Australia's environmental climate change challenge: overview with reference to water resources

*G. Newton**

Anthropogenic warming of the global climate system is beyond doubt. Impacts from a changing climate are already occurring and the latest scientific research suggests that some aspects are locked in for centuries to come. Climate change therefore poses one of the greatest challenges to Australia's environment and water resources. Historical experience and past trends may no longer be a reliable predictor of the future. This article provides a brief overview of the latest scientific research and thinking on the climate change challenge. Observed changes and projections for temperature, rainfall, extreme events and ocean acidification are presented in an Australian context. The impacts of a range of climate change drivers are summarised, expanding upon the well-accepted general warming and drying trend for southern and eastern Australia. Current thinking regarding 'dangerous' climate change is that we are tracking on the higher end scale or above of the worst case scenario predictions reported by the IPCC Fourth Assessment Report (IPCC AR4) released in 2007. The implications for Australia's water resources, and in particular the Murray-Darling Basin, are significant. There appears to be a brief window of opportunity to act and adapt to enhance resilience to climate change; however, this requires an urgent and sustained commitment, and investment in Australia's environmental assets.

Keywords: Climate change, environment, water resources, biodiversity, adaptation, Murray-Darling Basin

The release of the Fourth Assessment Report from the International Panel on Climate Change (IPCC 2007) saw unprecedented scientific and international consensus that climate change is occurring, with already observable impacts. The term *climate change* refers to a directional change in climate, beyond natural bounds of variability, that is attributable to human activity and that alters the composition of the atmosphere (Secretariat UNFCC n.d.). Over the past 100 years or so, the levels of carbon dioxide (CO_2) and other greenhouse gases have increased dramatically in the Earth's atmosphere – primarily from the burning of fossil fuels and land clearing. The current concentration of CO_2 in the atmosphere, about 385 parts per million (ppm), is already some 100 ppm higher than in pre-industrial times and during interglacial periods (Steffen 2006, 2009). Emissions of CO_2 continue to accelerate on a global scale, with their growth rate increasing from 1.1 per cent per year for 1990-1999 to more than 3 per cent per year for 2000-2004 (Raupack et al. 2007).

The 2007 report by Australia's CSIRO and Bureau of Meteorology, *Climate change in Australia: Technical report*, concurred that warming of the global climate system over the past century is beyond doubt – as evidenced by increasing atmospheric and oceanic temperatures, sea-level rise (from thermal expansion of sea-water and melting ice masses), increasing ocean acidity, and accelerated melting of snow and ice (CSIRO & BoM 2007). Importantly, the report stresses that, while global warming can be slowed through reductions in greenhouse gas emissions, we are now locked into a period of unavoidable change for hundreds of years. Warming of the atmosphere and oceans will continue – the rate and duration depending on prevailing greenhouse gas concentrations. Sea-level rise has substantial inertia and will continue beyond 2100 for many centuries, as will changes to ocean acidity and ice cover.

Indeed, recent analysis by Solomon et al. (2009) showed that human-induced climate change will continue for at least 1000 years after emissions cease. Furthermore, these authors considered that the physical climate changes due to anthropogenic CO_2 already in the atmosphere will be largely irreversible. In addition, experts have identified a decline in the efficiency of natural CO_2 sinks on land and in the world's oceans to absorb anthropogenic emissions (Canadell et al. 2007; Steffen 2009) – weakening of these natural carbon sequestering capacities in the Earth system is likely to further accelerate climate change.

The main concern with climate change is the *rate* of change, which may be unprecedented in geological history. IPCC AR4 (2007) projections suggest that global warming will average between 1.1°C to 6.4°C in 100

* *Gina Newton is a coastal ecologist, science communicator and a past National President of the Australian Marine Sciences Association. Email: gnewton@ homemail.com.au.*

years time (with best estimates in the range 1.8°C to 4.0°C), compared with thousands of years for similar changes historically. It seems likely that a substantial proportion of organisms and many natural systems may not be able to adapt to this rapid change, given the evolutionary timescales over which they typically adapt to change.

Another key factor adding to the vulnerability of natural systems to climate change is the present unprecedented levels of landscape fragmentation. Fragmentation leads to isolation and discontinuity of ecosystems and creates artificial barriers – each of which limits the dispersal, migration and resilience of biota. Many experts consider that climate change and its impacts may be the dominant future driver of biodiversity loss and change in ecosystem services globally. Warming is expected to be linked to changes in rainfall, which can adversely affect the supply of water for humans, agriculture and ecosystems (Solomon et al. 2009). This trend has significant implications for Australia's environment and for the quantity, quality and usability of Australia's water resources.

Observed changes and climate change projections

Temperature

Annual average temperatures in Australia are expected to rise in parallel with rises in global average temperature; however, there will be significant regional variation (Garnaut 2008). Since 1950, average temperatures have increased over most of Australia by 0.9°C, although with significant regional variations (CSIRO & BoM 2007). The frequency of hot days and nights has increased, while the frequency of cold days and nights has declined (CSIRO & BoM 2007).

The best estimate of annual warming over Australia by 2030 relative to 1990 is about 1.0°C under a scenario of mid-range greenhouse gas emissions, with the range of uncertainty about 0.5 to 1.8°C (CSIRO & BoM 2007). Substantial increases have been predicted for the frequency of days over 35°C, with less extreme cold days and fewer frosts. Although the pattern of warming varies little seasonally, projections suggest that there will be less warming in winter, particularly in the south (CSIRO & BoM 2007). Warming is also projected to be less in coastal than in inland areas (CSIRO & BoM 2007; Garnaut 2008).

Later in the 21st century, the level of predicted warming is more dependent upon the assumed greenhouse gas emission scenario, but temperature increases of up to 5°C are predicted for some parts of Australia by 2070 under a high emissions case, particularly in the north (CSIRO & BoM 2007). For the high emissions case, there is around a 30 per cent chance of exceeding 3°C in southern and eastern coastal areas, with a much greater chance inland (CSIRO & BoM 2007).

The IPCC AR4 (2007) estimated that water security and natural ecosystems in the Australia-New Zealand region will shift from adaptive capacity into a high vulnerability status at about a 2°C increase in temperature (see Hennessy et al. 2007). The maximum degree of climate change that can be tolerated without significant loss of biodiversity has been estimated as a temperature rise of about 1.5 - 2.0°C compared to pre-industrial levels (Steffen 2006; Steffen et al. 2009).

Rainfall

Since 1950, most of south-eastern and south-western Australia has experienced substantial rainfall declines, with the largest drying along the east coast exceeding 50 mm per decade (CSIRO & BoM 2007). The last decade or so also marks one of the most severe droughts in Australia's history (BoM 2006, 2007; Nicholls 2009). Conversely, in north-western and central Australia, extreme daily rainfall intensity and frequency has increased over the same period.

Australian rainfall patterns naturally show considerable annual variability, partly in association with the El Niño - Southern Oscillation (ENSO) phenomenon. Notable dry years generally coincide with major El Niño events, while very wet years coincide with La Niña events. Such high natural variability in rainfall patterns means that it is much harder to predict changes in rainfall for a particular region under future climate change than it is for temperature. Also, local rainfall patterns are highly sensitive to the amount of water available for evaporation, the local topography and cloud cover, and atmospheric and oceanic circulation patterns (Garnaut 2008).

Nevertheless, the long-term rainfall deficiency since late 1996 across south-eastern Australia (south of 33.5°S and east of 135.5°E), the driest in the 110 year instrumental record, has shown a change in the seasonal signature of rainfall decline (Timbal 2009). This change is dominated by a strong, highly significant decline in autumn rainfall (i.e. two-thirds of overall decline), supplemented by recent, smaller declines in spring (Timbal 2009). These changes resemble those predicted by climate models of enhanced greenhouse gases (Timbal 2009). However, the magnitude of rainfall decline has been considerably more severe than the IPCC AR4 (2007) model projections, except under the highest emission scenarios later in the century (2050 – 2070) (CSIRO & BoM 2007; Timbal 2009).

The 1958 to 2007 decline in March-August rainfall over southern Australia (south of 30°S) closely correlates with an increase in surface atmospheric pressure over Australia (Nicholls 2009). This rainfall decline is not explained by a change in the behaviour of the ENSO or the Indian Ocean dipole (with perhaps the exception of the spring signal), but it can be partly explained by the trend in the Southern Annular Mode (SAM) (Nicholls 2009; Timbal 2009). The SAM is a slow-moving system of alternating high and low pressure systems girding the Southern Ocean between Antarctica and Australia that influences rainfall across southern Australia (O'Neill 2008). Recent research into the correlations between autumn rainfall decline and various climate mechanisms found that the strongest correlation was with sea-level barometric pressures off the eastern Australian coast and a persistent high pressure zone called the sub-tropical ridge (which is part of the larger system known as the Hadley circulation, characterised by descending air motion, clear skies and relatively little rain) (O'Neill 2008; Timbal 2009). It seems that global warming has increased the intensity, and moved the average position, of the sub-tropical ridge towards the south (it now lies on a line between Adelaide and Canberra) (O'Neill 2008). This means that Australia's arid zone is moving pole-ward, with much of the rainfall falling farther south over the ocean.

Extreme events

There are some indications that climate change could alter the effects of the El Niño - Southern Oscillation phenomenon (ENSO), which has a strong influence on Australia's climate (Steffen 2006). In addition to changing rainfall patterns, climate change could increase the intensity and frequency of extreme weather events, such as tropical cyclones, droughts, fires, severe storms, floods and hail in some regions (CSIRO & BoM 2007). Of particular importance to Australia's agricultural sector is the finding of the CSIRO and BoM (2007) that the projected changes in rainfall and increased evaporation are likely to cause a decline in soil moisture over much of southern Australia. Land cover change in south-east Australia has contributed to a warmer, drier climate and enhanced climate extremes (Deo et al. 2009), with fragmentation of vegetation resulting in an increased frequency of hot days, and decreases in daily rainfall intensity. Drought is projected to become more extreme due to the exacerbating effects of climate change.

Ocean acidification

Increased CO_2 levels in the atmosphere are having a significant effect on the chemistry of the oceans. Globally, the world's oceans are experiencing a decline in pH; that is, they are becoming more acidic – with some of the most extreme change occurring in the Southern Ocean to the south of Australia (Morton et al. 2009). Much of the CO_2 produced by human activity does not stay in the atmosphere – it is naturally absorbed and stored in the oceans (about 30 per cent) or on land in plants and animals. The oceans actually help to regulate atmospheric CO_2 concentrations through air-sea exchange (the *carbonate buffering effect)*. However, as CO_2 dissolves in seawater, carbonic acid is formed. The pH of sea-water is generally about 8.1 ± 0.3 (i.e. alkaline) (Newton 2007a) and it has been stable at this level for millions of years. However, the pH of the ocean has already changed significantly since the pre-industrial era and is now about 0.1 pH unit lower (the pH scale is logarithmic, so a change of 1 pH unit corresponds to a 10-fold change in acidity) (Steffen 2009 and references therein).

This change in ocean acidity may have profound effects on marine organisms that build calcium carbonate shells (e.g. corals, oysters and other molluscs), and some forms of plankton (e.g. cocolithophores and pteropods) that fuel much of the oceans' food webs (Newton 2007a). It may also affect the oxygen-carrying capacity of larger organisms (e.g. fish and squid), which in turn may affect their growth and survival (Newton 2007a). There are significant implications of increased ocean acidification combined with rising sea-surface temperatures for Australia's iconic coral reef systems in the east (Great Barrier Reef) and west (Ningaloo) (Hobday et al. 2006; Johnson & Marshall 2007).

Climate change impacts

For Australia, in addition to a general warming and drying trend, the frequency and intensity of extreme events will be a critical feature of climate change impacts. Overall, the impacts of climate change are likely to subject Australia's terrestrial, freshwater, coastal and oceanic environments to major change and potential damage. As the driest inhabited continent and an ancient land of low productivity soils and oceans, Australia is highly vulnerable to the compounding effects of a changing climate. For a range of likely impacts see Table 1; there is emerging evidence that a number of these changes are already occurring. Natural disasters already cost the Australian community billions of dollars per year, and it is expected that climate change will reduce

Table 1 **Some likely impacts of climate change for Australia (adapted from Newton 2007b, 2008; websites of the CSIRO Marine and Atmospheric Research, the Bureau of Meteorology, and the Department of Climate Change).**

Likely biophysical changes from climate change drivers	
Sea-level rise and storms	• Sea-level rise from thermal expansion of the ocean and glacial melt, and increased frequency or intensity of extreme storms leading to higher risk of coastal inundation and flooding, and potential salinisation of coastal aquifers • impacts on estuaries, such as loss of nursery function, and changes to wetlands, saltmarshes and mangrove habitats • shoreline erosion and realignment leading to loss of amenity or damage to assets (natural and human)
Warmer ocean temperatures	• leading to thermal expansion and glacial melt, sea-level rise, and freshening of sea-water in Arctic regions • increased frequency of coral bleaching events (present models project the Great Barrier Reef may warm by 2 to 5°C by 2100) • potential impacts on biodiversity, including on the distributions, ecology and phenology (i.e. reproductive patterns, recruitment levels, migration etc) of marine and coastal organisms, and consequently productivity
Increased acidification	• increased CO_2 concentration in sea-water is altering ocean chemistry and impacting on calcitic organisms, such as planktonic coccolithophores, corals and molluscs • potential future risks to infrastructure • heavy rain induced runoff from exposed acid sulphate soils can cause the acidic water to flow into estuaries, thereby affecting plant and fish growth, and leading to fish kills in severe events
Tropical cyclones and storm surges	• combined with higher sea-levels, the projected increase in intensity, and possibly frequency, of tropical cyclones could cause more intense (and frequent) coastal flooding and damage • tropical cyclones may occur further south • there are likely to be shifts in prevailing wind and wave regimes
Ocean stability and currents	• changes to wind and water temperatures may affect water-column stratification and stability, and lead to changes in upwelling of nutrient-rich deeper waters and productivity of surface waters • changes to ocean currents may affect dispersal, recruitment and distribution patterns of marine organisms, and therefore biodiversity
Decreased rainfall and drought	• decreased rainfall may lead to reduced cooling from less cloud cover and higher evaporation • warmer temperatures will cause greater evaporation (and increased water demand from plants), increasing the severity of drought for a given decrease in rainfall and contributing to reduced soil moisture • reduced cloudiness from a warmer, drier atmosphere may lead to further temperature rises (i.e. more sunlight reaches the ground surface) and exacerbation of drought conditions
Runoff changes	• a 10–15 per cent decline in rainfall (combined with other climate change impacts, such as changing seasonality of rainfall and increased evaporation) may translate to a 30–50 per cent reduction in runoff • related changes in riverine flooding (and flushing) frequency and intensity may affect the ecosystem function of freshwater environments • changes in climate over land surfaces may cause changes in runoff reaching coastal and marine systems, altering the availability and quality of freshwater. This has implications for the productivity and ecosystem functioning of coastal and estuarine environments
Increased fire and wind	• a compounding influence on fire regimes and an increased risk of larger, more intense fires (including an increased susceptibility of fuel loads to burning and a likely increase in extreme fire weather days) • increased frequency and intensity of aeolian dust and fire-borne particulates can affect coastal productivity and promote algal blooms • shifts in prevailing winds may influence surge frequency and wave regimes
Snow, frost and hail	• decrease in snow cover, average season lengths and peak snow depths, and a tendency for maximum snow depth to occur earlier in the season • fewer frosts are likely • likely increases in hail risk along the south-eastern coastline, with a decreased risk along the southern coastline
Other effects of increased temperature	• Potential impacts on terrestrial and aquatic biodiversity, including on distribution, ecology and phenology • increased incidence of heat-waves (and average number of days above 35°C), and increased minimum temperatures • southerly spread of vector-borne diseases and pest species • damage to infrastructure • agricultural implications (e.g. effects on growing seasons, production, heat tolerance etc)

the return period, or increase the intensity, of some climate-driven weather extremes (e.g. winds, floods, fire etc) (DCC 2008). Also, from an Australian perspective, abrupt shifts in the behaviour of known modes of climate variability, such as the ENSO system, could have very significant consequences (Steffen et al. 2006). The ENSO phenomenon exerts a strong influence on eastern Australia, and a strong El Niño event can cause a one per cent decrease in Australia's Gross Domestic Product (Steffen et al. 2006).

For natural environments, the threat of climate change is compounded by other pressures such as pollution, invasive species, or extractive activities. In particular, Australia's coastal zone is highly vulnerable to the impacts of climate change due to the large proportion of the population living on the coast (about 85 per cent), the large number of assets in the region (human and natural), and the extent of likely biophysical changes at the land-sea interface (Newton 2007b). The coast is also the conduit to Australia's export economy, with over 70 onshore and offshore trading ports. One-third of ship losses are already linked to weather-related problems (Newton 2007b).

Importantly, as a result of reduced precipitation and increased evaporation, water security problems are projected to intensify by 2030 in southern and eastern Australia (Hennessy et al. 2007). Risks to major infrastructure are also likely to increase (DCC 2008). By 2030, it is expected that design criteria for extreme events are very likely

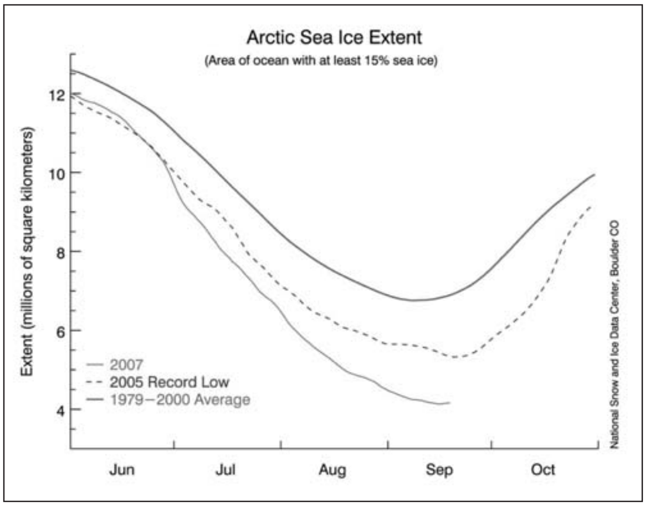

Figure 1 **New record low Arctic sea-ice extent in September 2007 compared with previous record low in 2005 and the 1979-2000 average. (Source: National Snow and Ice Data Center 2007 cited in Bodman et al. 2007).**

to be exceeded more frequently (Hennessy et al. 2007). Associated risks include the failure of floodplain protection and urban drainage and sewerage systems, increased storm and fire damage, and more heatwaves and blackouts.

Dangerous climate change

A symposium of leading climate experts held by the Australian Academy of Science in 2008 (AAS 2008) found that there was widespread concern that the IPCC AR4 (2007) underestimated the seriousness and rapidity of climate change, and therefore the urgency of taking action. A recent review by Steffen (2009), while acknowledging the outstanding contribution of the IPCC AR4 (2007), identified that the rapidly moving field of climate change science has resulted in many new developments and insights over the past few years. Most importantly, the climate system appears to be changing faster than earlier projections. Currently major climate change drivers, such as atmospheric CO_2 concentration, air and sea-surface temperature, rising sea-levels, and the frequency and intensity of extreme climate events, are tracking at the higher end-scale or above the worst-case scenario predictions reported by the IPCC AR4 (2007) (Steffen 2009). Modelling by the UK's Hadley Centre projected that at least half of the years in the decade after 2009 will exceed the warmest year on record, 1998 (Smith et al. 2007).

The IPCC AR4 (2007) identified the sea-ice biome as the ecosystem that is most likely to be affected by climate change, and declining trends in a range of marine species around the Arctic sea-ice biome have been confirmed (Sommerkorn & Hamilton 2008). The Arctic is often considered to be the global sentinel of climate change by magnifying what is happening elsewhere in the world. For several key Arctic systems, observed changes are happening at rates significantly faster than predicted – including temperature rise at double the rate of the rest of the world (already 2°C above the 20th century average) and hastened melting of the Greenland Icesheet and the Arctic sea-ice (Sommerkorn & Hamilton 2008; see Figure 1). Some experts consider that changes to the Arctic cryosphere may seriously destabilise the global climate system in the future. Several AAS (2008) symposium experts also suggested that the window of opportunity to avoid dangerous, irreversible climate change is shrinking and may be as little as five years – particularly with respect to irreversible Arctic ice melt.

Climate change is not necessarily a gradual process. Climate features such as extreme events, abrupt changes, and the non-linear behaviours of climate system processes will increasingly drive impacts on people and ecosystems (Steffen 2009). One of the most dangerous features of the climate system in terms of impacts on societies (and the environment) is the potential for abrupt and (essentially) irreversible changes when thresholds are crossed (Steffen 2009). A powerful example of a potential threshold or 'tipping element' is the disappearance of the Greenland Icesheet, which could lead to a seven metre rise in sea-level[1]. Many European experts consider that 450 ppm atmospheric CO_2 and 2°C are the trigger points for dangerous climate change (although this would vary according to the system and location). Many Australian experts similarly consider that Australia is extremely vulnerable to a 2°C increase in temperature, and we need to pre-emptively adopt a 'risk management' approach. As discussed earlier, we are already committed to a global average temperature of nearly 2°C or higher above pre-industrial levels for the rest of this century and beyond (Solomon et al. 2009; Steffen et al. 2009).

Water resources and climate change

Australia is the driest inhabited continent, and rainfall and stream-flow are naturally highly variable. Most lowland rivers experience periods of dry and flood, and often have large floodplains with connected wetlands. Southern rivers have been extensively dammed to provide a reliable water supply for agriculture and urban

[1] A useful discussion of 'tipping elements' in the climate system and their warning signs is provided by Steffen (2009).

use. In contrast, rivers in the northern, tropical regions are largely unmodified but they carry two-thirds of Australia's surface water (Beeton et al. 2006).

The often conflicting demands of irrigated agriculture, conservation of ecosystem services and biodiversity, and urban supply are placing Australia's scarce water resources under increasing pressure. This situation is exacerbated by drought and a growing dependence on groundwater (Beeton et al. 2006). Water extraction has already led to substantial changes in the structure and function of aquatic ecosystems, including those of surface waters, groundwater and wetlands (Morton et al. 2009). Significant proportions of Australia's wetland areas of international and national importance occur in regions likely to be highly vulnerable to climate change. For example, the CSIRO (2007) reported that Lake Albacutya in the Wimmera region of western Victoria, a Ramsar listed wetland, would be unlikely to ever fill under best estimate climate predictions for 2030.

Climate is a fundamental driver of the water cycle. The effect of climate change on the hydrological cycle, and the consequences for water resources, is one of the most important aspects of climate change for Australia (Steffen 2009). Climate change projections of future warming and associated rainfall decreases indicate likely increases in water demand but reduced supply, further increasing the pressure on this key resource (Steffen et al. 2006). In addition, increases in the intensity of daily rainfall extreme events are likely to increase the pressure on urban drainage capacity and catchment management. However, at present, little quantitative information is available about potential changes in flood risk in Australia.

Apart from Darwin and Hobart, all major Australian cities have been on water restrictions during recent years. Changes in the water supply of the city of Perth over the past few decades exemplify the risks that Australian cities are facing from climate change. An abrupt decline in rainfall occurred in south-western Australia in the mid-1970s (see Figure 2). This winter rain dominated region derives much of its precipitation from passing cold fronts and associated storms, but since the 1970s, these have decreased or moved more southerly over the ocean. Importantly, the average winter rainfall decline of 10-15 per cent in south-western Australia over the past 30 years has produced a corresponding reduction in average annual flows of up to 50 per cent in some rivers and streams (EPA 2007).

The Perth case highlights the sensitivity of aquatic systems to climate change and also that one of the major impacts of rainfall decline in southern and eastern Australia is the reduction in surface water available for storage. Water storage in the major cities of south-eastern Australia has dropped to around half of full capacity over the past decade or so (Garnaut 2008; Steffen 2009). Importantly, little is known about potential future impacts on groundwater in Australia – a resource that is increasingly being relied upon.

Runoff and the Murray-Darling Basin

Changes in rainfall combined with increased potential evaporation are likely to result in reduced runoff across much of Australia. As a rule, a one per cent reduction in rainfall typically causes catchment runoff to decline by about two to three per cent (O'Neill 2008). Changed seasonality of rainfall has been shown also to have a significant effect on runoff (Potter & Chiew 2009).

Streamflows in Australia's longest river system, the Murray-Darling Basin (MDB) have reached a historical low. The Basin produces more than 40 per cent of Australia's total gross value of agricultural production, uses over 75 per cent of the total irrigated land in Australia, and consumes 70 per cent of Australia's irrigation water (ABS 2007 cited in Garnaut 2008). Recent research has identified a strong link between rising temperatures, due to the enhanced greenhouse effect, and impacts on Australia's water resources, in addition to any reduction in rainfall (Cai & Cowen 2008). These authors found that a rise of 1°C leads to an approximate 15 per cent reduction in the climatological annual MDB inflow. Cowan and Cai (2009) also suggested that a 1 to 3°C temperature rise by 2050, as projected by the IPCC AR4 (2007), would lead to a 15 - 45 per cent reduction of inflow to the MDB, which would greatly exacerbate the impact of a projected 10 - 15 per cent rainfall reduction. Such research also supports the widely-held view that rising temperature from anthropogenic climate change is exacerbating Australia's current drought conditions.

The consequences of the drying trend for the Murray-Darling Basin are becoming particularly acute, with water levels and inflow at historical lows and insufficient to meet critical human and ecosystem needs for major regions of the system (e.g. O'Neill 2008; Steffen 2009). There is also a 50 per cent chance that, by 2020, the average salinity of the lower Murray River will exceed the 800 EC threshold set for desirable drinking and irrigation water (MDBMC 1999). It is expected that toxic algal blooms are likely to become more frequent and to last longer with climate change. However, at present, there are no integrated assessments of the impacts of climate change on runoff quantity and quality, salt interception

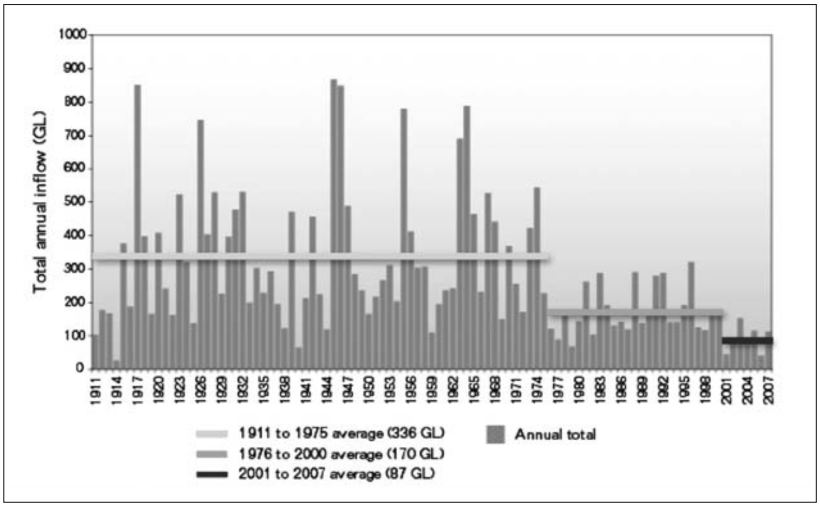

Figure 2 **Trends in total annual stream flow into Perth dams, 1911-2008 (excluding Stirling and Samson dams). (Source: Garnaut 2008 using data from Western Australia Water Corporation 2008. Note: values represent totals for May–April.)**

and revegetation policies, and water pricing and trading policies (Hennessy et al. 2007).

Adaptation and aquatic systems

According to the Garnaut Climate Change Review (Garnaut 2008), water is the central climate change adaptation challenge for Australia. Climate change has significant, critical implications for Australia's water resources and aquatic systems, including the ecosystem services they deliver, such as (Cullen 2002):

- provision of habitat for species of commercial, aesthetic and recreational value
- provision of fresh water, for domestic supply, irrigation, environmental and other purposes
- flood mitigation, by holding back water on floodplains and wetlands
- removal of sediment, nutrients and other pollutants, through riparian filtering, sedimentation and other mechanisms.

The inherent capacity for Australia's aquatic systems to adapt to climate change varies but is probably limited for most. Therefore, other stressors will need to be reduced to increase the resilience of aquatic systems to the likely impacts of climate change. Some examples of options for increasing their resilience include:

- maintaining riparian forests and vegetation
- restoring or maintaining ecological flows
- reducing nutrient loading
- minimising the spread of pests and weeds
- minimising groundwater withdrawal
- minimising the threat of acid sulphate soils
- enhancing connectivity
- assisting dispersal and migration via corridors and buffer zones
- strategic placement of any new reservoirs.

Important water reforms (e.g. the National Water Initiative, the *Water Act 2007*, the national plan for water) and related government initiatives (e.g. the Murray-Darling Basin Reform MoU and Murray-Darling Basin Plan) are all essential tools to help develop the adaptive capacity to adequately respond to climate change and its implications for Australia's water resources and aquatic ecosystems. However, there remains a critical need for data on water needs; that is, where the water is, what is its condition, and who is using it. The expansion of the Bureau of Meteorology's role in 2008 to significantly enhance the quality and utility of Australia's water information (i.e. via its new Water Division), as mandated by the *Water Act 2007*, should address much of this critical need. However, of vital importance is the need to address critical gaps in ecological and ecosystem function knowledge and to develop associated long-term data series.

Need to act and adapt now

A leading climate expert, Nicholls (2008), suggested that Australia needs to do four things to address climate change:

- monitor the climate for change – at a regional scale
- improve scientific understanding of climate drivers
- improve Australia's modelling capacity for predicting climate
- adapt: reduce vulnerability, build resilience.

The period through to 2030, and to a lesser extent 2050, is one that is most relevant today for decisions about adaptation strategies (Allen Consulting Group 2005). Over the last five years, knowledge of the likely impacts that Australia will face from climate change (including related flow-on socio-economic ramifications) has vastly improved. Related ecological information remains limited; however, pole-ward shifts in distribution and changes to phenology (e.g. breeding, flowering, migration times etc) have already been observed within some Australian terrestrial and marine ecosystems, which has implications for conservation and natural resource management (Edgar et al. 2005; Hobday et al. 2006; Steffen et al. 2009).

The recently published strategic assessment of the vulnerability of Australia's biodiversity to climate change proposed that management objectives will need to reorient from preserving all species in their current locations to maintaining the provision of ecosystem services through a diversity of well-functioning ecosystems (Steffen et al. 2009). These authors suggested several approaches to achieve the aim of enhanced resilience for Australia's biodiversity:

- maintenance of well-functioning ecosystems (terrestrial, aquatic and marine)
- protection of a representative array of ecosystems (underpinned by a National Reserve System)
- removing or minimising existing stressors
- building appropriate landscape and seascape connectivity (i.e. space for nature to self-adapt)
- identification and protection of refugia
- eco-engineering (e.g. of keystone or 'structuring' species)
- preservation of genetic stock (e.g. zoos, seed-banks etc)
- flexible policy and management approaches
- an effective monitoring network
- strong emissions mitigation action – globally and in Australia.

Prominent international reviews, such as Australia's Garnaut Review (Garnaut 2008) and the UK's Stern Review (Stern 2006), clearly recognised that the global benefits of taking early action to avoid climate change will far exceed the costs of not acting. Decision-makers from government, industry and the community need to consider options for reducing vulnerability to climate change. Climate change is occurring now, and despite the uncertainties, there is a window of opportunity, albeit small, to act and adapt now, before critical thresholds are breached. However, the non-climate factors affecting vulnerability and resilience remain poorly studied, including the social, economic, institutional, technological and governance conditions. Sensitivities, thresholds and 'tipping points' of human and natural systems also need to be determined to facilitate avoiding damage and irreversible change from climate change impacts.

Evaluation of past adaptation by the community may be beneficial in identifying cost-effective options. For example, the story of the south-western Australian wheat farmers represents a positive demonstration of adaptation, since their wheat yields increased over a 30 year period of abrupt rainfall decline. Capacity is required by communities to understand climate change information and to make informed decisions on adaptation responses. However, currently, decision-makers are hampered by a general lack of long-term data series and monitoring across a range of sectors and disciplines. People need to understand that historical experience and past trends may no longer be a reliable predictor of the future. Therefore, there is a need for national benchmarking to enhance confidence and consistency of decision-making, combined with effective education and extension programs to raise community awareness of climate change and its likely impacts.

In conclusion, two poignant, key messages from several leading Australian climate change experts highlight the need to act and adapt now:

> Climate change is no longer just a topic of scientific conversation, it has moved beyond the debate – climate change is now part of what we are living (David Jones, Bureau of Meteorology, pers. comm.).
>
> Climate change intensifies the need for an urgent and sustained increase in investment in the environment – in effect, in our own life support system (Steffen et al. 2009).

References

ABS (Australian Bureau of Statistics) 2007, *Year book Australia, 2007,* ABS, Canberra.

Allen Consulting Group 2005, *Climate change risk and vulnerability*, report to the Australian Greenhouse Office, Department of the Environment and Heritage, Canberra.

AAS (Australian Academy of Science) 2008, *Dangerous Climate Change: Is it inevitable?* Annual symposium, Science at the Shine Dome, 9 May 2008, AAS, Canberra, viewed 7 August 2009, <http://www.science.org.au/sats2008/symposium.htm>.

Beeton RJS, Buckley KI, Jones GJ, Morgan D., Reichelt RE & Trewin D (Australian State of the Environment Committee) 2006, *Australia state of the environment 2006*, independent report to the Australian Government Minister for the Environment and Heritage, Department of the Environment and Heritage, Canberra.

Bodman R, Falk F, Karoly D & Settle D 2007, *The science of climate change – a brief overview,* report commissioned for the Garnaut climate change review, Climate Adaptation - Science and Policy Initiative, University of Melbourne, Melbourne, viewed 29 August 2009, <http://www.garnautreview.org.au/CA25734E0016A131/pages/all-reports—resources-commissioned-reports>.

BoM (Bureau of Meteorology) 2006, *Special climate statement 9: an exceptional dry decade in parts of southern and eastern Australia: October 1996 – September 2006*, National Climate Centre, Melbourne, viewed 7 August 2009, <http://www.bom.gov.au/climate/current/statements/scs9a.pdf>.

BoM (Bureau of Meteorology) 2007, *Special climate statement 14: six years of widespread drought in southern and eastern Australia, November 2001 – October 2007*, National Climate Centre, Melbourne, viewed 7 August 2009, <http://www.bom.gov.au/climate/current/statements/scs14.pdf>.

Cai W & Cowan T 2008, 'Evidence of impacts from rising temperature on inflows to the Murray-Darling Basin', *Geophysical Research Letters*, vol. 35, L07701, viewed 8 August 2009, <http://www.agu.org/pubs/crossref/2008/2008GL033390.shtml>.

Canadell JG, Le Quéré C, Raupach MR, Field CR, Buitenhauis EL, Ciais PL, Conway TJ, Gillett NP, Houghton RA & Marland G 2007, 'Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks', *Proceedings of the National Academy of Science (USA),* vol. 104, pp. 18866-18870.

Cowan TD & Cai W 2009, 'Are declining river inflows linked to rising temperatures? A perspective from the Murray-Darling Basin', in RS Anderssen, RD Braddock & LTH Newham (eds), 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation, Modelling and Simulation Society of Australia and New Zealand & International Association for Mathematics and Computers in Simulation, July 2009, pp. 2763-2768, viewed 29 August 2009, <http://www.mssanz.org.au/modsim09/G5/cowan.pdf>.

CSIRO 2007, *Water availability in the Wimmera,* report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields project, CSIRO, Canberra, viewed 8 August 2009, <http://www.csiro.au/files/files/ph58.pdf>.

CSIRO & BoM (Bureau of Meteorology) 2007, *Climate change in Australia, technical report 2007,*viewed 15 February 2008, <http://www.climatechangeinaustralia.gov.au>.

Cullen P 2002, 'Environmental aspects of sustainability', presentation at the annual symposium, *Transition to sustainability*, Science at the Shine Dome, 3 May 2002, Australian Academy of Science, Canberra, viewed 8 August 2009, <http://www.science.org.au/sats2002/cullen.htm>.

Deo RC, Syktus JI, McAlpine CA & Wong KK 2009, 'The simulated impact of land cover change on climate extremes in eastern Australia', in RS Anderssen, RD Braddock & LTH Newham (eds), 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation, Modelling and Simulation Society of Australia and New Zealand & International Association for Mathematics and Computers in Simulation, July 2009, pp. 2035-2041, viewed 29 August 2009, <http://www.mssanz.org.au/modsim09/F5/deo.pdf>.

Department of Climate Change (DCC) 2008, *Fact sheet: climate change - potential impacts and costs*, DCC, Canberra, viewed 8 August 2009, <http://www.climatechange.gov.au/impacts/publications/pubs/fs-national.pdf>.

Edgar GJ, Samson CR & Barrett NS 2005, 'Species extinction in the marine environment: Tasmania as a regional example of overlooked losses in biodiversity', *Conservation Biology*, vol. 19, no. 4, pp. 1294-1300.

EPA (Environment Protection Authority) 2007, *State of the environment report: Western Australia 2007,* Environment Protection Authority, Perth, viewed 15 February 2008, <http://www.soe.wa.gov.au/home.html>.

Garnaut R 2008, *The Garnaut climate change review: final report,* Cambridge University Press, Melbourne.

Hennessy K, Fitzharris B, Bates BC, Harvey N, Howden SM, Hughes L, Salinger J & Warrick R 2007, 'Australia and New Zealand, climate change 2007: impacts, adaptation and vulnerability', contribution of Working Group II, in ML Parry, OF Canziani, JP Palutikof, PJ van der Linden & CE Hanson (eds), *Fourth assessment report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, pp. 507-540, viewed 15 February 2008, <http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter11.pdf>.

Hobday AJ, Okey TA, Poloczanska ES, Kunz TJ & Richardson AJ 2006, *Impacts of climate change on Australian marine life*, CSIRO Marine and Atmospheric Research report to the Australian Greenhouse Office, Department of the Environment and Heritage, Canberra, viewed 8 August 2009, <http://www.climatechange.gov.au/impacts/publications/marine life.html>.

IPCC (Intergovernmental Panel on Climate Change) 2007, *Fourth assessment report: climate change 2007 synthesis report: summary for policy makers*, IPCC, Geneva, viewed 15 February 2008, <www.ipcc.ch>.

Johnson, JE & Marshall, PA (eds) 2007, *Climate change and the Great Barrier Reef,* Great Barrier Reef Marine Park Authority & Australian Greenhouse Office, Canberra.

MDBMC (Murray-Darling Basin Ministerial Council) 1999, The salinity audit of the Murray-Darling Basin, MDBMC, Canberra, viewed 15 February 2008, <http://www.mdbc.gov.au/salinity/salinity_audit_1999>.

Morton SR, Hoegh-Guldberg O, Lindenmayer DB, Harriss Olson M, Hughes L, McCulloch MT, McIntyre S, Nix HA, Prober SM, Saunders DA, Andersen AN, Burgman MA, Lefroy EC, Lonsdale WM, Lowe I, McMichael AJ, Parslow JS, Steffen W, Williams JE & Woinarski JCZ 2009, 'The big ecological questions inhibiting effective environmental management in Australia', *Austral Ecology*, vol. 34, pp. 1-9.

National Snow and Ice Data Center (NSIDC) 2007, 'Figure 2: Summer melt season Arctic sea ice extent', *Arctic Sea Ice News and Analysis*, NSIDC, University of Colorado, Boulder, Colorado, viewed 29 August 2009, <http://nsidc.org/arcticseaicenews/2007.html>.

Newton G 2007a, 'Salt and vinegar – a taste of climate change and ocean acidification', *Waves,* vol. 13, no. 1, p. 7.

Newton G 2007b, 'Climate change impacts on Australia's coast and oceans', *Waves*, vol. 13, no. 1, pp. 1-3.

Newton G 2008, ‘Estuaries and climate change’, *Waves*, vol. 14, no. 2, pp. 7-8.

Nicholls N 2008, ‘Water/drying and climate change’, presentation at *Dangerous Climate Change: Is it inevitable?* Annual symposium, Science at the Shine Dome, 9 May 2008, Australian Academy of Science, Canberra, viewed, 8 August 2009, <http://www.science.org.au/sats2008/symposium-nicholls.htm>.

Nicholls N 2009, ‘Local and remote causes of the southern Australian autumn-winter rainfall decline, 1958-2007’, *Climate Dynamics*, vol. 32, doi: 10.1007/s00382-009-0527-6, viewed 8 August 2009, <http://www.springerlink.com/content/q72520r149221353/fulltext.pdf>.

O’Neill G 2008, *Living today with a future climate*, South eastern Australian Climate Initiative, Murray Darling Basin Commission, Canberra, viewed 8 August 2009, <http://www.mdbc.gov.au/subs/seaci/docs/factsheets/SEACIfactsheet-living-with-future-climate.pdf>.

Potter NJ & Chiew FHS 2009, ‘Statistical characterisation and attribution of recent rainfall and runoff in the Murray-Darling Basin’, in RS Anderssen, RD Braddock & LTH Newham (eds), 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation, Modelling and Simulation Society of Australia and New Zealand & International Association for Mathematics and Computers in Simulation, July 2009, pp. 2812-2818, viewed 29 August 2009, <http://www.mssanz.org.au/modsim09/G6/potter.pdf>.

Raupack MR, Marland G, Ciais PL, Le Quéré C, Canadell JG, Klepper G & Field CB 2007, ‘Global and regional drivers of accelerating CO_2 emissions’, *Proceedings of the National Academy of Sciences (USA)*, vol. 104, no. 24, pp. 10288-10293.

Smith DM, Cusack S, Colman AW, Folland CK, Harris GR & Murphy JM 2007, ‘Improved surface temperature prediction for the coming decade from a global climate model’, *Science,* vol. 317, no. 5839, pp. 796-799.

Solomon S, Plattner G-K, Knutti R & Friedlingstein P 2009, ‘Irreversible climate change due to carbon dioxide emissions’, *Proceedings of the National Academy of Sciences (USA),* vol. 106, pp. 1704-1709.

Sommerkorn M & Hamilton N (eds) 2008, *Arctic climate impact science – an update since ACIA*, WWF International Arctic Programme, Oslo, Norway, viewed 8 August 2009, <http://panda.org/what_we_do/where_we_work/arctic/publications/?131801/Climate-change-hitting-Arctic-faster-harder>.

Steffen W 2006, *Stronger evidence but new challenges: climate change science 2001–2205*, Australian Greenhouse Office, Department of the Environment and Heritage, Canberra, viewed 15 February 2008, <http://climatechange.gov.au/science/publications/science2001-05.html>.

Steffen W 2009, *Climate change 2009: faster change and more serious risks*, Department of Climate Change, Canberra, viewed 8 August 2009, <http://www.climatechange.gov.au/science/publications/faster-change-more-risks.html>.

Steffen W, Burbidge A, Hughes L, Kitching R, Lindenmayer D, Musgrave W, Stafford Smith M & Werner P 2009, *Australia’s biodiversity and climate change: a strategic assessment of the vulnerability of Australia’s biodiversity to climate change. Summary for policy makers 2009,* report prepared for the Australian Government by the Biodiversity and Climate Change Expert Advisory Group, Canberra, viewed 15 August 2009, <http://climatechange.gov.au/impacts/pubs/summary-policy-makers.pdf>.

Steffen W, Love G & Whetton P 2006, ‘Approaches to defining dangerous climate change: a southern hemisphere perspective’, in HJ Schellnhuber, W Cramer, N Nakicenovic, T Wigley & G Yohe (eds), *Avoiding dangerous climate change*, Cambridge University Press, Cambridge, pp. 219-225.

Stern N 2006, *Review on the economics of climate change*, HM Treasury, London, UK, viewed 8 August 2009, <http://www.sternreview.org.uk>.

Timbal G 2009, *The continuing decline in south-east Australian rainfall - update to May 2009*, Centre for Australian Weather and Climate Research, Melbourne, viewed 8 August 2009, <http://www.cawcr.gov.au/publications/researchletters.php>.

Secretariat UNFCC (United Nations Framework Convention on Climate Change) no date *United Nations Framework Convention on Climate Change,* Secretariat UNFCC, Bonn, Germany, viewed 29 August 2009, <http://unfccc.int/essential_background/convention/items/2627.php>.

Western Australia Water Corporation 2008, ‘Annual streamflows into Perth’s dams’, data supplied by the Western Australia Water Corporation to the Garnaut Climate Change Review (Garnaut 2008).