (GCM) is a numerical model that simulates the interactions between the main elements of the climate system: the atmosphere, the land surface and biosphere, the ocean and cryosphere. The model comprises equations that represent the fundamental physical processes involved. A more comprehensive Earth System Model (ESM) would include the full chemical and biogeochemical processes as well. The GCM or ESM is integrated forwards in time, typically in short (~15-minute) time-steps over a global grid for a period of months, years or centuries, to simulate daily weather and average climate patterns.

To address issues beyond the biophysical climate and weather system, Integrated Assessment Models (IAMs) (Proctor 1998) are employed to include the human system by considering demographic, political and economic variables. IAMs include simpler climate modelling but in a framework that enables the interaction between the climate and the human system to be assessed and, more specifically, to inform policy and decision makers.

Australia has recognised an ongoing demand for climate projection capability and the need for a national approach to climate and earth system modelling. A project was commenced in 2006 to develop the "Australian Community Climate and Earth System Simulator" (ACCESS), the next generation of Australian climate and earth system simulation capability. The vision is for ACCESS to be an internationally-competitive, fully coupled Earth system model that provides a consistent and national approach to weather and climate prediction and model development.

The Australian partners in this project are the CSIRO and the Bureau of Meteorology through CAWCR and participating Australian universities including the ARC Centre of Excellence for Climate System Science. Significant international collaboration is underway including work with the UK Meteorological Office's Hadley Centre and the Geophysical Fluids Dynamical Laboratory in the USA.

Consistent with the current paradigm in Earth System Modelling, ACCESS provides a unified approach to national weather prediction and climate projection capability, spanning the range of timescales from weather prediction over hours to days, through seasonal prediction, to climate change projection on centennial time scales. In this way, gains and expertise realised at one time scale are exploited or available for use at all time scales, all within a common approach to infrastructure development. The common approach also enables national expertise that resides in a number of organisations to contribute directly to the development of a national approach. This is required given the complexity of the earth system modelling task.

ACCESS already supports the Bureau of Meteorology in the provision of meteorological services and is being developed to meet the national demand for seasonal prediction, which is needed for natural resource management and agriculture, and the longer-term climate projections needed to underpin climate impact and adaptation work. ACCESS also will allow Australia to support the Assessment Reports of the Intergovernmental Panel on Climate Change through the provision of appropriate climate projections.

The components of the initial ACCESS coupled model include the atmosphere, ocean, sea ice and land surface. Components for the carbon and other key biogeochemical cycles, and for atmospheric chemistry, are to follow. Eventually, the ACCESS system will be linked to IAMs to support the modelling of socio-economic processes and to facilitate the investigation of coupled climate and socio-economic feedbacks.

Both global and regional climate modelling are in scope for ACCESS, with the global modelling having the initial priority to facilitate participation in the IPCC Fifth Assessment Report. The scope of activities planned for ACCESS over the medium term (three-five years) is summarised in Fig. 3.1. Resourcing to support this scope of activities and applications remains a significant challenge.

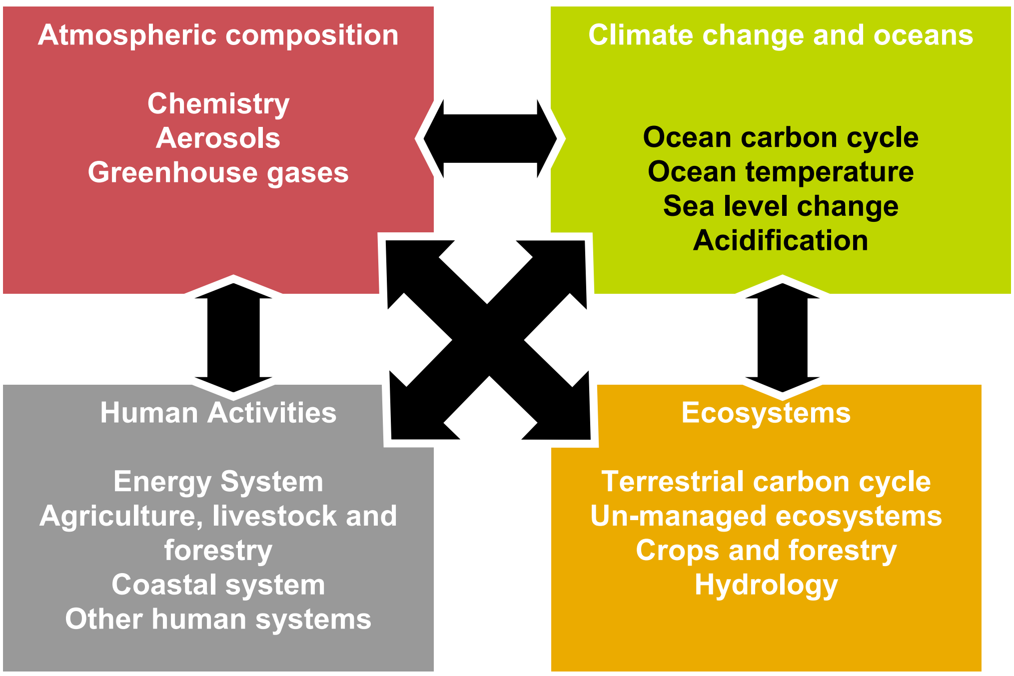

Fig. 3.1 Conceptual representation of the main components of a mature Earth System Modelling framework.

Significant progress has been made to date with ACCESS. The weather prediction version of the ACCESS model was introduced by the Bureau of Meteorology during 2010 to provide its operational numerical weather prediction capability. This upgrade has provided significant improvement in the predictive skill of weather forecasts over Australia.

Understanding and predicting climate variability is a significant national issue as the recent transition from drought to floods in eastern Australia demonstrates. Climate variability, whether due to natural variability or anthropogenic influences, can rapidly realise regimes expected under projected climate change scenarios. Obtaining skill in such predictions on both seasonal and decadal time scales remains a significant national challenge with large potential impact. Advances in dynamical multi-week and seasonal predictive capability via the Predictive Ocean Atmosphere Model for Australia (POAMA) are likely by 2015. The first realisation of an ACCESS-based POAMA for seasonal prediction is planned by 2011. The task of building a decadal prediction capability is more challenging and will require more time and resources.

ACCESS will also provide the modelling framework needed to support environmental monitoring and prediction including the carbon and water cycle. This capability is still developing and significantly more work is required through such activities as the National Plan for Environmental Information (NPEI).

Our contributions to national and international Earth system monitoring capability remain of paramount importance for all of these systems. The World Meteorological Organization (WMO) and Global Earth Observation System of Systems (GEOSS) provide important frameworks of which Australia is part. Nationally, however, it is essential that we integrate developing ESM with observation inputs associated with the National Collaborative Research Infrastructure Strategy (NCRIS) Terrestrial Ecosystem Research Network (TERN) and Integrated Marine Observing System (IMOS), as well as observation streams from other national and international sources. Enhancing our national earth monitoring capability through such initiatives as the Australian space research program also is important to effective progress (see Section 12).

The international climate modelling program supporting the IPCC AR5 is the Coupled Model Intercomparison Project phase 5 (CMIP5). CMIP5 is designed as a five-year scientific program beginning in 2011 to study the output of coupled ocean-atmosphere GCMs. It provides a community-based infrastructure in support of climate model diagnosis, validation, intercomparison, documentation and data access. The CMIP5 program will accept new model output throughout its life (2011–2015) but only that accepted by the end of 2011 will be likely to be used as part of the IPCC AR5. CMIP5 features a clearly defined experimental protocol including a set of required climate change simulations and model diagnostic experiments and a rigorous standard of model output data variables and format. The aim for ACCESS is to submit model output data to CMIP5 in 2011 from the initial ACCESS coupled model, in time for use by the IPCC AR5. Output from a subsequent version of ACCESS, including the key biogeochemical cycles, is planned to be submitted to CMIP5 in 2012-2013.

The CMIP5 model output data will be distributed to model analysts via the Earth Systems Grid (ESG), which comprises a network of major computer and data storage facilities around the world. The Australian ‘node’ of the ESG will be at the National Computational Infrastructure (NCI) facility located at the ANU, Canberra.

Supercomputer power is a significant challenge confronting national Earth system modelling. Significant ACCESS coupled model simulations are conducted at NCI and the processed model output data, both for CMIP5 and otherwise, will be placed on the node there for ready access by the Australian research community.

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4. OCEANS

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The oceans influence climate by storing and transporting vast amounts of heat and carbon dioxide. The warming of the oceans accounts for more than 90 per cent of the extra heat energy stored by the earth system over the last 50 years (Arndt et al. 2010). Ocean warming also contributes to sea-level rise, through thermal expansion. The oceans have absorbed about 25 per cent of human emissions of carbon dioxide, acting to slow the rate of climate change. This dominant role of the ocean in the planet's energy and carbon budgets means that any changes in the ocean have a significant influence on the earth's climate and sea level.

4.1 Ocean heat content

Recent analyses of ocean observations (Domingues *et al*. 2008; Isshii and Kimoto 2009; Levitus *et al*. 2009) have confirmed that the ocean has warmed in recent decades (Fig. 4.1). This ocean warming has now been observed over the full ocean depth and not just in the upper several hundred metres (Purkey and Johnson 2010). The warming trend has continued over the last fifteen years (Lyman *et al*. 2010). The increase in ocean heat content since the 1950s is not smooth but rather is characterised by periods of weak cooling or stasis and periods of warming (Fig. 4.1). Some of this variability is due to large volcanic eruptions (causing global cooling) or El Niño events, but the variability is not yet fully understood. Despite this, the growth in ocean heat content in fifteen-year periods is nevertheless robust since 1950.

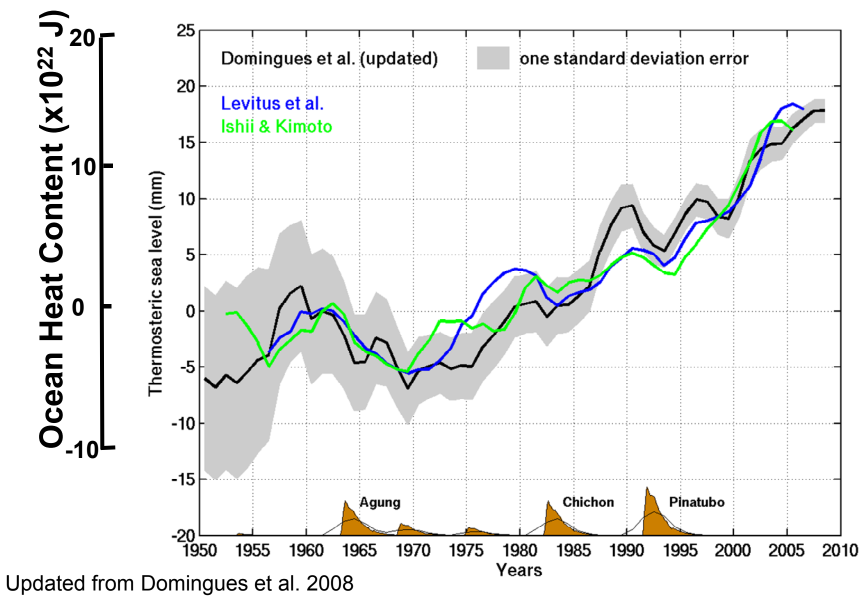

Fig. 4.1 Updated estimates of changes in upper ocean heat content relative to 1970. The time series updated by Domingues et al (2008) is shown in the black line, with one standard deviation uncertainty estimates shown by the grey shading. Uncertainties are reduced for recent years because of more numerous and accurate observations of ocean temperature. Volcanic eruptions are indicated along the x-axis.

4.2 Ocean salinity

Ocean salinity patterns are controlled by evaporation and precipitation, ocean circulation, and the formation and melting of sea ice and glacial ice. Ocean salinity can provide a clearer signal of changes in precipitation or evaporation than many land-based records because the ocean tends to smooth out short-term variability related to weather patterns. Ocean salinity therefore provides valuable information about changes to the Earth's hydrological cycle.

Several new global estimates of changes in ocean salinity have become available since 2008 (e.g. Durack and Wijffels 2010; Roemmich and Gilson 2009; von Schuckmann *et al*. 2009; Hosoda *et al*. 2009). These recent advances have been enabled by the ongoing compilation and assembly of historical ocean observations and the implementation for the first time of global sub-surface salinity observations via the Argo float array (Freeland *et al*. 2010). While various approaches have been taken to mapping and estimating long-term change in the ocean, the magnitude and spatial patterns of salinity change in recent decades are remarkably robust: areas of high salinity have become saltier, while areas of low salinity have become fresher. Changes are generally largest near the ocean surface and weaken with depth, becoming small near 2000 m except in the Atlantic, where significant changes in salinity occur down to 2000 m, and in dense waters formed near Antarctica, which have freshened since the 1970s (Rintoul 2007; Jacobs and Giulivi 2010).

The robust changes observed in ocean salinity are consistent with an intensification of the Earth's hydrological cycle over the past 50 years, with increased evaporation in the subtropics and increased precipitation at higher latitudes. The salinity changes observed below the ocean surface largely reflect the sinking of surface waters whose properties have been changed by warming or changes in precipitation, evaporation or ice melt.

The ocean tends to integrate over short-term variability and therefore can often provide a clearer signal of longer-term change than other observations. On the other hand, the observational record from the oceans is often sparse or of limited duration. There is a crucial need to enhance the network of sustained observations of the ocean so that it is possible to track the evolution of climate change. These observations need to include temperature, salinity, oxygen, and carbon measurements, throughout the full water depth, as well as measurements of sea ice. Sustained observations of the oceans are particularly crucial to test and improve the climate models used to project future change.

4.3 Sea level

There has been a significant focus since the IPCC AR4 on rates of sea level rise and the future of the ice sheets, with many new publications. Summaries of sea-level rise issues and recent results can be found in Church *et al*. (2010), Church *et al*. (2008a, b), Nicholls and Cazenave (2010) and Milne *et al*. (2009). The most important results are introduced briefly below.

4.3.1 Past sea level changes

The conditions during the last interglacial (warmer) period (about 125 000 years ago) are a useful guide to what we might expect towards the end of the 21st century and beyond. Temperatures at that time were 3-5°C warmer than today and similar to what could be expected late in the 21st century if greenhouse gas emissions continue on a 'business as usual' path. Analysis of geological records indicates a 95 per cent probability that global sea-level peaked at least 6.6 m higher than today but it is unlikely (33 per cent probability) it exceeded 9.4 m higher than today (Kopp *et al*. 2009). The average rate of global sea level rise about that time is very likely to have exceeded 5.6 m/millennium but is unlikely to have exceeded 9.2 m/millennium (Kopp *et al*. 2009). A record in the Red Sea indicates higher rates of 1.6 ± 0.8 m/century (Rohling *et al*. 2008). Higher rates of rise may have occurred over shorter periods but it is not yet possible to definitively quantify these from the available data.

Sea-level rose rapidly at average rates of about 1 m/century for many millennia from about 20 000 years ago, near the time of the last glacial maximum, until about 7000 years ago. A recent estimate suggests the rates during this period were mostly less than 1.5 m/century but with peak rates as high as 2.6 m/century (99 per cent confidence) (Stanford *et al*. 2011). These results are lower than other estimates of up to 4 m/century (Clark et al. 2002), that the Review referred to in 2008. However, these conditions are probably not analogous to the 21st century sea-level change because of the much larger and lower-latitude ice sheets present at that time.

From about 7000 years ago, sea level rose much more slowly. The little available evidence indicates the rate of global sea-level rise was less than a few tenths of a mm/yr over the two millennia up until the 19th century (Lambeck et al. 2004; Kemp et al. 2009). From the 19th century to the present, an increase in the rate of rise is indicated by the few long-term tide-gauge records (Woodworth 1990), evidence from salt marshes (Kemp *et al*. 2009; Donelly *et al*. 2004; Gehrels *et al*. 2005, 2006, 2008), and the available sea level estimates (Church *et al*. 2006, Church and White 2011; Jevrejeva *et al*. 2006; Woodworth *et al*. 2009).

4.3.2 Recent results

The IPCC Third and Fourth Assessments (2001, 2007) and recent publications (e.g. Rahmstorf *et al*. 2007) indicate that the rate of sea-level rise is currently near the upper limit of the IPCC Third Assessment (TAR) estimates, and by implication the AR4 estimates (including the scaled-up ice discharge). This does not imply that sea level rise will continue to follow this upper limit. This observation has raised concern that the IPCC projections may be underestimates, especially given the current inability to adequately model the ice-sheets' responses to global warming. These concerns have led to the development of several "semi-empirical" models of sea-level rise (Rahmstorf 2007; Horton *et al*. 2008; Grinsted *et al*. 2009).

These semi-empirical models all give larger rates of rise during the 21st century than the AR4 projections, with upper values as high as 1.9 m from 1990 to 2100. Significant concerns have been raised about the robustness of these projections, however, on several grounds (Holgate *et al*. 2007; Schmith *et al*. 2007; von Storch *et al*. 2008; Lowe and Gregory 2010) and they should be used with caution.

Most of the observed rise in sea level since the 19th century has been attributed to thermal expansion of the ocean as the water has warmed. Recent results, however, indicate an increased contribution to sea-level rise over the last decade from grounded glaciers, ice caps (Cogley 2009), and the ice sheets (e.g. Velicogna 2009). In particular, discharge from glaciers and ice streams of the Greenland and Antarctic Ice sheets are showing signs of a dynamic response, potentially leading to a more rapid rate of rise in sea-level than can occur from surface melting alone. Using kinematic constraints, Pfeffer *et al*. (2008) estimated that sea-level rise greater than 2 m by 2100 was not physically possible and that a more plausible estimate was about 0.8 m, more consistent with the upper end of the IPCC estimates and the present rate of rise. This value still requires a significant acceleration of the ice-sheet contributions compared to current rates of ice sheet loss.

A recent comprehensive study exploring high-end climate change scenarios and their implications for flood protection in the Netherlands (Vellinga *et al*. 2009; Katsman *et al*. 2011) suggested global-averaged sea level may rise by 0.55 to 1.1 m by 2100.

Observations show that sea level continues to rise, with the average rates since 1993 about 3.2 ± 0.4 mm/yr (Church and White 2011).

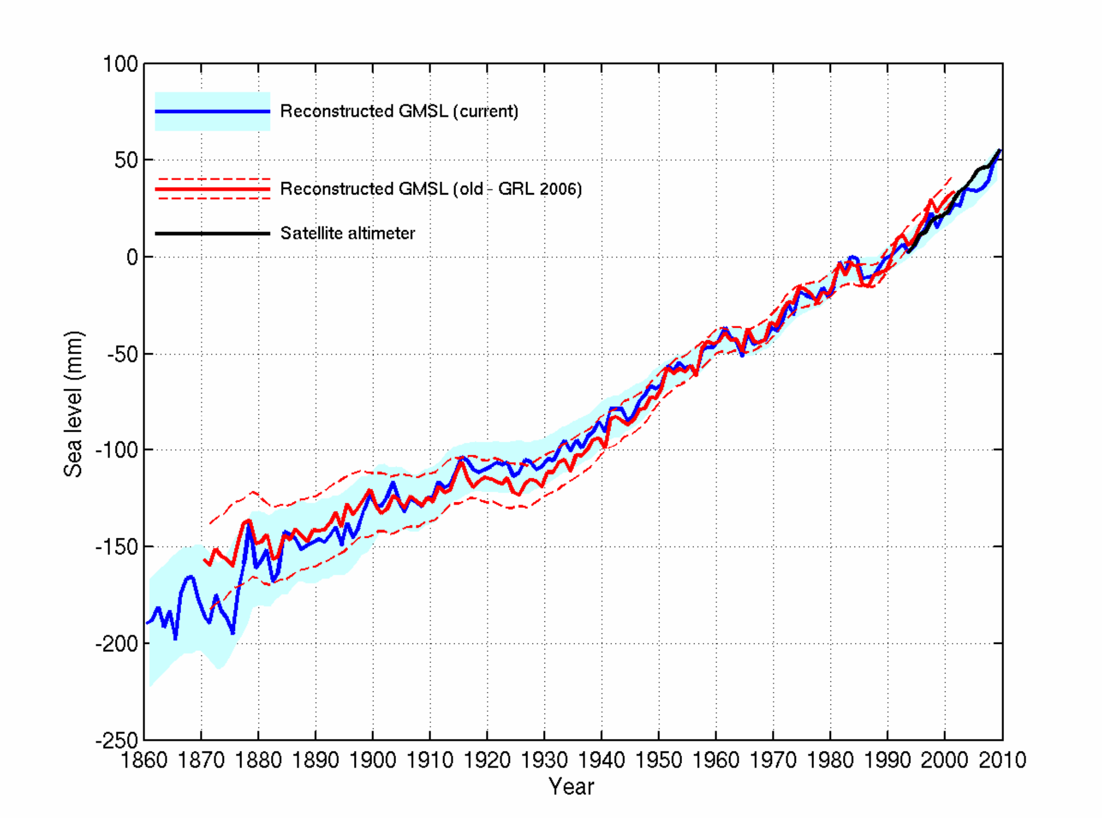

Fig. 4.2 Global averaged sea level changes since 1860, compared to 1990 average sea level. The blue line shows data from tide gauges and the red line shows sea level measured by satellite altimeters. The average rate of rise from 1900 to 2000 was about 1.7 mm/year. The rate of rise measured by satellite altimeters since 1993 has been about 3.2 mm/year and from tide gauges about 3.0 mm/year (from Church and White 2011).

4.3.3 The regional distribution of sea level rise during the 21st century

The regional distribution of sea-level rise is important because it is the regional or local sea-level change and local land motion that most directly affects society and the environment. Satellite-altimeter data show significant regional variations in the rate of sea-level rise, with some regions having experienced substantially larger rates than the global-averaged rate of rise since 1993. This regional variation in the relatively short altimeter record is at least partly a result of climate variability, however, particularly in the equatorial Pacific Ocean. Such climate variability and its consequences for local sea levels will continue during the 21st century. Model projections of long-term regional rates of sea-level rise differ significantly among various climate models (Pardeans *et al*. 2010; Yin *et al*. 2010).

In addition to changes in ocean conditions, changes in the mass of the ice sheets, glaciers, and ice caps also influence the regional distribution of sea-level rise through corresponding changes in the Earth's gravitational field and the elastic movement of the Earth's crust (Mitrovica *et al*.

2001, 2009). As a result, the contribution from the ice sheets results in a lower relative sea level and possibly a sea-level fall near decaying ice sheets and a larger than the globally averaged rise (up to about twenty per cent) far from the decaying ice sheets, including around Australia and for many of our Pacific neighbours.

4.3.4 Sea-level rise beyond 2100

It is important to recognise that the oceans and the ice sheets take a long time to respond to changes in climate and that sea-level rise will continue for centuries after 2100 as a result, irrespective of what mitigation measures we take in the interim. The Antarctic and Greenland Ice Sheets are the biggest concern for longer term sea-level rise. The area and mass of melt from the Greenland Ice Sheet, which contains enough water to raise sea level by about 7m, continues to increase (Hanna *et al*. 2008; Mote 2007; Tedesco *et al.* 2011). Recent model simulations have indicated that at least a partial melting of the Greenland Ice Sheet may be essentially irreversible (Ridley *et al*. 2010), with the amount of reduction in ice sheet mass depending on the degree of warming experienced over coming decades and centuries.

4.3.5 Extreme events

Observations indicate that there has been a significant increase in the frequency of extreme high sea levels around Australia (Church *et al*. 2006, 2008b) and globally (Menendez and Woodworth 2010). Rising sea levels will continue to increase the frequency and intensity of coastal flooding events during the 21st century. Methods for assessing the risk of these extreme events on coastal infrastructure have recently been developed (Hunter 2009).

4.4 Ocean acidification

The ocean is a critical sink for anthropogenic CO_2 emissions, removing about 25 per cent of the global CO_2 emissions and slowing the rate of global warming (see Section 6). As the ocean takes up anthropogenic CO_2 emitted to the atmosphere (see Section 7), profound changes in seawater chemistry occur. As these changes continue to alter ocean biogeochemistry, there is mounting concern for the ensuing impacts on marine organisms and ecosystems.

Ocean acidification is the term used to describe the decrease in seawater pH that occurs in response to rising CO_2 in the ocean. The seawater chemistry changes associated with the decline in pH are well known. The average surface-ocean pH, which is currently close to 8.1, has already fallen by 0.1 units since the beginning of the industrial era, a 30 per cent increase in acidity. It is likely to decline by another 0.2 to 0.4 units by the end of this century, a further increase in acidity of about 100 per cent (Raven *et al*. 2005; Orr *et al*. 2005; Caldeira & Wickett 2005).

Ocean acidification is occurring at an unprecedented rate and magnitude due to anthropogenic CO_2 emissions to the atmosphere. The projected surface ocean pH at the end of this century will be at its lowest level in more 30 million years (Pelejero *et al*. 2010). Large regions of the surface ocean to the south of Australia will become corrosive to calcium carbonate structures if the ocean continues to acidify as atmospheric CO_2 increases beyond 450 ppm (McNeil and Matear 2008).

Ocean acidification affects marine organisms that use carbonate to build shells or skeletons. For example, the acidification of the ocean will make it more difficult for coral's reef building organisms to calcify (Hoegh-Guldberg *et al*. 2007), hence adversely affecting coral ecosystems that support about 25 per cent of the world's biodiversity. Likewise, economically important shellfish such as oysters will display reduced growth under acidifying conditions (Parker *et al*. 2009). Observations are already showing that the ability of organisms to calcify has declined with the present level of acidification (De'ath *et al*. 2009; Moy *et al*. 2009). Such effects will only increase and become more widespread in future as CO_2 levels in the atmosphere increase (Silverman *et al*. 2009).

Present research on the biological impacts of ocean acidification is focused on calcifying organisms because of the strong link between ocean pH and calcification (Cohen and Holcomb 2009) but other significant impacts also will occur. For example, many physiological processes such as reproduction are influenced by pH, meaning that ocean acidification has the potential to affect reproductive success of many marine species. A recent study also showed that the ability of fish to navigate was compromised as the ocean acidifies (Munday *et al*. 2009). Synergistic effects of ocean acidification with other environmental changes associated with global warming also may occur. For example, a recent study showed ocean acidification reduces the thermal tolerance of coral to bleaching (Anthony *et al*. 2008).

It is not known how various marine organisms will adapt to the acidification of the ocean. Current knowledge suggests that there will be ecological winners and losers (Hendriks *et al*. 2010) causing shifts in the composition and function of marine ecosystems (Fabry *et al*. 2008). More information is needed to fully understand and address the threat ocean acidification poses to marine ecosystems and the services they provide. Australian efforts could accelerate by developing a national program, in line with other developed countries to tackle this emerging issue.

Australian research into ocean acidification needs to evaluate the potential impacts of ocean acidification by:

- Understanding the processes affecting the acidification in coastal waters;
- Understanding the physiological mechanisms by which biological organisms respond to acidification;
- Assessing the potential for acclimation and adaption to acidification by marine organism;
- Investigating the responses of individual organisms, populations and communities to acidification
- Understanding the whole of ecosystem consequences of ocean acidification;
- Investigating the cumulative effects of multiple stressors of global warming and ocean acidification on marine organisms;
- Understanding the implications of ocean acidification for biogeochemical cycles and ecosystem services;
- Understanding the socioeconomic impacts of changes in marine ecosystems caused by ocean acidification and the implications for management decisions.

A national network of chemical and biological observations is needed to monitor changes in ocean conditions attributable to acidification. Existing observations were not originally designed to tackle this issue and future observations will need to be tailored to provide key measurements (e.g. ocean carbon parameters) and target ecosystems vulnerable to ocean acidification (e.g. coral reefs).

International collaboration is critical to success because of the global nature of the problem, the diverse range of ecosystems affected and the difficulty in projecting how the whole ecosystem will respond to ocean acidification.

4.5 Surface wind-waves

Coastal impacts of climate change received considerable attention in the IPCC's Fourth Assessment (2007) although the focus was on the influence of sea level rise and inundation effects. The IPCC recognised that risks to coastal population, infrastructure and ecosystems require inclusion of a broader range of coastal drivers of change. Surface wind-waves were recognised as one of eight key drivers in the coastal zone, but received insufficient attention in the IPCC AR4 of observed historical change, and assessments of projected change. It was noted that more information was required on projected wave conditions if the effects of climate change on coastal erosion were to be assessed. Since the IPCC AR4, increased research effort has been aimed at assessing the relatively short observational wave record, and projecting future wave climate under climate change scenarios.

4.5.1 Past wind-wave changes

The IPCC AR4 reports statistically significant positive significant wave height (SWH) trends of order 1 cm/decade over the period 1950 to 2002 for most of the mid-latitudinal North Atlantic and North Pacific, as well as in the western subtropical South Atlantic, the eastern equatorial Indian Ocean and the East China and South China Sea. Negative SWH trends of order 0.5 cm/decade were reported around Australia and for parts of the Philippine, Coral and Tasman Seas. Information is predominantly from Voluntary Observing Ship data (Gulev and Grigorieva 2004). Further studies since AR4 assessing approximately 20-year records from in-situ buoys and satellite altimeter measurements have provided further confirmation of previously reported trends. These trends show strong regional variability.

Palaeo-wave climate changes have been considered in recent studies. Goodwin *et al*. (2006) interpreted late Holocene evolution of a section of the east Australian coast as responding to fluctuations in mean wave direction, oscillating between south-south-easterly and east-south-easterly directions over centennial time-scales.

Analysis of reliable long-term trends in the wave record remains a challenge due to limited in-situ data and problems of temporal in-homogeneity in reanalysis products, particularly in the Southern Hemisphere. Hemer *et al*. (2010a) assessed available in-situ buoy and satellite altimeter records (each of approx 25-year duration) and the 45-year ERA-40 waves reanalysis data and found the southern hemisphere wave climate was significantly correlated to the Southern Annular Mode (SAM). Larger, more southerly waves were observed in the mid-latitudes during positive SAM anomalies. Trends in SWH derived from satellite data over 1998-2001 relative to 1993-1996 were positive only over the Southern Ocean south of 45°S, whereas reanalysis trends were positive across most of the Southern Hemisphere. An in-situ buoy situated on the west coast of Tasmania records no statistically significant trend in frequency of wave events exceeding the 98^{th} percentile over the period from 1985-2002, whereas a strong positive trend was found in equivalent fields from the ERA-40 reanalysis (Hemer 2010). Positive SWH trends are reported in the northern hemisphere ocean basins, predominantly associated with increasing intensity and frequency of hurricanes in those regions (Komar and Allan 2008; Menendez *et al*. 2008; Adams *et al*. 2008; Sasaki *et al*. 2005).

4.5.2 Projected wind-wave changes

Since the IPCC AR4, several studies have investigated the potential climate driven change in wind-waves, using both dynamical downscaling (Derbenard *et al*. 2002; Andrade *et al*. 2007; Debenard and Roed 2008; Grabemann and Weisse 2008; Lionello *et al*. 2008; Mori *et al*. 2010; Wang *et al*. 2010) and statistical approaches (Wang and Swail 2006; Caires *et al*. 2006; Wang *et al*. 2010), on both global and regional scales. These studies have shown strong regional variability in the sign and magnitude of projected trends but a relatively robust signal of an approximately 30 cm increase in mean SWH in the Southern Ocean and a 20-30 cm decrease in SWH in the mid-latitudes is projected over the 21st Century (Wang *et al*. 2009; Mori *et al*. 2010). These studies have several sources of uncertainty associated with climate forcing, climate model uncertainty, downscaling methods and wave modelling approaches, which to date are largely unquantified. Hemer *et al*. (2010b) proposed an internationally coordinated program with the aim of quantifying these uncertainties, which is being actively pursued.

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5. PALAEOCLIMATE

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Palaeoclimate studies continue to contribute to our understanding of how the climate system varied before reliable direct measurements of climate variables were made (such as temperature, precipitation, atmosphere and ocean circulation, ice sheet extent). They enable assessment of the key factors that have driven climate (such as solar output, concentrations of greenhouse gases and aerosols in the atmosphere) and the associated climate responses. Palaeoclimate data also provide a basis for the evaluation of how well models of climate and biogeochemistry simulate conditions of past decades to millennia, improving their ability to project into the future.

5.1 Gases

The prominent variations in atmospheric CO_2 concentrations (between about 170 and 300 ppm) that parallel the periodic climate changes of the past 800,000 years have been closely tied to Antarctic temperatures, which in turn indicate that the changes originated mainly in the Southern Ocean (reviewed by Fischer *et al*. 2010). Several processes contributed to these ocean-driven changes, including changing ventilation rates influenced by ocean and sea ice dynamics, changes in iron fertilisation of the ocean that limits primary production and associated CO_2 drawdown from the atmosphere, and changes in the chemical capacity of the ocean to retain dissolved CO_2 (Archer *et al*. 2000). A similar range of atmospheric CO_2 concentrations has been found extending back to 2.1 million years before present based on boron isotopes in foraminifera shells (Honisch *et al*. 2009), suggesting that present global CO_2 levels are higher than observed over at least the past 2 million years.

The historical record of atmospheric methane concentration also has been extended to 800,000 years before present (Loulerge *et al*. 2008) using Antarctic ice cores. Concentrations varied cyclically between about 800 ppb and 350 ppb, dominated by the 100 000 year cycle of glaciation and deglaciation and believed to have been controlled mainly by associated changes in wetland sources of methane.

Concerns have strengthened that large amounts of carbon in permafrost and hydrates (a stored source of methane) in the Arctic (Zimov *et al*. 2006; Tarnocai *et al*. 2009) might be released to the atmosphere as CO_2 and CH_4 as a result of warming. Such releases could cause a positive feedback in the climate system with accelerated warming leading to further melting of permafrost and release of hydrate-sourced methane which leads to further warming. These concerns have stimulated studies of past and present emissions from these sources. For example, Shakhova *et al*. (2010) observed recent CH_4 venting from the East Siberian Arctic Sea hydrates and Schuur *et al*. (2009) documented carbon losses from tundra in past decades. The rates are small relative to present net global emissions, however, and it isn't known whether the sources are new or simply newly observed (Petrenko *et al*. 2010; Kerr 2010). Methane locked up in hydrates and permafrost was found not to be the cause of the large and rapid increase in CH_4 concentrations during the warming at the end of the last glacial period 11 500 years ago (Petrenko *et al*. 2009). The increase in emissions at that time, previously considered to be an analogue for future climate-carbon feedbacks involving CH_4 hydrates, was likely to have been caused mainly by the growth of CH_4 emissions from wetlands as the planet warmed. This discovery suggests that hydrates may be less susceptible to warming than previously thought (Petrenko *et al*. 2009; Nisbet and Chappellaz 2009).

5.2 Climate

Global temperatures during the past 1000-2000 years have been reassessed from proxies by Mann *et al*. (2008) and Juckes *et al.* (2007). Previous conclusions from palaeoclimate studies (NRC 2006; Mann *et al*. 1998, 1999) have been confirmed, including that recent warmth is likely anomalous for the past 1300 years or more, at least in the northern hemisphere. Significant warming and cooling were found during the Medieval Warm Period and the Little Ice Age respectively, though global temperatures during Medieval times were below those of the past decade (Mann *et al.* 2009). Similar trends to these land-based temperature proxies have now been reconstructed for the tropical ocean (Oppo *et al*. 2009). Less definitive conclusions were found by Mann *et al*. (2008) for the Southern Hemisphere due mainly to sparser proxy data, but Southern Hemisphere and global temperatures were possibly similar to present during brief periods within the past 1500 years. Kaufman *et al*. (2009) found that the warming of the past century reversed a cooling trend in the Arctic over the last 2000 years driven by local summer solar radiation levels.

Proxies of past climate in the Australian region, particularly of temperature and precipitation, continue to be developed. These include the use of tree rings, speleothems, ice cores, corals, and sea and lake sediments (reviewed by Jones *et al*. 2009). The decline of southwest West Australian rainfall in recent decades has been linked to a regional Antarctic precipitation increase identified in ice cores, suggesting that it is the largest precipitation anomaly for the past 750 years (van Ommen and Morgan 2010). A 350 year record of rainfall from tree rings for this region also suggests that the dry period is longer than expected for natural variations (Cullen and Grierson 2009). A 300-year record of flood events obtained from luminescence bands in massive coral skeletons shows an increase in rainfall and rainfall extremes since the late 19th century (Lough *et al*. in press), consistent with multi-proxy evidence of ENSO variability (Braganza *et al*. 2009; Gergis and Fowler 2009).

Recent evidence of long term changes in the oceans (including sea level, acidity and wave climate) is discussed in section 4 (Church *et al*. this report).

5.3 Simulations

Greenhouse gas records over the past 2 millennia (MacFarling Meure et al. 2006), proxy evidence of other climate forcings such as volcanic and anthropogenic aerosols and solar output (Ammann et al, 2007; Foukal et al. 2006) and the proxies of temperature continue to provide major observational constraints with which to test global climate models and evaluate the influence of various factors driving climate variability and change. Simulations (for example, Tett et al. 2007; Wanner et al. 2008; Hegerl et al. 2007) reinforce earlier conclusions that natural drivers (volcanic aerosols, solar variations, orbital variations) and anthropogenic drivers (greenhouse gases and aerosols) of climate are required to explain the observed hemispheric and global temperature variations and that the greenhouse gas increases are the main cause of the warming over the past century.

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6. CARBON AND OTHER BIOGEOCHEMICAL CYCLES

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The recent trends in global and regional carbon sources, sinks and inventories, including the impact of land use change are highlighted. Recent major advances in understanding changes, and irreversibility in the carbon cycle, are also discussed.

6.1 Emissions from the combustion of fossil fuels and cement production

Global fossil fuel emissions continued to grow at two per cent per year during the decade Jan 2000 to Dec 2009 (Friedlingstein *et al*. 2010 and Fig. 6.1). This is close to the long-term average growth rate from 1950-2010. The global financial crisis (GFC) had a discernable effect in 2009, for which the growth rate was −1.3 per cent, compared to +2.0 per cent in 2008 and above +3 per cent for 2000 to 2007. It is estimated that 2010 will see a return to fossil fuel emissions growth rates above 3 per cent per year, following the trend of fossil fuel emission growth for the early 2000s.

Some of the major national rates of change in fossil fuel emissions for 2009 were as follows:

- Developed world: US −6.9%, UK −8.6%, Germany −7.0%, Japan −11.8 %, Russia −8.4%, Australia: −0.4%.
- Emerging economies: China +8 %, India +6.2%, South Korea +1.4%.

The top five emitters in 2009, in decreasing order, were China, USA, India, Russia, and Japan. Emissions from the combustion of coal have overtaken emissions from oil after over four decades of oil dominance, with coal contributing 40 per cent and oil contributing 36 per cent of emissions in 2009. This has led to a slowdown in the long term-trend of improvements in the carbon intensity of the global economy.

Country level fossil fuel emission data continue to improve but uncertainty for large emitters, such as China, can be as high as fifteen per cent.

6.2 Emissions from Land Use, Land Use Change and Forestry (LULUCF)

CO_2 emissions from deforestation and other non-urban land management activities decreased by over 25 per cent between the 1990s and the last ten years (Fig. 6.1), mainly due to reduced forest clearance in Brazil and Indonesia. LULUCF emissions accounted for about ten per cent of all anthropogenic CO_2 emissions in 2009.

The decrease in emissions due to land use change is also related to:

- New data availability on tropical forest regrowth, which has led to smaller estimates of net CO_2 flux into the atmosphere. This has been particularly important for South-East Asia.

- New land use management policies, particularly in Brazil, which have resulted in the slowdown of deforestation, accompanied by stronger controls on illegal logging in Brazil and Indonesia.

Established forests, including old growth forests, constitutes the dominant terrestrial carbon sink, indicating the importance of forest conservation to maintain current sink capacity (Luyssaert *et al*. 2008).

Global estimates of emissions due to land use change are becoming more robust but uncertainty remains large for individual tropical countries.

6.3 Natural carbon sinks and sources

6.3.1 CO2 sinks (land and oceans)

Oceanic and terrestrial reservoirs continue to absorb more than half of the total emissions of CO_2 (Fig. 6.1). A long-term decline in the efficiency of the natural CO_2 sinks, specifically in the Southern Ocean, is shown in recent studies (Le Quere *et al*. 2009) but there is scientific controversy over some of these results and so uncertainty remains as to the magnitude of the decline (see Section 8 for more detail).

Increased droughts globally, and particularly in the Southern Hemisphere, over the period from 2000-2010 limited global plant productivity from continuing to increase as expected (Zhao and Running 2010). The droughts in the Amazon in 2005 and 2010 were most important in limiting increases in plant productivity, and associated photosynthetic drawdown of CO_2 from the atmosphere.

6.3.2 Methane emissions

The concentration of methane has reached almost 1800 ppb. There was renewed annual methane growth in 2007 and 2008 after a decade of little change (Rigby *et al*. 2008). It is likely that changes in global temperatures were responsible for increased methane emissions from high latitudes and tropical wetlands (Bousquet *et al*. 2010 and Section 8).

6.4 Global carbon budget

Figure 6.1 shows the sources and sinks of CO_2 in the global carbon budget, based on observations and models, produced by the Global Carbon Project (2010). The y-axis shows the human perturbation to each of the budget terms from 1850 and the figures alongside the right-hand axis indicate the magnitude of each of the budget terms for the 2000 – 2009 period.

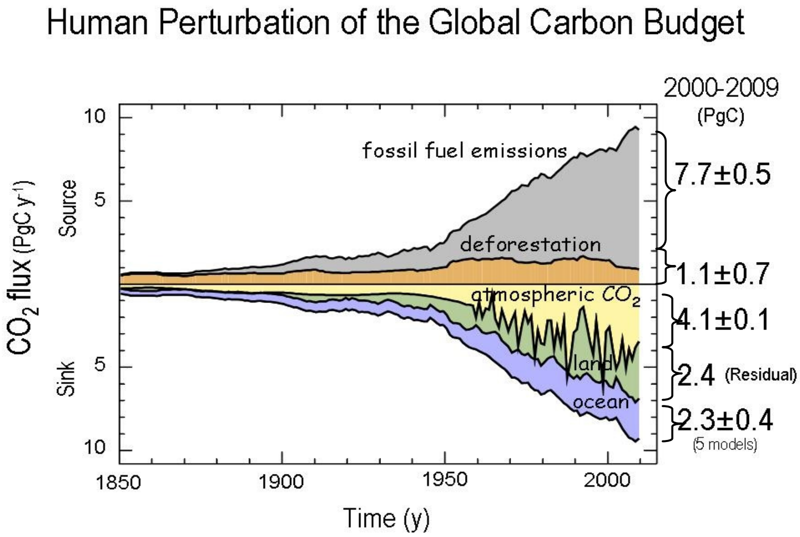

Fig. 6.1 All sources and all sinks in the global carbon budget. Values above the zero-line represent additional, anthropogenic inputs of CO_2, and values below the zero-line indicate the sinks for CO_2 (outputs) in the atmosphere, land and oceans. Units are in petagrams (Pg) of carbon per year. Source: Global Carbon Project, 2010.

The land and ocean CO_2 sinks combined to remove about 55% of the anthropogenic CO_2 emissions from 2000-2008 (Canadell *et al* 2007; Raupach *et al* 2008a; Le Quere *et al* 2009). The remaining 45% of anthropogenic CO_2 emissions accumulate in the atmosphere and is known as the airborne fraction (AF). An increase in this AF of about 5%, albeit with considerable interannual variability, has been observed over the period from 1960 to 2008 (Canadell *et al* 2007; Raupach and Canadell 2008b; Le Quere *et al* 2009). This suggests that the land and ocean CO_2 sinks are progressively 'losing the race' against ever more rapidly growing emissions, although uncertainty remains, as noted in 6.3.1. Several factors that are likely to cause this (Raupach *et al* 2008b), including the effect of stronger winds over the Southern Ocean causing the upwelling of deep, carbon-rich waters that release CO_2 back into the atmosphere. Importantly, the Earth's land and ocean sinks are diminishing in their capacity to soak up CO_2 emissions.

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7. GEOENGINEERING – CARBON CYCLE MODIFICATION

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The concept of geoengineering has received growing attention in recent years, partly due to the slow progress in reducing greenhouse gas emissions. Geoengineering is categorised broadly into actions that either remove CO_2 from the atmosphere by modifying the carbon cycle or that manage incident solar radiation. We have purposefully included carbon capture and storage (CCS) even though CCS removes CO_2 **before** it makes its way into the atmosphere rather than a technology that enhances the sequestration of CO_2 from the atmosphere.

Carbon cycle modification aims to reduce net CO_2 emissions to the atmosphere. This directly addresses the major source of anthropogenic climate forcing and, unlike solar radiation management, helps address the problem of ocean acidification.

7.1 Carbon capture and storage

Carbon capture and storage extracts CO_2 produced from fossil fuel energy or industrial processes, followed by storage into geological formations (Orr 2009) onshore or offshore, or in deep sea sediments (Schrag 2009). Storage directly in the ocean, where CO_2 can form deposits as liquid CO_2, solid CO_2-H_20 clathrates, or dissolve in seawater (Brewer *et al*. 1999, Warzinski *et al*. 2006), is becoming less likely due to questions of storage longevity and concerns about acidification and ecosystem impacts (Barry *et al*. 2004, Pörtner *et al*. 2005). Such storage is not allowed under international conventions, such as OSPAR, the Oslo and Paris Conventions for the protection of the marine environment of the North-East Atlantic. Storage of the captured CO_2 by forming minerals or by enhanced weathering also appears to have limited opportunities.

The recent IEA Technology Roadmap (IEA 2009) concludes that CCS will need to contribute 19 per cent of emissions reductions to reach a total of 50 per cent emissions reductions by 2050 under the most cost effective portfolio of solutions. Actual progress is slow, however, with mainly pilot scale projects or small scale operational projects being developed at well below the rate needed to make such reductions (Haszeldine 2009; Global CCS Institute 2009). Only about 100 MT CO_2 is likely to be stored globally by 2015. Limits to progress are less related to storage capacity and other technical matters than to commercial, regulatory, or public acceptance challenges (Haszeldine 2009). Both carbon pricing and enforced emission policies will be required to encourage CCS (Haszeldine 2009; Global CCS Institute 2009).

Difficulties in progressing significant CCS include costs, with capture costs currently dominating over storage, matching sink and source locations (Orr 2009), public confidence, regulatory matters, and concerns over storage longevity. Recent climate-carbon model simulations (Schaffer 2010; Enting *et al*. 2008) conclude that even gradual leakage from CCS stores could negate the long-term climate mitigation of CCS, though it would still help society to make the transition to a low carbon future (van der Zwaan and Gerlagh 2009). Developments in CCS regulation, legislation, and carbon accounting (such as its recent inclusion into the United Nations Framework Convention on Climate Change (UNFCCC) Clean Development Mechanism) are, in general, reducing the barriers for CCS to proceed internationally and in Australia (Global CCS Institute 2009).

There is renewed interest in post-combustion capture due to high costs of pre-combustion capture plants and the need to retrofit existing power plants with CCS technology (Haszeldine 2009). Some energy-related activities such as natural gas production and geothermal plants provide CO_2 streams that are already amenable to geological storage (e.g. Gorgon project in Western Australia).

Direct air capture followed by geological storage is often proposed as being able to remove the CO_2 already released to the atmosphere (Keith 2009). There are significant efficiency and cost challenges, however (Ranjan and Herzog 2011), mainly associated with capturing the CO_2 after it has been diluted in the atmosphere rather than in a more concentrated form at the point of emission.

Biological energy coupled with CCS (BECCS) offers greater potential for CO_2 sequestration (e.g. Gough and Upham 2010). Biological waste or purposefully grown products, such as algae, fix carbon from the atmosphere and can then be used as an energy source, displacing fossil fuel sources, with the produced CO_2 stored geologically.

Australian experience with CCS is mainly with the prominent CO2CRC Otway demonstration project (see http://www.co2crc.com.au/about/) and the three post combustion capture pilot plants, involving CSIRO with partners Loy Yang Power, Delta Electricity and Tarong Energy. The Gorgon project (CO2 removed from natural gas) will store 4 Mt CO_2 per year by 2015 and be the world's largest CCS project. In addition, a number of CCS projects have been proposed under the Australian Government's Clean Energy Initiative.

7.2 Enhancement of ocean CO_2 uptake

A wide range of options for enhancing ocean CO_2 uptake have been proposed, including chemical, biological, and physical approaches. A brief digression into the nature of CO_2 storage in the ocean helps to explain and differentiate these options, particularly their long and short term effects.

The dominant form of CO_2 in the ocean is as total dissolved inorganic carbon dioxide (DIC) and not as organic carbon within biomass or detritus, in contrast to terrestrial systems. The total DIC in the ocean is the sum of three inorganic forms, H_2CO_3, HCO_3^-, and CO_3^{2-}, with the second bicarbonate ion form dominating. The conversion of CO_2 into anionic forms by reaction with seawater is the reason that most CO_2 is in the ocean, in contrast to other gases for which the atmosphere is the largest reservoir. The conversion happens because seawater is slightly alkaline, owing to the chemical composition it acquires during the weathering of continental and oceanic rocks. Increasing the alkalinity of seawater is thus a possible way to chemically store additional CO_2 in the ocean. Proposals have included passing the emissions from power plants through seawater amended with crushed limestone (Rau and Caldeira 1999; Caldeira and Rau 2000), and direct supply of limestone into the ocean, although the latter must be done at depth. The addition of more basic compounds such as calcium oxide (lime) also has been proposed by the entity *Cquestrate*, with some funding by Shell Oil (www.Cquestrate.com). This chemical approach has the advantage that it would sequester for many, many millennia owing to the long residence time of calcium in seawater. The main challenge is the large amount of limestone required – similar to the amount of petroleum emissions that would be offset – and the associated requirement for large infrastructure. The process is probably feasible for nations such as Australia, which have abundant limestone adjacent to CO_2 emission sources and coasts (Rau and Caldeira 1999), although costs may exceed those of conservation or alternate energy generation.

Most biological approaches contrast to this chemical approach because rather than increasing the total solubility of CO_2 in the sea, they instead depend on driving the CO_2 content of the surface ocean to below atmospheric values (to allow CO_2 to move into the ocean), and accept higher than atmospheric levels in the deep sea (where it is isolated from the atmosphere). The depth gradient is driven by photosynthetic conversion of CO_2 into biomass at the surface followed by particles sinking and bacterial respiration back to CO_2 at depth; a process that already maintains atmospheric CO_2 well below what it would be without this "biological pump" (Sarmiento *et al*. 1988). Addition of nutrients could stimulate the biological. The amount of nutrient supplementation required ranges from trace levels of the micro-nutrient iron in the Southern Ocean and a few other regions where the main plant macro-nutrients (nitrogen and phosphorous) are naturally abundant, to much larger additions in other regions such as the subtropical gyres, where the pump already strips macro-nutrients to very low levels. Phosphorous availability in the sea restricts the additional carbon capture capacity catalysed by iron or nitrogen additions to about one gigatonne of carbon sequestered per year (Matear and Elliot 2004), with addition of sufficient phosphorous to go beyond this capacity appearing to be uneconomical.

Iron addition (fertilisation) is the best studied option, with more than a dozen such experiments already done, though many have been unclear about levels of deep ocean carbon sequestration and contributed limited understanding of ecological impacts because of their short duration (de Baar *et al*. 2005; Boyd *et al*. 2007). Some studies of naturally-fertilised regions suggest that iron does stimulate carbon sequestration and has generally benign ecological effects (Blain *et al*. 2007; Pollard *et al*. 2007). It is not yet known whether these results can be applied to proposed artificial iron fertilisation. Fertilisation-driven sequestration depends on the maintenance of the surface to deep DIC gradient and so its duration is linked to the residence times of the added nutrients in seawater. Residence times extend to millennia for phosphorus or nitrogen additions but only to decades for iron additions. Thus, iron fertilisation, once started, must be continued or the CO_2 will again be released to the atmosphere on the approximately centennial timescales of ocean mixing.

It has been suggested that stirring the ocean to bring nutrients to the surface could lead to increased primary production and associated photosynthetic carbon sequestration and possibly also the production of dimethyl sulphide (DMS), which could induce increases in cloud cover that might lead to atmospheric cooling (Lovelock and Rapley 2007). The efficacy of this approach is doubtful; however, for many reasons including that CO_2 would be upwelled along with the nutrients, uncertainty over whether upwelling would induce DMS production, and the requirement for very large scale deployment of structures in the ocean sufficient to provide significant stirring. Simulations with a climate model suggest that the approach would sequester little carbon in the ocean but might lead to lower atmospheric temperatures by mixing heat downward into the ocean. This in turn would slightly increase carbon sequestration on land by slowing respiration losses of fixed carbon (Oschlies *et al*. 2010). Overall, the mixing approach is perhaps best characterised as a heat-management rather than a carbon-management approach.

The potential ecological impacts of ocean fertilisation by either nutrient addition or nutrient translocation by mixing have not been evaluated in any detail. Concern over addition of macro-nutrients, such as urea, is particularly strong, owing to its links to deleterious impacts in coastal waters (Glibert 2008). Strong *et al*. (2009) state that the risks are too large even for iron fertilisation given its low potential capacity, though this view has been countered by others who note that no approach offers great capacity so that carbon management will need to involve many approaches, and so research on the risks of iron fertilisation needs to continue (Buesseler 2008).

The International Maritime Organisation via the London Convention and London Protocol on the Prevention of Pollution by the Dumping of Wastes in the Ocean proposed in 2008 a non-binding moratorium on ocean fertilisation activities other than research (Anonymous 2008a), and in 2010 agreed to an assessment framework for research until the possible impacts of ocean fertilisation are better understood (Anonymous 2010). The United Nations Convention on Biodiversity has proposed a similar halt (Anonymous 2008b). An introduction to regulatory and policy issues for Australia is available in Trull *et al*. (2008).

7.3 Terrestrial uptake

7.3.1 Biochar definition and uses

Biochar is the product of thermal degradation of organic materials in the absence of air (pyrolysis), and is distinguished from charcoal by its use as a soil amendment (Lehmann and Joseph 2009). Biochar production and use as a soil amendment has been suggested as a possible means to improve soil fertility and to sequester carbon to mitigate climate change and land degradation (Lehmann and Joseph 2009; Krull 2009; Cayuela *et al*. 2010; Sohi *et al*. 2009, 2010; Whitman *et al*. 2010). The production and application of biochar to soils needs to be viewed as integral to a system of bioenergy generation, biomass waste management, renewable energy generation and sustainable agriculture.

7.3.2 Federal funding for biochar research in Australia

The Australian government, through its Climate Change Research Program (CCRP), funded a 3-year "National Initiative for Biochar Research" project in 2009, led by CSIRO (http://www.csiro.au/science/Biochar-Overview.html). This project is investigating: a) important properties of biochar, as a function of feedstock and pyrolysis temperature, that affect agronomic and carbon sequestration processes; b) the relative stabilities of selected biochars in the soil environment; c) the effect of biochar on nitrous oxide (N_2O) emissions from soil (with a greenhouse gas equivalent of 298 times that of CO_2); d) assessment of the presence of potentially toxic substances in biochar; and e) a complete life-cycle assessment of climate change impacts of biochar production and application to soil (utilising production facilities in Australia). In 2011 the Australian government announced an additional Biochar Capacity Building Program with a greater emphasis on collaboration between landholders and researchers.

7.3.3 Biochar scientific advances since 2008

Since 2008, there has been a substantial increase in scientific studies of biochar for agricultural and/or carbon sequestration purposes, and in conjunction with bioenergy production. ISI publications with the term 'biochar' increased from 20 (2006 to 2008) to 140 for the two years (2009-2011) (not including books and book chapters and non-scientific articles).

The main advances in the scientific field are in the areas of:
- Differentiation between different biochar products and classifying their properties and intended uses and potentials for C sequestration
- Gaining understanding of the underlying processes that result in changes in agricultural productivity and soil carbon sequestration upon biochar application
- Quantifying stabilities of different biochars in soil as well as impacts of biochar on native soil carbon and interactions with pesticides

- Using life-cycle assessment methods to assess the greenhouse gas mitigation potential of biochar and inclusion of biochar in greenhouse gas (GHG) accounting frameworks

Recent studies have confirmed earlier reports that some biochars can increase crop yields significantly and that some biochars are stable in soil for decades, centuries and up to millennia. Woolf *et al*. (2010) estimated the global technical potential mitigation through biochar systems to be around 1.8 Gt CO_2-e, equivalent to about twelve per cent of current global emissions. 50 per cent of the 1.8 Gt CO_2-e reduction is derived from carbon sequestration, 30 per cent from replacement of fossil fuel energy, and 20 per cent from avoided emissions of CH_4 and N_2O. Recent studies have shown that crop yield responses to biochar can range from -30 to +200 per cent, however, thus indicating a wide range of possible responses. Biochar can bind to agrochemicals and nutrients and the possible negative effects of this need to be investigated; these are some of the few areas that require further investigation in order to confidently quantify biochar effects.

Some of the observed benefits of biochar additions to soil fertility have been explained mainly by a pH increase in acid soils, improved nutrient retention and changes to the soil biological community (Lehmann and Joseph 2009). The structure of biochar (high porosity, high adsorptive capacity) is thought to play a critical role. However, research has also recognised the vast differences between biochars produced from different organic materials, such as manures versus wood residues, and under different temperature regimes. Thus, a greater differentiation and targeted application of biochars to specific application and soil types are required. In the absence of long-term (decades) field trials, the stability of biochar currently has to be extrapolated through shorter-term (months to one-two years) incubation experiments and possibly with the use of radiogenic or labelled isotopes. Figure 7.1 illustrates that biochar properties are a function of feedstock and temperature and their use needs to be tailored to these properties. Stabilities of biochar differ widely according to feedstock and production temperature, similarly to the results gained from targeted studies investigating the agricultural effects of biochar. In general, the higher the production temperature and carbon content of the starting material, the greater the stability and longevity of the biochar product. Some biochars may not be suitable for long-term sequestration of carbon in soil but may serve as ideal amendments for enhancing agricultural productivity. For those biochars, suitable for carbon sequestration, residence times well in excess of centuries have been estimated (Lehmann and Joseph 2009).

Life-cycle assessment (LCA) is essential to determine whether biochar production and application in conjunction with bioenergy generation and waste management truly provide net climate change mitigation benefits. LCA takes into account greenhouse (GHG) emissions incurred through transport and storage as well as potential emissions through land use change (in comparison to the fossil fuel reference system). Roberts *et al*. (2010) concluded that certain biochar-bioenergy-crop systems have a net GHG emissions mitigation potential and that most of the emissions abatement is derived from carbon sequestration in biochar (around 64 per cent). However, currently the economic viability of biochar production and application depends on the costs of feedstock and pyrolysis, the impact on crop yield and fertiliser requirements, and the returns from renewable energy and emissions trading. Hence, in order for biochar to be adopted by the agricultural community and industry, its inclusion in a carbon reduction program needs to be ensured.

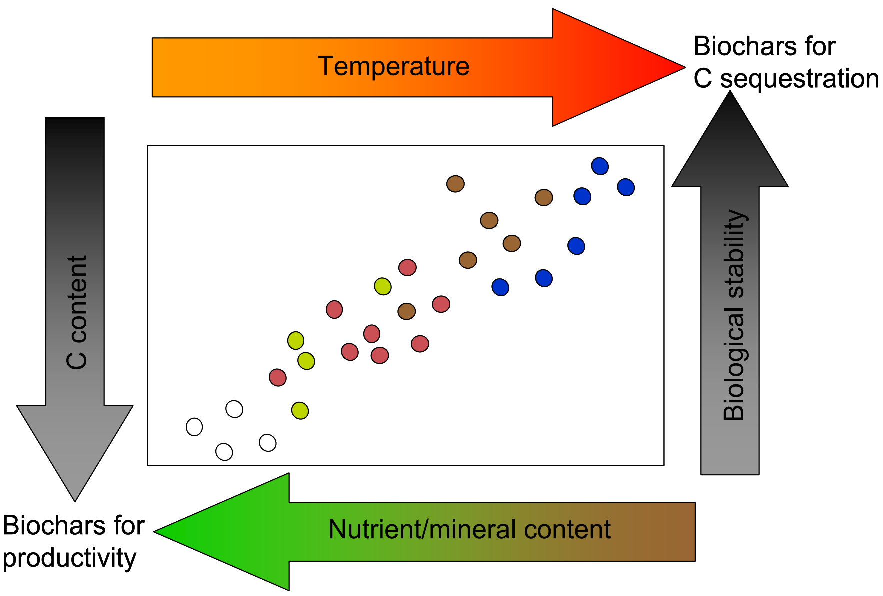

Fig. 7.1 Example of properties of biochars produced from different feedstocks (coloured circles) at different temperatures on carbon sequestration and productivity

7.3.4 International biochar organisation, research centres and climate change meetings

The international biochar community has been formalised since 2008 via the registration of the International Biochar Imitative http://www.biochar-international.org/ as a non-governmental organization (NGO). The Australian and New Zealand biochar researchers network also was founded in 2008 http://www.anzbiochar.org/about.html. Dedicated biochar research centres were founded in 2009 and 2010 in the UK and New Zealand respectively: UK Biochar research centre http://www.biochar.org.uk/ and the New Zealand biochar research centre http://www.biochar.co.nz/. Biochar has been included and has been discussed in UNFCCC meetings since 2008 and biochar was included in the agenda for the 2009 Copenhagen meeting.

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8. ATMOSPHERIC CONSTITUENTS AND RADIATIVE FORCING

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The climate change science, in relation to atmospheric constituents and radiative forcing, commented on in Garnaut (2008) was based on Chapter 2 (Forster *et al*. 2007) of the IPCC Fourth Assessment of Climate Change. The following provides an update to 2010 of some of the science of greenhouse gases and their impact on climate change.

8.1 Radiative forcing and the long-lived greenhouse gases

Table 2.1 of Chapter 2 of the IPCC Fourth Assessment provided long-lived greenhouse gas (LLGHG) concentrations and radiative forcings for 2005 and trends since 1998.

CSIRO has measured in the CSIRO-GASLAB at Aspendale, Victoria, the three biogenic LLGHGs, i.e. carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), from air samples collected at the Cape Grim Baseline Air Pollution monitoring station (operated by the Bureau of Meteorology) and at a number global sites since the early 1990s (Francey *et al*. 2003). All seventeen of the synthetic LLGHGs have been measured at Cape Grim since 1978, either directly or as part of the Cape Grim Air Archive (Krummel *et al*. 2007). The Advanced Global Atmospheric Gases Experiment (AGAGE) has measured some of these seventeen species in its global network since the late 1990s and others since 2004 (Prinn *et al*. 2000). Global average concentrations of these seventen synthetic LLGHGs prior to the late 1990s can be constructed from Cape Grim data by assuming a constant ratio of Cape Grim annual average concentrations to global annual average concentrations (derived in those years where both Cape Grim and global observations are available).

Table 8.1. Long-lived greenhouse gases (LLGHGs) used by the IPCC (Forster et al. 2007) and CSIRO (Raupach and Fraser, 2011) to derive radiative forcings for 1998, 2005 and 2009.

	Concentrations						Radiative forcing (W/m2)					
Gas	1998		2005		2009		1998		2005		2009	2009/ 2005
	IPCC	CSIRO	IPCC	CSIRO	CSIRO		IPCC	CSIRO	IPCC	CSIRO	CSIRO	CSIRO
CO2 (ppm)	366	366	379	379	386		1.47	1.46	1.66	1.65	1.76	1.06
CH4 (ppb)	1763	1764	1774	1771	1789		0.48	0.49	0.48	0.49	0.50	1.01
N2O (ppb)	314	314	319	320	323		0.14	0.15	0.16	0.16	0.18	1.07
CFCs1 (ppt)	881	883	868	871	853		0.260	0.263	0.257	0.260	0.254	0.98
HCFCs 2 (ppt)	149	151	202	203	239		0.029	0.030	0.039	0.039	0.047	1.18
CH3CC l3 (ppt)	66	64	19	18	8.9		0.002	0.004	0.001	0.001	0.000	0.41
CCl4 (ppt)	100	98	93	92	87		0.013	0.013	0.012	0.012	0.011	0.95

HFCs3 (ppt)	25	24	61	61	89		0.004	0.004	0.010	0.010	0.015	1.44
SF6 (ppt)	4.1	4.1	5.6	5.6	6.7		0.002	0.002	0.003	0.003	0.003	1.19
PFCs4 (ppt)	-	73	77	79	82		-	0.004	0.004	0.005	0.005	1.07
other LLGHGs5 (ppt)	-	34		36	35		0.009	0.009	0.009	0.010	0.010	1.00
synthetic GHGs (ppb)	1.22	1.226	1.33	1.337	1.40		0.319	0.3248	0.335	0.340	0.346	1.02
Total							2.41	2.438	2.63	2.65	2.78	1.05
CO2-e (ppm)								438		456	465	

[1]CFCs: CFC-11 (CCl_3F), CFC-12 (CCl_2F_2), CFC-113 ($CClF_2CCl_2F$)
[2]HCFCs: HCFC-22 ($CHClF_2$), HCFC-141b (CH_3CCl_2F), HCFC-142b (CH_3CClF_2)
[3]HFCs: HFC-23 (CHF_3), HFC-125 (CHF_2CF_3), HFC-134a (CH_2FCF_3), HFC-152a (CH_3CHF_2)
[4]PFCs: PFC-14 (CF_4), PFC-116 (CF_3CF_3)
[5]CFC-13 ($CClF_3$), CFC-114: $CClF_2CClF_2$ & CF_3CCl_2F, CFC-115 ($CClF_2CF_3$), H-1211 ($CBrClF_2$), H-1301 ($CBrF_3$)
[6]not including PFCs and other LLGHGs
[7]not including other LLGHGs
[8]not including PFCs

Table 8.1 shows a comparison of the concentrations and radiative forcings of all the LLGHGs that were used by the IPCC (Forster *et al.*, 2007) and Raupach and Fraser (2011, in press) for 1998, 2005 and 2009. For 1998 and 2005 the IPCC and CSIRO total radiative forcings for these 20 LLGHGs agree to within 0.02 W/m^2 (>99%), for example in 2005, 2.63 W/m^2 (IPCC) and 2.65 W/m^2 (CSIRO). This close agreement enables us to use the CSIRO observations to provide an update on the global concentrations and radiative forcings of the LLGHGs since 2007.

The radiative forcing calculated for 2009 from the CSIRO/AGAGE global network is 2.78 W/m^2, an increase since 2005 of 4.9% (1.2%/yr), a slightly lower annual increase than the 1.3%/yr or 9.1% increase from 1998 to 2005. Carbon dioxide increased by 1.8 ppm/yr from 2005 to 2009 compared to 1.9 ppm/yr from 1998 to 2005. Methane increased by 4.5 ppb/yr from 2005 to 2009 compared to the near-stationary trend (1 ppb/yr) from 1998 to 2005. Nitrous oxide increased by 0.8 ppb/yr (2005-2009) compared to 0.9 ppb/yr (1998-2005). The synthetic LLGHGs increased by 11 ppt/yr (2005-2009) compared to 4 ppt/yr (1998-2005), due largely to the recent growth in emissions of HFCs and HCFCs in South-East Asia.

By 2009, CO_2 was responsible for 63% of the radiative forcing due to LLGHGs; CH_4 18%; N_2O 7%; and the synthetic GHGs 12%. The change in radiative forcing between 2005 and 2009 was driven by CO_2 growth (79%), CH_4 growth (7%) and N_2O growth (14%), with the total contribution of the synthetic GHGs to the growth in radiative forcing during this period being approximately zero. Although the growth rate of the concentration of the synthetic LLGHGs is increasing, The contribution of the synthetic LLGHGs to radiative forcing is not increasing, although the growth rate of their concentrations is, because those synthetic LLGHGs that are increasing (HFCs for example) are less radiatively important than those that are decreasing (CFCs for example).

The growth in radiative forcing due to the LLGHGs over the period from 1900 to 2009 is shown in Fig. 8.1. By 2009, radiative forcing reached 2.78 W/m^2 or 465 ppm CO_2-e. The expanded period (1990 to 2020) is shown in Fig. 8.2. The radiative forcing due to LLGHGs is following a ‘middle-of-the-road’ path with respect to the SRES scenarios used by the IPCC in the 2007 Fourth Assessment Report. This contrasts to emissions where a ‘close-to-upper-limit path’ is being followed with respect to the SRES scenarios (Raupach and Fraser 2011 in press).

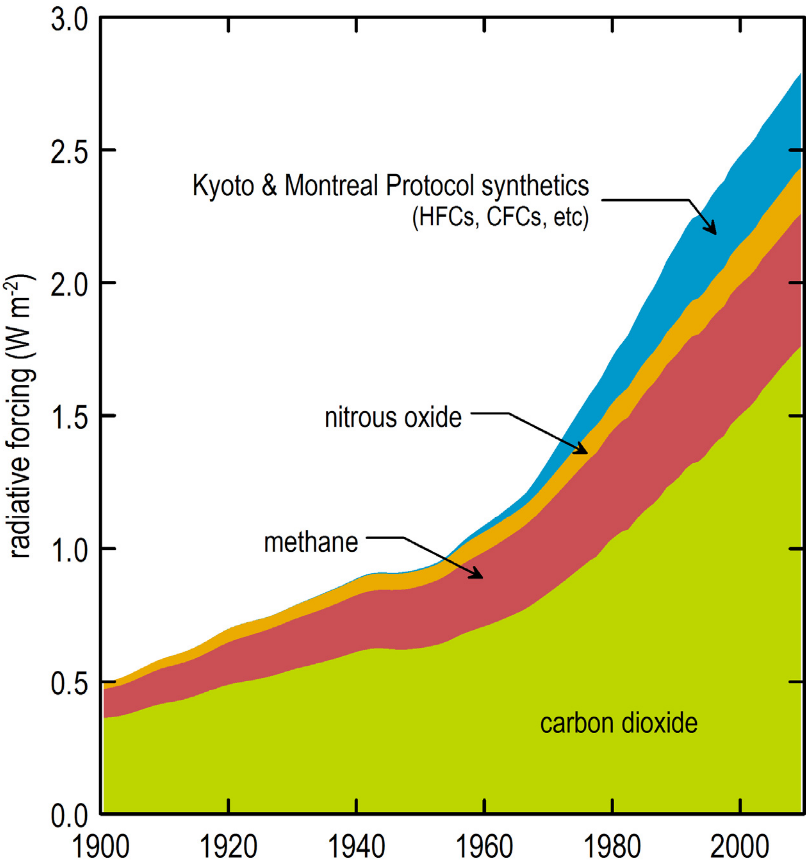

Fig. 8.1 Growth in radiative forcing due to the 20 LLGHGs used by IPCC in Forster *et al.* (2007), from CSIRO global measurements, to derive radiative forcing.

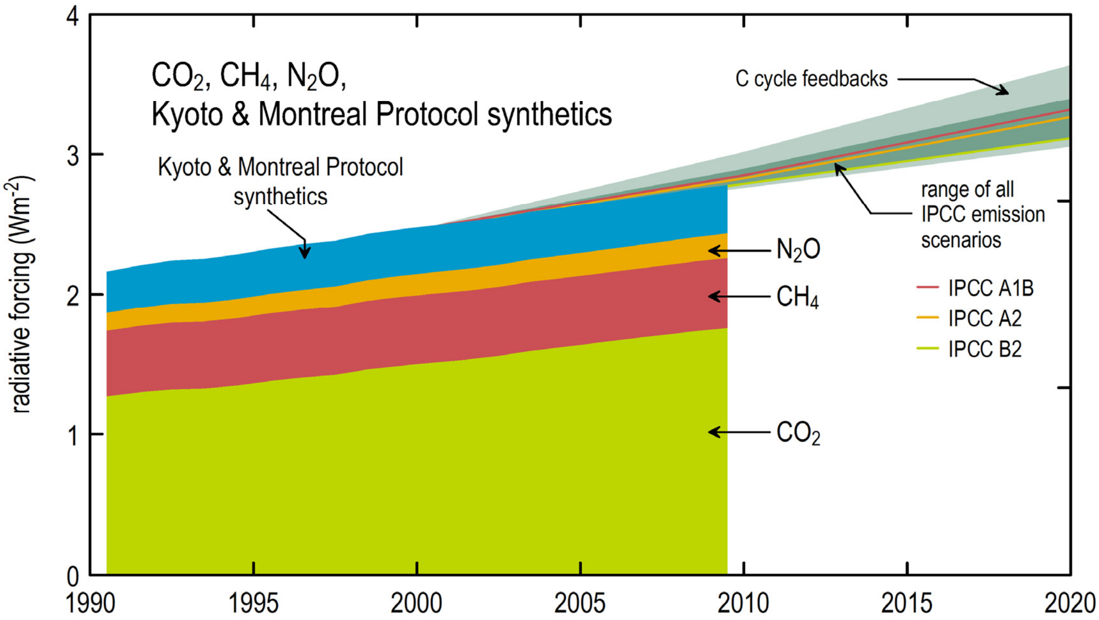

Fig. 8.2 Growth in radiative forcing compared to IPCC Fourth Assessment SRES scenarios.

8.2 Literature highlights for the long-lived greenhouse gases since the IPCC Fourth Assessment (2006-2010)

Carbon dioxide

- Measurements of atmospheric CO_2 made at Cape Grim were used as a verification tool for global total emissions of CO_2 from human activities (Francey *et al*. 2010). Francey *et al.* suggest that bottom-up estimates of fossil fuel CO_2 emissions — derived from reported emissions from each country — for the 1990s (e.g. Canadell *et al*. 2007; Le Quere *et al*. 2009) may be slightly low. This atmospheric-based result does not diminish the conclusion that CO_2 emissions are rising, and this increase is driven by increases in fossil fuel consumption, but it does provide us with a way of reducing the uncertainty in bottom-up estimates as presented in Section 6. It also may affect how actual fossil fuel emissions of CO_2 are compared to emission scenarios that drive climate change models.
- The post-above-ground-nuclear-bomb-tests global distribution of $^{14}CO_2$ has been used to constrain the global carbon budget (Levin *et al*. 2010a) for the first time.
- Modelling non-baseline CO_2 data from Cape Grim helped constrain carbon flux estimates from southern Australia (Law *et al*. 2010).
- Inversion of both global CO_2 and global $\delta^{13}CO_2$ data demonstrated the terrestrial nature of the large CO_2 inter-annual variations on decadal timescales (Rayner *et al*. 2008).
- There is some uncertainty as to whether the Southern Ocean CO_2 sink is decreasing, as reported by Le Quere *et al*. (2007, 2008). Law *et al*. (2008) found the estimated trend from an atmospheric CO_2 inversion was highly sensitive to the choice of observing sites in the Southern Ocean.
- The Northern Hemisphere terrestrial (largely mid-latitude) uptake of industrial CO_2 emissions plays a smaller role than previously thought and, after subtracting land-use

emissions of CO_2, tropical ecosystems may currently be strong sinks for CO_2 (Stephens *et al*. 2007).

Methane

- The resurgence in growth in atmospheric CH_4 in the late 2000s has been attributed to enhanced boreal and tropical wetland emissions, driven by inter-annual variations in boreal summer temperatures and tropical rainfall (Rigby *et al*. 2008). These CH_4 increases were unlikely to be driven by a potentially catastrophic destabilisation of frozen Arctic CH_4 deposits (Petrenko *et al*. 2010).
- A modelling study of global CH_4 fluxes for the period 1984-2003, constrained by high quality atmospheric methane measurements, found that wetland emissions dominated the inter-annual CH_4 variability, with fire emissions playing a smaller role, except during the 1997-1998 El Niño event. Possible increases in anthropogenic emissions of CH_4 during this period were likely to have been masked by temporary decreases in natural emissions of CH_4 from wetlands (Bousquet *et al*. 2006).

Nitrous oxide

- Huang *et al*. (2008) conducted an inverse modelling study on global N_2O data to show that tropical sources of N_2O were more important than previously realised and that tropical land use change was likely to have contributed to the growth of atmospheric N_2O.

Synthetics

HFCs

- Miller *et al*. (2010) have shown how the recent rapid global growth of HFC-23 (CHF_3) in the atmosphere has been curtailed by capture and destruction activities, especially in the developing world, where emissions of this potent LLGHG are still significant due to expanding production of HCFC-22 ($CHClF_2$).

PFCs

- Muhle *et al*. (2010) have shown that 'bottom-up' global inventories of PFCs (for example CF_4) underestimate global emissions by as much as 50%. The source of the unidentified emissions is South-East Asia, and is likely to be from aluminium and/or electronics production.

SF_6

- Recent studies (Levin *et al*. 2010b; Rigby *et al*. 2010) present compelling demonstrations of the feasibility of atmospheric verification of greenhouse gas emissions at the global scale, over decadal time-scales. They also demonstrate the critical importance of international scientific cooperation in achieving such goals.

SO_2F_2

- Muhle *et al*. (2009) identified a new greenhouse gas in the atmosphere, sulfuryl fluoride (SO_2F_2), a replacement fumigant for methyl bromide (CH_3Br), and produced a detailed global record of the long-term growth of this potent greenhouse gas.

NF_3

- Weiss *et al*. (2008) have identified another new LLGHG, nitrogen trifluoride (NF_3), a replacement for PFCs in the electronics industry, growing rapidly in the atmosphere. This species has been included in the list of synthetic LLGHGs included within the Kyoto Protocol.

CCl_4

- A comprehensive modelling study of the potent ozone depleting substances (ODS) and LLGHG carbon tetrachloride (CCl_4) demonstrates significant remaining, slowly declining global sources (70-80 k tonnes/yr) after Montreal Protocol phase-out, whose origins are very uncertain (Xiao *et al*. 2010). Bottom-up estimates of CCl_4 emissions are declining rapidly and by early 2000s were about 40 per cent of observed emissions. There could be unreported (illegal) production or emissions from landfills or other unidentified sources.

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9. CLOUDS AND AEROSOLS

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9.1 Cloud and water vapour feedback

A number of studies since 2008 have bolstered confidence that the magnitude of the water vapour feedback is similar to that simulated in climate models. These studies include theoretical studies on water vapour transport and its interaction with convection (Sherwood *et al*. 2010), analysis of the inter-annual variation in water vapour (Dessler *et al*. 2008; Dessler and Wong 2009) and analyses of water vapour trends derived from radiosondes (McCarthy *et al*. 2009; but note the alternative result found by Paltridge *et al*. 2009) and satellites (Gettelman and Fu 2008). These studies support relative humidity changing little under large scale warming, as is simulated by climate models. These results increase our confidence in the overall level of warming projected by global climate models (GCMs) since the water vapour feedback is the most important positive feedback in these models.

A number of recent studies have looked at cloud changes and their implications for feedbacks (and therefore model 'climate sensitivity'). Two in particular have found that variation of global clouds on interannual timescales (Dessler 2010) and subtropical low level clouds on decadal timescales (Clement *et al*. 2009) are consistent with positive cloud feedbacks. Uncertainties remain in these studies, and the magnitude of cloud feedback in general, but these papers provide additional support for the scale of warming found in GCMs (which in general also find positive cloud feedback).

9.2 Aerosols

The discussion in Garnaut 2008 pertaining to the influence and role of aerosols remains generally correct, although some additional aspects should be mentioned.

One point from Garnaut's 2008 report should be clarified, because it is ambiguous as previously worded: "Even if there were no further human-induced increases in aerosols and greenhouse gases, the long-lived greenhouse gases would remain for hundreds and even thousands of years, leading to continued warming. Aerosols are removed from the atmosphere over much shorter periods, so their cooling effect would no longer be present. Therefore, in the long term, the major influence of humans on the climate will be through activities that lead to increased concentrations of greenhouse gases in the atmosphere."

The problem with the above wording is that it is easily read as *concentrations* of aerosols and greenhouse gases, which is incorrect since if aerosol and greenhouse gas concentrations both remain constant with time, then there would be little future warming. The statement is correct if *concentrations* is replaced by *emissions*. So the sentence should read: "Even if there were no further human-induced increases in emissions of aerosols and greenhouse gases…". This distinction does matter, because even if the assumption of decreasing future aerosol emissions (discussed in the next paragraph) turns out to be wrong, the much longer lifetime of greenhouse gases means that their warming effect will eventually become much larger than the cooling effect of aerosols.

Anthropogenic aerosol levels are projected to decrease in coming decades, due to concerns about the adverse health effects of aerosols and associated efforts to reduce air pollution. Atmospheric aerosols generally have a cooling effect on the atmosphere and so mask to some degree the warming effects of greenhouse gases. Masking of anthropogenic greenhouse warming by aerosols is expected to decrease, therefore, if anthropogenic production of aerosols decreases. This is likely to cause a substantial acceleration of global warming by 2030, amplifying the effect of increasing greenhouse gases alone (Kloster *et al*. 2010). This acceleration is sometimes referred to as the "release of the aerosol brake" on global warming.

Aerosols can strongly excite changes in atmospheric and oceanic circulation because of spatial inhomogeneity in aerosol distributions, with many consequent effects on climate. It has been hypothesised that anthropogenic aerosols have contributed to increased rainfall over parts of tropical Australia (Rotstayn *et al*. 2007) and other regional climate changes (Cai *et al*. 2007) via this mechanism. Recently observed Australian climatic trends are unlikely to be representative of future forced trends if this is correct, as aerosol production declines and future climate becomes increasingly dominated by the effects of anthropogenic greenhouse gases.

Selective reduction of black carbon emissions may be an effective short-term climate change mitigation approach, in part because the short lifetime means that the effects of reduced emissions will be seen quickly (e.g. Ramana *et al*. 2010).

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10. PROJECTIONS

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10.1 Overview

The most recent national climate change projections for Australia were released in 2007 (CSIRO and BoM 2007) and were used in Garnaut (2008). These projections were primarily based upon global climate modelling experiments prepared for the Fourth Assessment Report (AR4) of the IPCC (2007a). CSIRO and BoM (2007) also used the SRES greenhouse gas and sulphate aerosol emission scenarios, highlighting climate changes associated with the B1 scenario (low emissions case), A1B (mid emissions case) scenario and A1FI (high emissions case) scenario.

These projections gave a median estimate of annual average warming by 2030 (above 1990 temperatures) of around 1.0°C across Australia, with warmings of 0.7-0.9°C in coastal areas and 1-1.2°C inland. Projected warming by 2050 ranged from 0.8° to 1.8°C and by 2070 warming was projected to be between 1.8°C (low emissions) and 5°C (high emissions). An increase in extremely hot days is very likely (Table 10.1).

Table 10.1: Annual average number of days above 35°C for present (1971 - 2000) and median estimates for 2030 and 2070, with ranges of uncertainty in brackets. The mid, low and high emissions are A1B, B1 and A1FI.

	Present average (1971-2000)	2030 average (mid emissions)	2070 average (low emissions)	2070 average (high emissions)
Sydney	3.5	4.4 (4.1-5.1)	5.3 (4.5-6.6)	8.2 (6-12)
Melbourne	9.1	11.4 (11-13)	14 (12-17)	20 (15-26)
Adelaide	17	23 (21-26)	26 (24-31)	36 (29-47)
Brisbane	1.0	2.0 (1.5-2.5)	3.0 (2.1-4.6)	7.6 (4-21)
Hobart	1.4	1.7 (1.6-1.8)	1.8 (1.7-2.0)	2.4 (2.0-3.4)
Perth	28	35 (33-39)	41 (36-46)	54 (44-67)
Darwin	11	44 (28-69)	89 (49-153)	230 (140-308)

A reduction in rainfall was projected for southern areas of Australia, especially in winter, and in southern and eastern areas in spring (based on the median and the majority of individual model results, Fig. 10.1), caused by the contraction in the rainfall belt towards the higher (more southern) latitudes . Future changes in summer tropical rainfall in Northern Australia were uncertain with results for individual results ranging across increases and decreases.

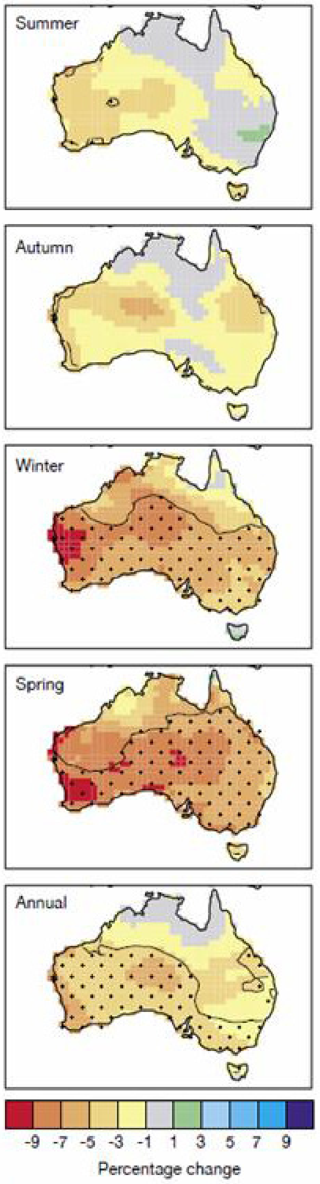

Fig. 10.1 Median projected rainfall change (%) for 2030 relative to 1990 under a mid-range emissions (A1B) scenario. Stippling indicates where a decrease is 'likely' (more than two thirds of the 23-model range less than zero). No areas show a 'likely' increase. Source: CSIRO and BoM (2007).

It is also likely that the most intense rainfall events in most locations will become more extreme, driven by a warmer, wetter atmosphere. The combination of drying and increased evaporation means soil moisture is likely to decline over much of southern Australia.

Global climate modelling groups throughout the world are currently undertaking a new set of climate model experiments (known as CMIP5, see Section 3 and Taylor *et al*. 2011) which will be examined by the IPCC AR5. These experiments will be with improved versions of many of the global climate models (GCMs) including those from Australia, France, USA, Germany, Canada, UK, and Japan (Taylor 2010). Some GCMs will include some which will also model atmospheric chemistry and the carbon cycle (Taylor 2010). These simulations represent the most important new resource for the task of assessing regional climate change and will be the basis for updated national projections to be delivered for Australia in 2013- 14.

These simulations are being run with a set of concentration scenarios known as representative concentration pathways (RCPs) (Moss *et al*. 2008). This parallel approach means that the climate model simulations are undertaken with a set of concentration scenarios and the integrated assessment modelling community explore the socio-economic and emission scenarios consistent with the concentration pathways. This approach enhances the integration between the assessment of the physical basis of climate change (IPCC Working Group 1) and the assessment of impacts, adaptation and vulnerability (IPCC Working Group 2) and mitigation options. It will not represent a fundamental shift in the range of projected future emissions and atmospheric GHG concentrations from those represented in the SRES scenarios of AR4.

There has not been a major update to the set of climate modelling experiments used in the regional projection work in 2007, upon which the Garnaut report in 2008 was based, but there have still been significant developments in our understanding of how climate is likely to change regionally in Australia. Recent work has provided more detail in projected climate change through application of high resolution downscaling techniques (e.g. Grose *et al.* 2008), and also provided further insight to changes to climatic extremes (e.g., Hennessy *et al.* 2008). There have also been some significant developments in methods used for regional projections in Australia and in our understanding of what processes drive the regional climate changes simulated by the models. Key developments are summarised below with selected references. None of this new work has contradicted our broad understanding of Australia's future climate at the time of the 2008 Garnaut review.

10.2 Regional detail

Climate change projections for Tasmania at 14 km resolution have been prepared by CSIRO using the CCAM stretch grid model to downscale six of the AR4 global climate models (Grose *et al*. 2010). High resolution techniques are particularly relevant to Tasmania as the global models are not able to represent adequately its climatically significant topographical variations and this coarse resolution means that climate variations across small areas cannot be simulated. The high resolution approach indeed revealed detail on projected rainfall change not discernible in the GCM results, such as a pattern of increased rainfall over the coastal regions, and reduced rainfall over central Tasmania and in the north-west. High resolution simulation work is progressing for other areas of Australia, including the further development of statistical approaches to downscaling output from GCMs to provide higher resolution insights to regional climate behaviour (e.g. Timbal *et al*. 2009).

10.3 Addressing uncertainty

A number of recent studies have graded GCMs based on evaluation of their current climate simulation in the Australian region (e.g. Smith and Chandler 2010; Perkins *et al*. 2009; Perkins and Pitman 2009) and the impact on projections of excluding models with a poor simulation of current climate was then examined. There is some evidence that this approach can narrow the range of uncertainty in projection results. For example, Smith and Chandler (2010) found that the models which they assessed as having a more accurate simulation of current climate tended to show rainfall decrease in the Murray-Darling Basin more strongly than the full set of models. However other assessment approaches (e.g. Perkins and Pitman 2009) can delete to different selections and different results. Presently the best way to assess model performance is not well established and, in general, this approach is yet to provide major reductions in projection uncertainty for Australia. Indeed, Kirono and Kent (2010) advised against the approach for future drought assessment.

10.4 Projection methods development

A method has been developed so that the probabilistic projections of CSIRO and BoM (2007) can include estimates of the effect of decadal-scale climate variability (Watterson and Whetton 2011). The previous approach gave only the range of change due to anthropogenic forcing, but the climate in any decade in the future will also be determined in part by natural fluctuations. The original approach also is being extended to provide a projected time series as well as joint probabilities for multiple variables.

An alternative way of presenting climate projection information has also been developed which casts the projection information as a small set of categories of climate change with probabilities attached to each category. This approach has a number of advantages (Whetton *et al*. 2010), particularly in simplifying the communication of climate change information. The approach is currently being developed further, including an associated web-based tool called "Climate futures".

10.5 Drought

Hennessy *et al*. (2008), in a major study to support government drought policy formation, assessed how climate change may affect the occurrence of a 1-in-20 year exceptionally hot or dry year in future for seven regions over Australia using the output of 13 AR4 GCMs. Critical thresholds were defined for the 20th-century simulation from each GCM and then projections (up to ~2030) were constructed relative to these thresholds. The areas experiencing exceptionally hot years are likely to increase to 60-80 per cent on average. Exceptionally dry years are likely to occur more often and over larger areas in the south and south-west (i.e. south-west of Western Australia and Victoria and Tasmania regions) with little detectable change in other regions for 2010-2040. Years with exceptionally low soil moisture are likely to occur more often, particularly in these same regions.

Considerable uncertainty remains regarding the projection of droughts in the future, with one key issue being the most appropriate drought metric to employ. Mpelasoka *et al*. (2008) argued that soil moisture-based drought indices were more relevant to resource management. They also demonstrated, using the results of two GCMs, that increases in drought frequency were greater in a soil moisture based index than in an equivalent rainfall based index.

10.6 Rainfall extremes

Rafter and Abbs (2009) used extreme value theory to examine changes in the intensity of extreme daily rainfall, with return periods of 10 to 50 years. Their results showed a tendency for increases in all regions for 2055 and 2090, for most of the 11 GCMs considered. The spatial patterns were consistent with previous studies, with smaller increases in the south of Australia and larger increases in the north. Fine-scale regional climate modelling has been performed for several locations (e.g. Abbs *et al*. 2007; Abbs and Rafter 2009) and suggests increases in daily precipitation extremes on average, although with large fine-scale spatial variability. They found short duration (sub-daily) rainfall will change more rapidly than longer duration (daily and multi-day) rainfall.

10.7 Temperature extremes

Some studies have further examined projected changes to extreme temperatures in Australia. Alexander and Arblaster (2009) analysed AR4 GCM data and found more warm nights (90^{th} percentile of T_{min}), fewer frosts (below 0^oC), and longer heatwave duration (period of at least five consecutive days with T_{max} at least 5^oC above the 1961-90 mean) likely throughout Australia. Perkins and Pitman (2009) used generalised extreme value distributions fitted to AR4 GCM data and found more extremely high temperatures (1 in 20 annual daily events) and fewer extremely low temperatures were predicted for the future climate in Australia.

10.8 Fire weather

Lucas *et al*. (2007) examined fire-weather risk in Australia using various climate model results. Simulations showed that the number of days with very high fire danger ratings is likely to increase by 2% to 30% by 2020 and by 5% to 100% by 2050. The number of days with extreme fire danger ratings is projected to increases between 5% and 65% by 2020 and between 10% and 300% by 2050. For example, Canberra is projected to have an annual average of 19 to 25 very high or extreme fire danger days by 2020 and 22 to 38 days by 2050 compared with a present average of seventeen days. They also concluded that it is likely that the fire season will become significantly longer.

10.9 Tropical cyclones

Abbs (2009) examined regional climate model outputs to infer changes in tropical cyclone (TC) occurrence in the Australian region. The simulations showed on average an approximately 50 per cent decrease in occurrence of TCs for the Australian region for the period 2051-2090 relative to 1971-2000. They also reported a likely small decrease (0.3 days) in the duration of a given TC and a southward movement of 100 km in the genesis and decay regions. The southward movement in decay region was greater on average off the Queensland coast than off the coast of Western Australia. Five of the seven simulations showed statistically significant decreases in TC occurrence. Application of empirical indices, such as those used by Camargo *et al*. (2007), to GCM outputs agreed with the projection of a decrease in the frequency of occurrence of TCs in the Australia-Pacific region. An analysis of likely changes in precipitation change showed an average increase of seventeen per cent in TC-related rainfall occurring within 300 km of the TC centre. There were no changes projected in the seasonality of TCs. Further downscaling of a sample of individual TCs showed a distinct shift towards deeper pressures and a flattening of the maximum wind speed distribution, with a larger percentage of TCs producing higher wind speeds in the 2070 climate than either the 1980 or 2030 climates. These findings are consistent with recently published international studies (Knutson *et al*. 2010, Bender *et al*. 2010).

The WMO Expert team assessment of Tropical Cyclones and Climate Change by Knutson *et al*. (2010) noted that "In the absence of a detectable change, we are dependent on a combination of observational, theoretical and modelling studies to assess future climate changes in tropical cyclone activity. These studies are growing progressively more credible, but still have many limitations. Given the important societal impacts of tropical cyclones and the apparent sensitivity of these storms to details of regional and tropical climate, further research is strongly recommended to enhance climate-relevant observations, theory and modelling of tropical cyclones and related regional climate changes".

10.10 Processes driving projected regional climate changes

A number of recent studies have examined the atmospheric circulation processes associated with model projected changes to Australia's regional climate. This has included aspects of the northern Australian monsoon and southern Australian storm tracks (e.g. Frederiksen *et al*. 2011a and b) and the plausibility of the processes involved have added to confidence in model results. Projected declines in southern Australian rainfall have been shown to be related to a reduction in winter storm formation, which is a similar process seen in the observations associated with the decline in rainfall in recent years.

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11. IMPACTS ON AUSTRALIA

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11.1 Background

Chapter 6 of Garnaut (2008) addressed climate change impacts on Australia. The focus was on 2030 and the period 2030-2100. Sectors included:

- Resource-based industries and communities, e.g. irrigated and dryland agriculture, tourism;
- Critical infrastructure, e.g. water and electricity supply, buildings, ports;
- Human health, e.g. heat-related deaths, dengue fever, gastroenteritis;
- Ecosystems and biodiversity; and
- Indirect impacts, e.g. international trade, geopolitical stability, food security, climate refugees, overseas disasters and diseases.

The chapter didn't cite the IPCC Working Group 2 Chapter 11 synthesis on impacts in Australia and New Zealand (Hennessy *et al*. 2007) but it did cite a few reports from within the IPCC chapter.

11.2 Update from 2008-2010

Some of the issues not discussed in Chapter 6 or in papers commissioned by the Review are covered by Hennessy *et al*. (2007). These include forestry, horticulture, viticulture, fisheries and Indigenous communities. Some of the key reports to emerge since 2008 are summarised below.

11.2.1 Observed climate impacts

The impacts of existing extreme weather and climate events provide insight into the likely impact of future climate change. The evidence for a human contribution through increases in greenhouse gases varies regionally and for different climate variables, and it is very difficult to attribute specific causes to individual extreme weather events. There are statistical methods, however, for assessing whether an extreme event may have been made more likely because of increases in greenhouse gases (Allen *et al*. 2007).

Water resource development in the Murray Darling Basin (MDB) in conjunction with drought has caused major changes in the flood regimes that are important for floodplain wetland systems (CSIRO, 2008). Run-off in the southern MDB between 1997 and 2006 was the lowest ever recorded. The Australian Government committed more than A$3.5 billion to drought assistance from 1992-93 to 2007-08, of which A$2.5 billion has been paid since 2003-04 (Productivity Commission 2009).

Three hundred and seventy four heat-related deaths were recorded in Victoria during a two-week heatwave in early 2009 (Vic DHS, 2009). The temperature was above 43°C for three consecutive days from 28-30 January and reached a peak of 45.1°C on 30 January 2009 (Bureau of Meteorology 2009). There were power failures, transport disruptions, and fires during the same period. The Victorian bushfires in early February 2009 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). This event was associated with a step change in the forest fire danger index (FFDI) which increased around 1997 (Lucas *et al*. 2007).

Severe flooding occurred in Queensland, New South Wales and Victoria during late 2010 and early 2011 (see Sections 1.2 and 1.5). The cost of rebuilding infrastructure was estimated at $5 billion (Bligh and Fraser, 2011). There were 35 flood-related deaths (Qld Police, 2011) and significant impacts on agriculture, mining and tourism (Qld Treasurer, 2011).

11.2.2 Water availability and use

Future water availability in southern and eastern Australia, in spite of high uncertainty, is likely to decline due to reduced average rainfall and higher rates of evaporation (CSIRO and BoM, 2007; Sections 2 and 10). This is despite a projected increase in heavy rainfall events over most of Australia. For example, the change in average streamflow from Melbourne catchments under a median 2030 climate is a decline of ten per cent (Post *et al*. 2010) and the change in average stream flow in south-western Australia under a median 2030 climate is a decline of 25 per cent (CSIRO 2009).

The probable decline in water supply is likely to be accompanied by a growth in water demand as our population expands. It is the combination of growing demand and reduced supply that makes water potentially one of Australia's most critical national issues. Such a combination of factors is likely to be increasingly common by 2030 and beyond.

Surface water availability across the entire MDB is more likely to decline than to increase, especially in the south, where the reduction could be substantial. The change in average water availability under a median 2030 climate for the MDB is a nine per cent decline in the north of the basin and a thirteen per cent decline in the south. This would further reduce long-term average flow at the Murray River mouth by around a quarter under present water-sharing arrangements. In the driest years and under current water sharing arrangements, water use in the Condamine–Balonne basin could fall by over 20%; by around 40–50% in NSW water regions (except the Lachlan); by over 70% in the Murray region; and by 80–90% in the main Victorian regions (CSIRO, 2008).

Droughts are expected to become more frequent and more intense in southern Australia in future (Hennessy *et al*. 2008). The social and economic impacts of drought are already significant and likely to increase in future (Productivity Commission 2009; Drought Policy Review Expert Social Panel 2008).

11.2.3 Coastal development

Continued development and population growth in Australia's coastal regions – where around 85 per cent of the population now resides – will exacerbate human and infrastructure risks from sea-level rise and increase the likely severity and frequency of coastal flooding of infrastructure caused by climate change (Hennessy *et al*. 2007; Department of Climate Change 2009). There is likely to be an increased risk of coastal flooding, especially in low-lying areas exposed to cyclones and storm surges.

The Department of Climate Change (2009) stated: "many coastal environments such as beaches, estuaries, coral reefs, wetlands and low-lying islands are closely linked to sea level. There is a lack of detailed knowledge as to how these environments will respond to sea-level rise, but the risk of beach loss, salinisation of wetlands and inundation of low-lying areas and reefs beyond their capacity to keep pace must be recognised. With a "mid-range" sea-level rise of 0.5 m in the 21st century, events that now happen every ten years would happen about every ten days in 2100. The current 1-in-100 year event could occur several times a year".

Coastal inundation maps have been produced for sea level increases of 0.5, 0.8 and 1.1 metres by 2100 for Sydney, Melbourne, the Hunter Valley and central NSW coast, southeast Queensland and Perth to Mandurah (OzCoasts, 2010). Communities in these areas, along with remote Indigenous communities in northern Australia (especially on the Torres Strait Islands), are particularly vulnerable to sea level rise.

11.2.4 Ecosystems

Future climate change is likely to have impacts on the ecosystems within Australia through increases in temperatures, increased variability in rainfall but with a tendency for less rainfall. Major threats to ecosystems include extended drought periods, invasive weeds and pests, altered fire regimes, land-use changes including water storages, direct temperature effects, increases in salinity and other water quality issues and changes in water availability.

Freshwater aquatic ecosystems are one of the most productive and diverse habitats in the world and include rivers, wetlands, floodplains and freshwater contributions to estuaries. It was noted in Section 2 that small reductions in rainfall can lead to much larger reductions in available surface run-off contributing to freshwater aquatic ecosystems. Reduced rainfall and run-off also reduces groundwater recharge, impacting on the many groundwater-dependent ecosystems in Australia. The use of water resources for agricultural, industrial and domestic purposes reduces the water available for aquatic ecosystems, compounding the effects of reduced run-off as a result of climate change.

CSIRO (2008) reported on the likely impacts of climate change on aquatic ecosystems within the Murray-Darling Basin. They identified that reductions in surface water availability due to climate change are most likely to occur in the high water use Murray, Goulburn-Broken and Murrumbidgee regions. They considered that much of the impact of reduced surface water availability would be transferred to the riverine environments along the Murray River including the Lower Lakes and the Coorong. CSIRO (2008) found that under a median climate change scenario the average duration of the dry periods between important flood events would double for floodplains in the lower Murray River compared to current conditions and eight times compared to natural return periods. The median climate change scenario also indicates that the average annual volumes of environmentally beneficial floods would be halved for most of the Murray River from current conditions and approximately one-tenth of the flooding volume the river received before river regulation. These outcomes have implications for future water sharing plans under the National Water Initiative.
Hydrological changes to other aquatic ecosystems in Australia have been modelled for Northern Australia (CSIRO 2009), Tasmania (CSIRO 2009) and South-west Western Australia (CSIRO 2009). Climate change impacts on aquatic ecosystems are likely to include:

- Increased low-flow episodes and water stress;
- Shifts in the timing of floods and freshwater pulses;
- Increased evaporative losses, especially from shallow water bodies;

- Higher and/or more frequent floods;
- Shifts in the seasonality and frequency of thermal stratification of lakes;
- Saltwater encroachment in coastal, deltaic, and low lying ecosystems, including coastal aquifers;
- Generally more intense runoff events leading to increased sediment and pollution loads; and
- Increased extremes of water temperatures leading to algal blooms and black water events.

The results of these changes can be a loss of habitat and a reduction in biodiversity, population size and viability. These changes are likely to be seen as a gradual change in ecosystem health and structure or as a tipping point that causes a change of ecosystem type. Loss of diversity is likely to disrupt ecosystem function and cause the loss of ecosystem services (Dunlop and Brown 2008). These changes have major implications for Australia's 9000 protected areas, including national parks, nature reserves, private conservation reserves, Indigenous Protected Areas, and other reserve types that cover 88 million hectares (11.5 per cent of the continent). One of the key tasks in response to these risks will be to protect native habitat at the landscape scale, ensuring habitat connectivity so that native species can readily relocate as climatic conditions change.

A CSIRO report (Poloczanska *et al*. 2009) outlines a range of projected impacts on marine ecosystems, including:

- the expansion of mangroves into newly flooded coastal lands;
- declines in seagrass meadows and seaweed beds due to storms and warmer water;
- the southward migration of tropical pelagic fish and other marine species;
- a loss of diversity in coral fish and other coral-dependent organisms; and
- a risk to marine food chains from ocean acidification, potentially affecting fisheries.

Assisting the survival of aquatic ecosystems under climate change can be supported by iterative, risk-based approaches to water management. Reducing existing pressures on freshwater ecosystems will reduce their vulnerability to climate change. Environmental flow allocations have been postulated as a mitigation strategy for freshwater aquatic ecosystems around the world.

11.2.5 Agriculture and forestry

Higher levels of CO_2 increase the rate of photosynthesis and improve the efficiency of water use in plants, hence stimulating plant growth (known as CO_2 fertilisation). Experiments where CO_2 concentrations have been increased by around 50 per cent (to approximately 550 ppm) have produced growth increases of around 15 per cent in crops (Tubiello *et al*. 2007) and 10–50 per cent in tropical savanna grasses (Stokes *et al*. 2008). These factors indicate the potential for some positive effects of climate change on agriculture and forestry, unlike most other sectors where there are few positive impacts. The positive effects of increased CO_2, however, can be more than offset by accompanying changes in temperature, rainfall, pests, and the availability of nutrients. The review by Steffen and Canadell (2005) provides a useful summary.

A CSIRO report (Stokes and Howden 2010) discusses adaptation options to manage the potential impacts of climate change on agriculture, forestry and fisheries.

11.2.6 Health

The IPCC report outlined the direct and indirect health impacts (Hennessy *et al*. 2007). It is likely also that tropospheric ozone pollution will increase due to warmer temperatures. Under the SRES A2 scenario, increased ozone pollution is projected to cause a 40 per cent increase in the projected number of hospital admissions by the period 2020–2030, relative to 1996–2005, and a 200 per cent increase by 2050–2060 (Cope *et al*. 2008).

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12. UPDATES ON SIGNIFICANT NATIONAL ACTIVITIES

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Helen Cleugh
CSIRO Marine and Atmospheric Research

12.1 The Centre for Australian Weather and Climate Research (CAWCR)

CAWCR is a partnership between the Bureau of Meteorology and CSIRO, Australia's two leading climate, atmosphere, and ocean research agencies. The Centre was established in September 2007 to provide the combined critical mass in Earth system science necessary to keep Australia at the forefront of weather, climate, and oceans research. The partnership has grown rapidly from 250 staff in late 2007 to over 300 in 2010. Our CAWCR staff operate in integrated teams located in Melbourne (CSIRO's Aspendale Laboratory and the Bureau's Head office in central Melbourne), Hobart, Canberra, and Perth.

CAWCR's research outputs are delivered either directly from the Bureau of Meteorology, through support for Bureau services, or through various CSIRO portfolios, including the Wealth from Oceans, Climate Adaptation, Water for a Healthy Country, and Energy Transformed Flagships, and the Climate and Atmosphere Theme in CSIRO Marine and Atmospheric Research. Research products include publications in the scientific literature, new technologies, reports to clients, collaborations, and conference papers.

CAWCR is organised into five research programs:

- Atmosphere - Land Observation and Assessment;
- Climate Variability and Change;
- Earth System Modelling;
- Ocean Observation Assessment and Prediction; and
- Weather and Environmental Prediction.

CAWCR operates under three main research objectives that encapsulate the major science expertise available to the Centre and require an integrated effort across the Centre to achieve:

- **Earth system simulation:** To lead the Australian science community in the development of a world-competitive coupled climate and Earth system simulator and modelling system.
- **An Australian Earth system observatory:** To transform the Centre's current observational science into a comprehensive, integrated information system that informs decisions.
- **Water in the Earth system:** To advance scientific knowledge of the major drivers of Australia's water cycle and their predictability, characterise and, where possible, reduce prediction uncertainty based on this knowledge, and deliver the strategic science to underpin strategies for managing water use across the nation.

12.2 The Intergovernmental Panel for Climate Change

The Intergovernmental Panel for Climate Change (IPCC) has provided assessments of climate change for twenty years, including the physical basis of climate change; Impacts, adaptation and vulnerability; and response strategies – mitigation – adaptation.

The IPCC's Fifth Assessment Report, due in 2014, will provide an update of knowledge related to climate change including information on:
• Socio-economic aspects of climate change and its implications for sustainable development;
• More detailed regional information;
• More precise considerations of risk, economics and ethics; and
• Stabilisation of greenhouse gas concentrations.

It will be made up of four reports: the three IPCC Working Groups' contributions dealing respectively with "The Physical Science Basis", "Impacts, Adaptation and Vulnerability", and "Mitigation of Climate Change", and the Synthesis Report (SYR). Each report will contain its own Summary for Policymakers (SPM) which is approved in detail by all member countries of the IPCC and represents a formally agreed statement on key findings and uncertainties.

Some new features will be:
- A new set of scenarios based on representative concentration pathways for analysis across Working Group contributions;
- Dedicated chapters on sea level change, the carbon cycle, clouds and aerosols, and climate phenomena such as monsoon and El Niño;
- A greater focus on the oceans, including ocean acidification;
- Much greater regional detail on climate change impacts, adaptation and mitigation interactions; inter- and intra-regional impacts; and a multi-sector synthesis; and
- Risk management and the framing of a response (both adaptation and mitigation), including scientific information relevant to Article 2 of the UNFCCC referring to the "…stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system".

The following cross-cutting issues have been identified as being important to be treated consistently throughout the three Working Groups' contributions:
- Water and the Earth system: changes, impacts and responses;
- Carbon cycle including ocean acidification;
- Ice sheets and sea-level rise;
- Mitigation, adaptation and sustainable development; and
- Article 2 of the UNFCCC.

Key AR5 cross-cutting methods will be:
- Consistent evaluation of uncertainties and risks;
- Costing and economic analysis;
- Analyses of regional aspects;
- Treatment of scenarios; and
- Greenhouse gas metrics.

Australia is making a major contribution to AR5 through, for example, the involvement of many Australian coordinating lead authors, lead authors, and review editors, as well as through contributions to the published scientific literature that will inform the AR5. Australia also will submit two sets of climate change simulations to IPCC's AR5.

See http://www.ipcc.ch/pdf/press/ipcc_leaflets_2010/ipcc_ar5_leaflet.pdf and http://www.ipcc.ch

12.3 The National Framework for Climate Change Science

The then Department of Climate Change in 2009 prepared a National Framework on Climate Change Science (the Framework hereafter —

http://www.climatechange.gov.au/publications/science/cc-science-framework.aspx)

to complement the Australian Government's three pillar policy response to the challenge of climate change (adaptation, mitigation and helping to shape a global solution).

The Framework articulates the research required to provide the science basis for informing Australia's climate adaptation and mitigation strategies and climate policy development. It identifies the priority research challenges for the coming decade, where climate change science is needed to provide the information and knowledge needed to inform decision-making, and the key capabilities that the Australian community must harness, maintain, and build to meet these challenges.

These research challenges are:

- Understanding and predicting future changes in greenhouse gases and the carbon cycle;
- Better projections of future rainfall, evaporation, and other climate features that affect Australia's water resources;
- Processes in the atmosphere such as cloud physics that limit our ability to predict future climate;
- Climate change influences on coasts and oceans, such as sea level rise and acidification; and
- Future extreme events including cyclones, flooding rain, and storm surge.

The critical capabilities needed to meet these challenges are identified as:

- Improved climate observations;
- Better understanding of key climate processes such as El Ninõ that affect Australia;
- Integration of climate observations and climate change modelling;
- Predicting future climate, especially over the 10-20 year 'window' where current methods require substantial development; and
- Integrated assessment models that link climate to social and economic systems.

The Framework also acknowledges the limitations Australia faces in mustering the requisite people and infrastructure needed to support these capabilities and address the challenges, with particular shortfalls in skills and infrastructure in the areas of earth system modelling, supercomputing, and ocean observations.

The Framework's focus is purposefully in fundamental climate system science, to provide the "essential system knowledge to understand climate change impacts, develop adaptation strategies, and manage carbon emissions." The priority research areas identified are intended to interact closely with activities in the adaptation and mitigation science and technology domains.

A plan for implementing the Framework is being coordinated nationally, which will include a plan for coordinating and building both the science capability and investment required to meet the challenges articulated in the Framework.

12.3.1 Australian Climate Change Science Program

Australia already is recognised internationally for the quality of its climate change science and has a strong and comprehensive climate research program in the Australian Climate Change Science Program (ACCSP). The ACCSP and its predecessors have enabled this expertise to be built over two decades and have significantly enhanced Australia's science capacity and increased the global research effort in our region.

The current ACCSP has the overall aim of improving our understanding of the causes, nature, timing, and consequences of climate change so that industry, community, and government decisions can be better informed and so is consistent with the scope of Framework. The following research themes, which reflect the Framework's research challenges and capability priorities, were identified in 2009 for priority attention in the ACCSP:

- Global and regional carbon budgets;
- Land and air; observations and processes;
- Oceans and coasts; observations, processes, projections;
- Modes of climate variability and change;
- Earth system modelling and data integration;
- Predicting Australia's future climates; and
- Communication and coordination.

The ACCSP is now in its 23rd year; it is administered by the Department of Climate Change and Energy Efficiency and is implemented in partnership with CSIRO and the Bureau of Meteorology.

12.3.2 The ARC Centre of Excellence for Climate System Science

The Australian Research Council announced a suite of new Centres of Excellence in July 2010. One of these was the Centre of Excellence for Climate System Science. Centres of Excellence are major national research hubs within the Australian University sector.

The ARC Centre of Excellence for Climate System Science is led by the University of New South Wales in partnership with Monash University, The Australian National University, The University of Melbourne and the University of Tasmania. It is partnered nationally with the Bureau of Meteorology and CSIRO through CAWCR, along with the National Computational Infrastructure (NCI) that provides nationally significant supercomputing. International links include the Hadley Centre, GFDL, National Center for Atmospheric Research (NCAR), NASA and Laboratoire de Météorologie Dynamique (LMD) du Centre National de la Recherche Scientifique, France. The Centre is also linked to the Federal Department of Climate Change and Energy Efficiency to ensure research aligns with that being done by other major research providers.

The focus on the centre is process-level climate system science – so this includes the mathematics, physics, and biology of the climate system, integrated via information technology. The Centre aims to invest in the science and software development required to regionalise climate models – to enhance their skill to provide better skill in regional projection. This involves science themes relating to large-scale models of variability, regional-scale phenomena including the parameterisation of convection and land surface processes, extreme events, and the detection and attribution of extremes.

The Centre is funded for seven years from January 2011 and will be able to offer a large number of PhD scholarships, honours scholarships, postdoctoral research positions and some more senior appointments. Centre research at the five primary partner universities will be designed to link with colleagues at CSIRO, the Bureau of Meteorology, and our international partners.

Further details can be obtained from Professor Andy Pitman, the Centre Director, a.pitman@unsw.edu.au.

12.4 Australian Academy of Science

The Science of Climate Change: Questions and Answers (2010) (http://www.science.org.au/policy/climatechange.html) was prepared by a Working Group and Oversight Committee made up of Academy Fellows and other Australian scientists with internationally recognised expertise in climate science. This booklet and web page explain the latest understanding in climate change science based on a series of key questions about climate change. It also provides a clear statement of those science areas where there is consensus and those areas where uncertainty still exists.

The *National Committee for Earth System Science* (http://www.science.org.au/natcoms/nc-ess.html), established by the Academy, in 2010 published a decadal science plan for Earth System Science (*To live within Earth's limits: An Australian plan to develop a science of the whole Earth system*), which identifies the important science questions facing Australia and the planet.

The National Committee for Space Science (http://www.science.org.au/natcoms/nc-space.html), another Academy committee, in 2010 published the *Decadal plan for Australian space science – Building a national presence in space* which includes strategic priories for Earth observations and climate science.

12.5 National Research Programs

12.5.1 The Pacific Climate Change Science Program (PCCSP)

The PCCSP is part of the Australian Government's commitment through the International Climate Change Adaptation Initiative (ICCAI) to meet high priority climate change research needs that will inform adaptation in vulnerable countries in the Asia-Pacific region, especially the Pacific island countries and East Timor.

The PCCSP works closely with the another key ICCAI program, the Pacific Adaptation Strategy Assistance Program, which aims to enhance in-country capacity to assess their vulnerability to climate change and develop evidence-based adaptation strategies.

The PCCSP aims to strengthen the capacity of fifteen countries in the region to participate in and undertake climate change science research. This investment in better climate change science for the region is intended to improve the basis for future decision-making about effective adaptation and development planning.

The objectives of the PCCSP are to undertake research into climate change and variability; build research capacity in partner countries; and disseminate research findings.

The PCCSP is supported by the Australian Agency for International Development (AusAID) in collaboration with the Australian Department of Climate Change and Energy Efficiency (DCCEE). The Program is delivered by the Bureau of Meteorology and CSIRO, through their research partnership in The Centre for Australian Weather and Climate Research.

The fifteen partner countries are the Cook Islands, East Timor, Fiji, Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, and Vanuatu

The Program also works in close cooperation with regional Pacific organisations and other research institutions, including Secretariat of the Pacific Regional Environment Programme (SPREP), Secretariat of the Pacific Community (SPC), Pacific Islands Applied Geoscience Commission (SOPAC), and the University of the South Pacific (USP).

12.5.2 Pacific Adaptation Strategy Assistance Program (PASAP)

The $12 million Pacific Adaptation Strategy Assistance Program sits within the same overall Initiative as the PCCSP and aims to enhance countries' capacities to assess their vulnerability to climate change and develop evidence-based adaptation strategies. The fifteen partner countries are the same as those of the PCCSP. Activities include:

- Country-specific projects to enhance in-country capacity to assess their vulnerability to climate change and develop evidence-based adaptation strategies; and
- An overview of adaptation in the region, which will describe regional trends and variability in climate change impacts, vulnerability, and adaptive capacity, and identify common needs, lessons learned, relevant good practice, and significant knowledge/research gaps.

PASAP is being developed and implemented in close consultation with partner countries and regional organisations.

12.5.3 The South Eastern Australian Climate Initiative: Phase 2 (SEACI2)

Phase 2 of the South Eastern Australian Climate Initiative (SEACI) is a three year, $9 million research program investigating the causes and impacts of climate change and climate variability across south-eastern Australia.
SEACI2 is a partnership between CSIRO, the DCCEE, the Murray–Darling Basin Authority, the Bureau of Meteorology, and the Victorian Department of Sustainability and Environment. The current SEACI2 program follows Phase 1 which concluded in 2009.

Two recent major reports are available from http://www.seaci.org/.

12.5.4 National Sustainable Yields Assessments

In 2007 and 2008, the Water for a Healthy Country National Research Flagship was commissioned by the Australian Government to undertake a comprehensive assessment of the surface and groundwater resources of the Murray-Darling Basin and the likely consequences of climate change on these resources and their use. This project was a partnership involving state governments, industry and universities. In March 2008, the Council of Australian Governments expanded this assessment to provide a comprehensive scientific assessment of water yield including under future climate change in all major water systems across the country to allow a consistent analytical framework for water policy decisions across the nation.

Detailed studies – known as "Sustainable Yields" projects – have now also been completed for northern Australia, south-west Western Australia and Tasmania. A water resource assessment of the Great Artesian Basin, a major groundwater resource which underlies parts of Queensland, New South Wales, South Australia and the Northern Territory, commenced in July 2010. This research (representing a research investment of over $30M to-date) is providing governments and industry with an unprecedented level of climate-water information to guide future resource planning, management and investment. Details of these studies are available at http://www.csiro.au/partnerships/SYP.html.

12.5.5 The Indian Ocean Climate Initiative (IOCI)

IOCI is a research partnership between the Western Australia State Government, CSIRO and the Bureau of Meteorology. IOCI, formed in 1997, investigates the causes of the changing climate in WA and develops projections of the future climate in WA. IOCI formally began its Stage 1 programs in January 1998; Stage 2 started in July 2003; and Stage 3 in 2008.

The IOCI Seminar and Workshop 'Living in our Changing Climate', held in August 2005, laid the foundation for the proposed climate research program of IOCI Stage 3. Priorities were further developed in a workshop held in April 2006 which identified the core focus and the outcomes that would be sought for decision support and capacity building in Western Australia.

Consequently, the economically important north-west of the State will be a major focus of the research program for IOCI 3. Work will continue on the south-west to contribute to outstanding knowledge and data gaps identified by the State. For example, the program will draw heavily on the extensive modelling studies carried out as a part of the recently released Fourth Assessment Report of the IPCC, and will produce climate change scenarios for both the south west and north west at spatial and temporal resolutions that are useful for adaptation decision-making.

The three parties to the IOCI partnership in March 2008 signed the research agreement which indicated the formal start of Stage 3 of IOCI. Research work is carried out in the CSIRO and BoM facilities both in Perth and in Melbourne. Results from this research effort will be delivered in ways that will readily inform decision-making by the State Government, Local Governments, industry and the community.

12.6 Infrastructure Programs (NCRIS and EIF)

The Australian Government provides funds for public research infrastructure and facilities through the Australian Research Council (ARC) and direct budget allocations. The National Collaborative Research Infrastructure Strategy (NCRIS) (http://ncris.innovation.gov.au/) and the Educational Infrastructure Fund (EIF) were established in 2004 and in 2008-2009, respectively. These funds enabled two key observing networks to be developed, the Integrated Marine Observing System (IMOS, www.imos.org.au) and the Terrestrial Ecosystem Research Network (TERN, www.tern.org.au).

The Australian Government's Super Science Initiative in 2009, formulated from consideration of the *Strategic roadmap for Australian research infrastructure* developed during 2008 by the Department of Innovation, Industry, Science and Research, provided additional infrastructure resources to support observational and advanced computing infrastructure in climate and marine sciences.

IMOS: the Integrated Marine Observing System

- IMOS was established under NCRIS with initial funding of $50m in 2007 and is a distributed set of equipment and data-information services which collectively contribute to meeting the needs of marine and climate research in Australia.
- The IMOS Office coordinates the deployment of a wide range of equipment and assembles the data through Facilities distributed around the country. The data are made available to researchers through the electronic marine information infrastructure (eMII) located at the University of Tasmania.
- IMOS provides data from the open oceans around Australia out to a few thousand kilometres as well as the coastal oceans: that is, observations are at ocean-basin and regional scales. In this way, IMOS aspires to go a considerable way to meeting the needs of the research community, address issues of national importance, and contribute to international ocean observing programs.
- Observations being undertaken are guided by science plans developed within the marine and climate science community, and these identify five major research themes: multi-decadal ocean change, climate variability, major boundary currents, continental shelf processes, and biological responses.
- IMOS operates as a matrix of Nodes and Facilities:
  - A bluewater and climate node, and regional nodes in Western Australia, Queensland, New South Wales, South Australia and Tasmania; and
  - IMOS Facilities operated by nine different institutions, which are responsible for deploying infrastructure and delivering data streams for use by the nodes and other stakeholders.

TERN: the Terrestrial Ecosystem Research Network
TERN is a national collaboration of world-class researchers and infrastructure supporting the collection, storage, management and sharing of scientific data and knowledge. It provides infrastructure and procedures through which a wide array of ecosystem research data and knowledge can be stored, accessed and analysed. This includes networks of dedicated

observation sites, standardised measurement methods, equipment and data, and information servicing Australian ecosystem science and management.

High performance computing at NCI
The Super Science Initiative included funding for new building and high performance computing facilities to "analyse and model information on climate change, earth systems and national water management". This facility is to be developed and administered by the National Computational Infrastructure (NCI), which is hosted at the Australian National University, and is scheduled to be commissioned in mid-2012.

Marine National Facility
The Super Science Initiative also included funding to purchase a new blue-water research vessel for Australia with considerably enhanced capacity over the existing facility. The new vessel will provide enhanced capacity to take observations of the ocean around Australia and undertake process studies central to increasing our understanding of the ocean's roles in climate variability and climate change.

12.7 A Marine Nation: National Framework for Marine Research and Innovation

The Oceans Policy Science Advisory Group (OPSAG) is the peak marine science advisory body to the Australian Government. Its role includes the promotion of coordination among Australian Government marine science agencies and across the broader marine science community. The OPSAG report *A Marine Nation: National Framework for Marine Research and Innovation* (2009) recognises that Australia's ocean domain is under stress from climate change, there is mounting pressure to increase exploration for energy and mineral resources, our coastal regions are under stress from population growth and human impact, and marine biodiversity needs to be protected. The report also notes the important roles the ocean around Australia play in climate process that affect the nation and, hence, in moderating and responding to climate change.

Understanding and predicting climate change and its relationship with Australia's ocean domain is recognised as a significant challenge. The oceans and their rich biodiversity, including our entire coastal zone, will be affected severely by the impacts of global climate change. Sea-level rise, increasing sea temperatures, ocean acidification, and extreme weather will affect all biological systems and coastal areas, including human-made infrastructure such as marinas, harbours, and off-shore platforms. The OPSAG report notes that ocean modelling, climate change modelling, and, increasingly, ecosystem modelling are all highly dependent on supercomputing as researchers take the necessary steps towards inclusion of social and economic data in a true "Earth Systems" approach to biogeophysical modelling.

Australia will need a strong commitment to making strategic and ongoing investments in high performance supercomputing and associated observations to support this need.

12.8 Antarctic Science Plan

The Antarctic Advisory Science Committee, through the Australian Antarctic Division (AAD), assists the Minister for Sustainability, Environment, Water, Population and Communities and has developed an Australian Antarctic Science Strategic Plan for 2011-12 to 2020-21. The plan has a theme focussed on climate change. The goal is to improve understanding of the role of Antarctica and the Southern Ocean in the global climate system, with special focus on addressing critical gaps in knowledge identified by the Intergovernmental Panel on Climate Change.

The research will be divided into four streams:
- The Antarctic ice sheet;
- Oceans and marine ice in the Southern Hemisphere;
- Atmospheric processes and change; and
- Antarctic palaeoclimate.

12.9 National Climate Change Adaptation Research Facility (NCCARF)

An initiative of the Australian Government, the National Climate Change Adaptation Research Facility was established in November 2007 at Griffith University's Gold Coast Campus. The key roles of NCCARF include:

- Developing national adaptation research plans to identify critical gaps in the information available to decision-makers;
- Synthesising existing and emerging national and international research on climate change impacts and adaptation and developing targeted communication products;
- Undertaking a program of integrative research to address national priorities; and
- Establishing and maintaining adaptation research networks to link together key researchers and assist them in focussing on national research priorities.

The Facility is hosted by Griffith University in partnership with seven other universities and the Queensland Government.

The Australian Government is providing $10 million to support core functions of the Facility. In addition, through the Climate Change Adaptation Research Grants Program the Australian Government is providing seed-funding to address priority research identified through National Climate Change Adaptation Research Plans, developed by NCCARF.

12.10 Prime Minister's Science Engineering and Innovation Council (PMSEIC) foresight process

The PMSEIC foresight activity was in direct response to 'Powering Ideas', which emerged from a 2008 review of Australia's innovation system. A structured process has been developed, managed by the Office for the Chief Scientist, to brainstorming possible future challenges and opportunities involving science and technology, over the next 5 – 50 years.

Experts are brought together into themed groups, called thematic foresight clusters (TFCs). Their role is to identify potential futures for their theme. Four TFCs have been established, each one focussing on a specific theme of national importance. The four broad foresight themes are:

- Climate Change, energy, water and environment: impact on Australia;
- Knowledge generation, skills and perception in a global world;
- National health, wellbeing and security; and
- Science as an engine for innovation in commerce, industry and the arts.

12.11 Integrated Carbon Pathways (formerly Australian Integrated Sustainability and Carbon Assessment Service)

CSIRO and collaborators are proposing the establishment of a significant new national capability for integrated analysis of interacting social, economic and biophysical systems. Formerly known as AISCAS but recently renamed to Integrated Carbon Pathways, this new capability will provide the first systematic analysis and projections of Australia's physical economy and development pathways: identifying and assessing opportunities and threats, crafting pathways forward, and building the understanding required for desirable policy action.

This new initiative (see http://www.csiro.au/science/AISCAS.html) will better inform Australia's shift to a low carbon, sustainable and climate adapted future. It recognises that with climate change, a reduction in greenhouse emissions must occur and that Australian has significant adaptation challenges. AISCAS is proposed to provide an integrated view of these challenges and identification of suitable pathways

AISCAS is proposed to involve CSIRO researchers, in collaboration with universities, industry and the government in developing integrated assessment frameworks and models that expose options and associated outcomes at global, regional and industry levels. In doing this it will build on advances in earth system modelling, and our understanding and modelling of the economy, to ensure that decision makers have the information necessary to assess and develop policy options.

The Centre for Australian Weather and Climate Research is a partnership between CSIRO and the Bureau of Meteorology.