Local Government Association
of South Australia

The Voice
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Government

Update on climate change science and changes in South Australia
May 2011

Since the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) was released in 2007 there has been significant research on many of the key aspects of climate change science that are crucial to our understanding of global warming. These aspects include recent trends, uncertainties, sea level rise, abrupt changes associated with climate thresholds, and feedbacks – natural processes that can increase or decrease the effects of global warming. This update was prepared in May 2011 and contains the latest publicly available information on climate change science up to that time and puts it into context with the latest data for South Australia.

Climate change – Latest trends

Greenhouse gas emissions

Increased concentrations of greenhouse gases in the atmosphere enhance the naturally occurring greenhouse effect and further heat the lower levels of the atmosphere by allowing short-wave radiation from the sun to heat the earth, but preventing long-wave thermal radiation from escaping back out into space. This process is now validated by global surface, balloon and satellite data (IPCC 2007).

Between 1960 and 2009, humans released 273 billion tonnes of carbon dioxide into the atmosphere via the burning of fossil fuels (coal, oil, gas) (Mikaloff-Fletcher 2011) and other greenhouse gases as a result of industrial processes and land clearing. As a result of these activities, the atmospheric concentration of all greenhouse gases has risen since the beginning of the industrial revolution. In 2008, global emissions of carbon dioxide (CO_2) from the burning of fossil fuels were nearly 40% higher than those in 1990 (Allison, Bindoff et al. 2009) and the level of CO_2 in the atmosphere by the end of 2010 was 387 parts per million (ppm), up from 280 ppm prior to the industrial revolution and the highest in over 800,000 years. Methane levels are now 1800 parts per billion(ppb) (Allison, Bindoff et al. 2009) and have increased since 2007 after nearly a decade of little change for reasons that are not yet fully understood (Figure 1). Total greenhouse gas emissions in the atmosphere by 2010 were equivalent to 465 ppm CO_2 (Garnaut 2011).

Emissions of CO_2 from fossil fuels have continued to rise above the IPCC A1F1 emissions scenario (the worst-case scenario) at 3.4% per year from 2000 – 2008, more than 10 times faster than natural increases at any time over the past 22,000 years (Allison, Bindoff et al. 2009). The largest of these emissions are the result of burning fossil fuels, followed by land use changes including deforestation and conversion to crops (Garnaut 2011). This worst-case scenario is now regarded as the most likely future in the absence of determined intervention. In addition, the efficiency of natural carbon sinks, including the oceans, that to date have absorbed close to half the total emissions of CO_2, has declined by about 5% over the past 50 years (Allison, Bindoff et al. 2009).

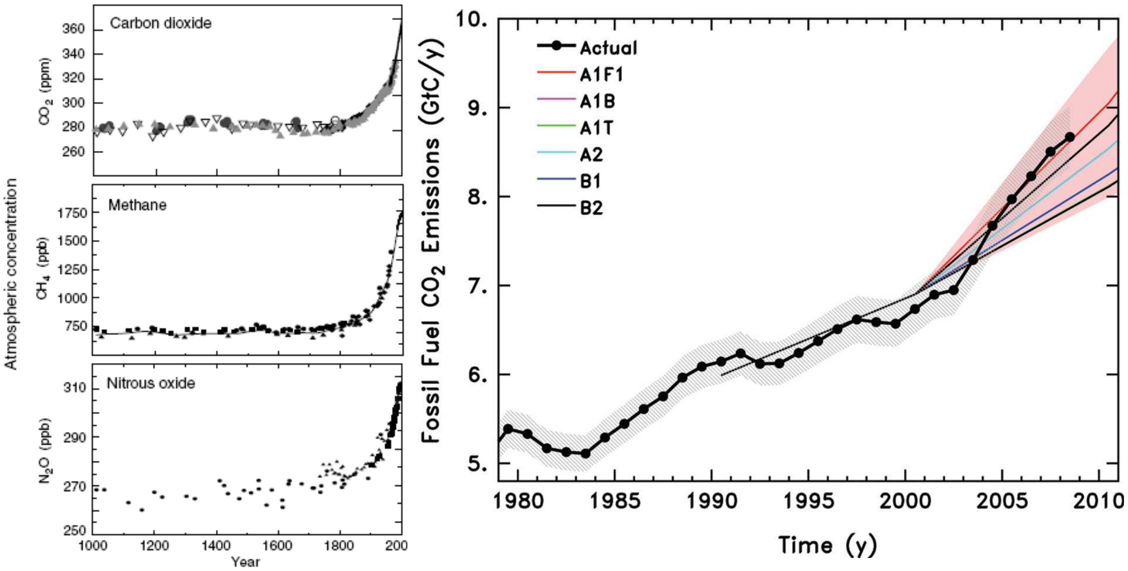

Figure 1: Observations of anthropogenic carbon dioxide, methane and nitrous oxide emissions 1000AD – 2000AD (left) and CO_2 emissions from 1980 – 2008 compared to the IPCC AR4 greenhouse gas emissions SRES scenarios (right) (IPCC 2007; Allison, Bindoff et al. 2009).

Temperature

Including 2007, the global surface temperature has increased by approximately 0.76°C since 1850 (IPCC 2007). The eight warmest years have all occurred since 1998, and the 14 warmest years have all occurred since 1990 (Scientific Committee on Antarctic Research 2009). The World meteorological Organization concluded that “the year 2010 ranked as the warmest year on record, together with 1998 and 2005” and that the decade ending 2010 was the warmest on record. Temperatures over land have increased at roughly twice the rate of ocean surface temperatures and the poles are warming faster than the equatorial regions (Figure 2).

Both maximum and minimum temperatures have increased equally (IPCC 2007). The rate of warming over the last 50 years is almost double that for the last 100 years (IPCC 2007). Short-term changes (less than 10 years) in the temperature trend show natural variation and do not change the long-term observed global warming trend (Allison, Bindoff et al. 2009). There is now no credible explanation (e.g. solar activity, volcanos) for the level of observed warming except the emission of greenhouse gases by human activity (Allison, Bindoff et al. 2009).

Aerosols such as dust, smoke and haze both absorb and reflect heat in the atmosphere, although the net effect is one of cooling and has masked some of the warming from long-lived greenhouse gases such as CO_2 (Garnaut 2011). It is likely that over the coming years the concentration of aerosols in the atmosphere will be decreased by measures to reduce the associated health risks. However, changes to clouds and water vapour in the atmosphere are now understood to create positive feedbacks and so warm the planet further as they increase in the warming world (Sherwood 2011). Additionally, increased humidity is likely to lead to a significant rise in heat stress and make tropical areas unliveable (Sherwood 2011).

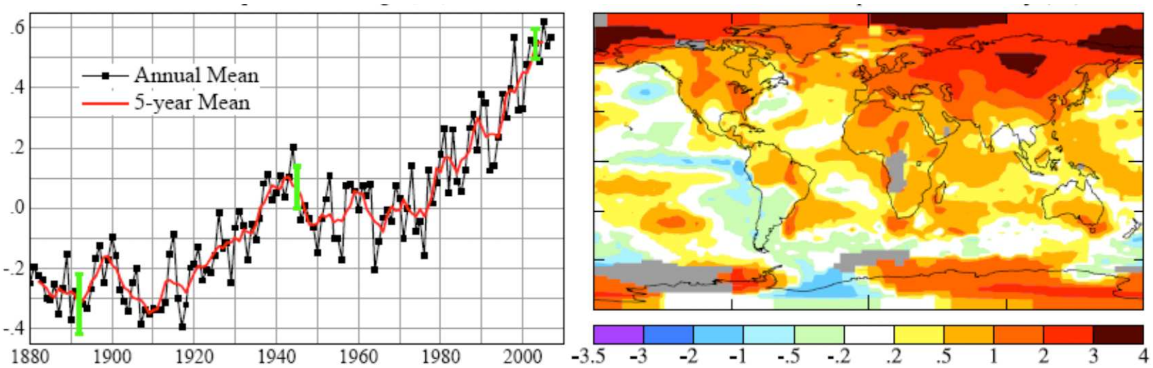

Figure 2: Global temperature change (^{o}C) 1880 – 2007 (left) and the 2007 surface temperature anomaly (^{o}C) relative to average 1951 – 1980 temperature (right) (Scientific Committee on Antarctic Research 2009) .

From 1910 to 2010, the continental average annual temperature of Australia increased by 0.9^{o}C, mostly in winter and spring (Suppiah, Preston et al. 2006; Bureau of Meteorology 2009). Over the same period, the South Australian maximum temperature increased by 0.96^{o}C, the minimum by 1.13^{o}C and the average by 0.96^{o}C (Suppiah, Preston et al. 2006). Since 1950, the average temperature for South Australia increased by 0.2^{o}C/decade and the frequency of cold weather in summer has decreased (Figure 3).

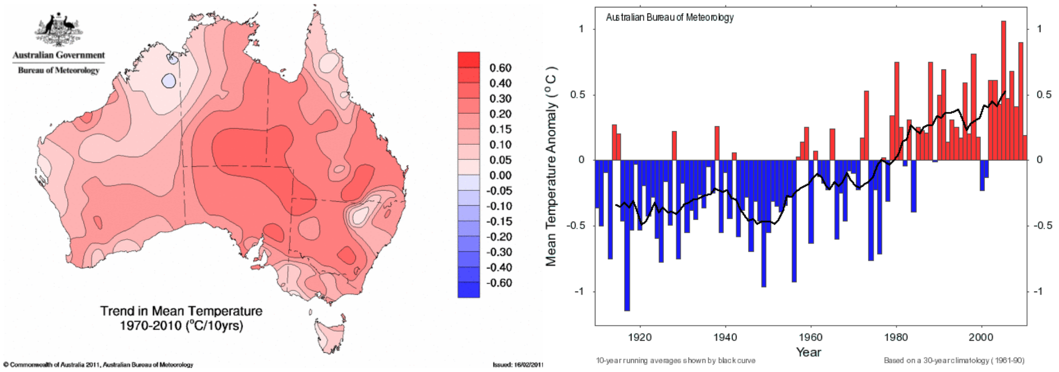

Figure 3: Increase in Australian mean temperature (left) in ^{o}C/decade and length of hot spells (a measure of heatwaves) in number of days from 1960 – 2010 (Source: Bureau of Meteorology 2011).

Ice extent

As expected in a warming world, ice reserves in all forms have been melting. The Greenland ice sheet has thinned dramatically, especially along the coastline, and the rate glacier flow and ice melt has accelerated. These changes are all the result of a temperature increase of 1.5^{o}C between 2000 - 2006 and a melt area increase of 30% between 1979 - 2008 (Allison, Bindoff et al. 2009). Measurements of the Antarctic ice sheet show a net loss and acceleration in ice loss since 2003. The largest losses have occurred in the West Antarctic Basin and there have now been seven ice shelf collapses over the past 20 years (Allison, Bindoff et al. 2009).

The southern boundary of the permafrost in North America has moved north and the Tibetan permafrost has thinned (Allison, Bindoff et al. 2009). Melting of permafrost reduces the stability of the landscape and results in “drunken trees” and infrastructure damage. In addition, organic matter is broken down by bacteria that release methane and/or carbon dioxide into the atmosphere and so amplify global warming (Allison, Bindoff et al. 2009). It is estimated that if the earth’s permafrost was to melt, 1672 Gt (billion tonnes) of carbon or twice the current amount of greenhouse gases currently in the atmosphere, would be released. Methane also stored in frozen soils would account for a further 7.5 – 400 Gt.

Arctic sea ice extent in January 2011 was the lowest since satellite records began in 1979 and has shown a “precipitous” decline in over the last two years, particularly during summer (Steffen 2009; Garnaut 2011) (Figure 4). The measurements suggest that this is one aspect of the climate system that is responding to warming in a non-linear way and at a rate much faster then predicted in the IPCC AR4 (Allison, Bindoff et al. 2009).

The world Glacier Monitoring Service measures annual changes in over 30 reference glaciers world wide. The recorded mass balance in 2008 was negative again for the 18th year in a row (Garnaut 2011).

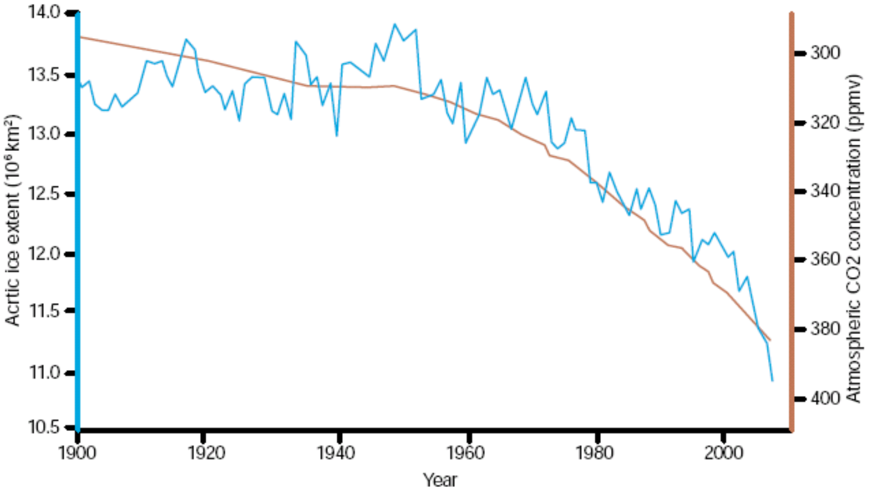

Figure 4: Arctic sea ice extent and CO_2 concentration 1900 – 2007. Note the CO_2 scale is inverted (Steffen 2009).

Rainfall

At a global scale, increased temperatures lead to an increase in evaporation and hence atmospheric water vapour and rainfall. As a result of the enhanced hydrological cycle, atmospheric water vapour has increased several percent per decade, and cloud cover by some 2% (IPCC 2001) since 1900. However, there are large differences in rainfall from one region of the globe to another. The tropics are expected to get wetter and the mid-latitudes drier but with an increase in the chance of intense precipitation and flooding (Steffen 2009; Garnaut 2011).

Rainfall across Australia has increased slightly, although, on a continent wide basis the trend is not statistically significant due to the high inter-annual variability (Smith 2004). For regions where precipitation has increased (north-west Australia) there has been more rain in summer than winter, probably as a result of increases in heavy rainfall events and the number of rain days (Hughes 2003), and influences from atmospheric aerosol pollution from south-east Asia (Steffen 2009). However, since 1976 the frequency and intensity of El Niño events has also increased and resulted in a rainfall decrease along the east coast of the continent, mostly in summer and autumn (Steffen 2009) (Figure 5).

The drying trend across southern Australia since the early 1990s is most likely the result of an intensification of the sub-tropical ridge (or high pressure belt) (Post 2011) and changes to the Southern Annular Mode (which also affects atmospheric pressure across southern Australia) and which may explain up to 70% of the observed rainfall declines (Nicholls 2009). Each of these changes is consistent with a warming planet and so trends are likely to continue (Steffen 2009; Garnaut 2011). Recent research on the alternating patterns of warm and cool sea surface temperatures across the Indian Ocean, now known as the Indian Ocean Dipole (IOD), suggests that the pattern may be linked to significant droughts across our region (Steffen 2009).

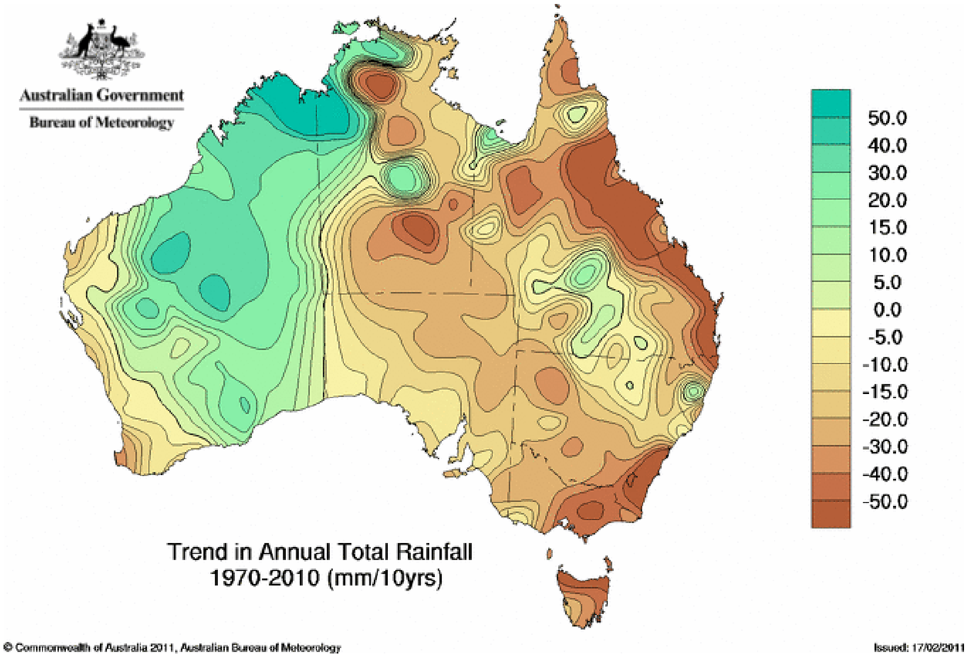

Figure 5: Annual rainfall trends across Australia 1970 – 2010 (mm/10 years) (Source: Bureau of Meteorology 2011).

Rainfall for South Australia has decreased since 1900, most notably in the second half of the century (Suppiah, Preston et al. 2006). Annual rainfall since 1970 has decreased by 10 – 40 mm/decade, most dramatically across the north-east of the state. It should be noted that rainfall in the 1970s was relatively high compared to other decades.

South-west western Australia had it's driest year and lowest river inflows on record in 2010 and the extended drying trend seen in this part of the continent is now considered to be likely linked to anthropogenic climate change (Cook 2011).

Evaporation

As the earth warms, the atmosphere will hold more water vapour and thus humidity in some areas will increase depending on atmospheric circulations (Allison, Bindoff et al. 2009). Across Australia, evaporation declined by approximately 4 mm/year from the early 1970s through to the late 1990s (although values and trends vary by location). However, since 1990, evaporation has increased as would be expected in a warming environment. The trend may also be the result of a decrease in aerosol emissions and resultant increase in solar radiation in many areas (Gifford, Farquhar et al. 2004; Wild 2004). An increase in the number of El Niño events over the same period may also explain the change (Gifford, Farquhar et al. 2004).

High quality evaporation data have been recorded in South Australia at only five locations: Ceduna, Woomera, Adelaide, Nuriootpa and Mount Gambier. Since 1970 evaporation across the north of the state has increased by up to 10 mm/year. However, in the south-east corner evaporation has *decreased* by up to 10 mm/year (Bureau of Meteorology 2009).

Available water

Changes in rainfall and evaporation result in changes to the amount of water available for plants, animals and humans. Across eastern and southern Australia available water has decreased. This trend has resulted in a 55% decrease in the Murray-Darling Basin stream flow since 1950. During the 2000-07 period the average annual inflow to the river system was 4,150 GL/year compared to a long-term average of about 12,300 GL/year (Cai and Cowan 2008) (Figure 6). The impacts of these conditions are obviously severe for South Australia.

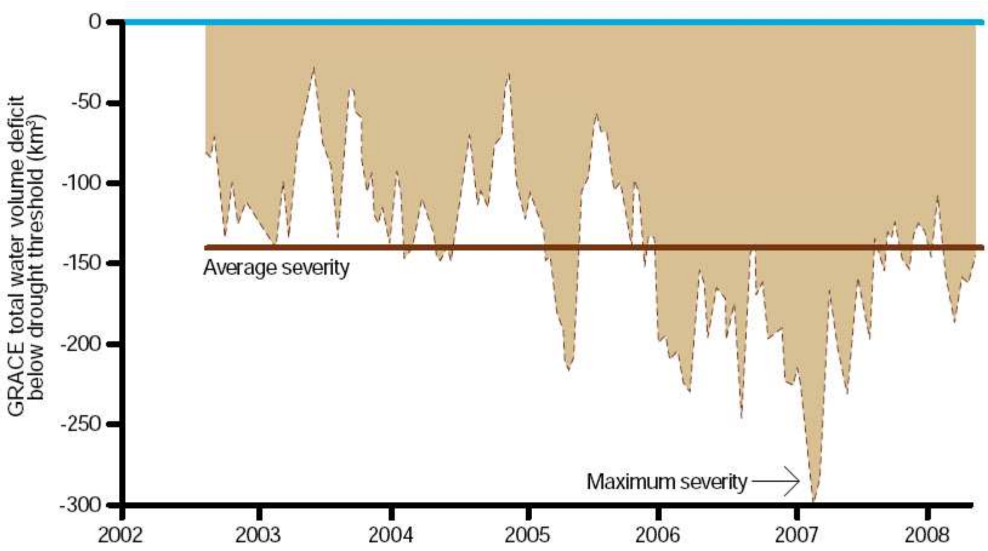

Figure 6: Changes in total water volume in the Murray-Darling Basin (2002 – 2008) (Source: Steffen 2009).

Ocean changes

The oceans have warmed approximately 0.7°C since 1870, mostly in the top 1000 m (Roemmich and Gilson 2011). Analysis by many groups around the world now confirms that the oceans have so far absorbed more than 90% of the increased heat associated with global warming (Church 2011). Sea surface temperatures around Australia are also rising and most of the warmer water appears to be pooling around the south / southeast of the continent due to ocean currents (Karl Braganza, National Climate Centre *pers. comm*. June 2010). During 2010, the sea surface temperatures in the Australian region were the highest on record at 0.54°C above the 1961 to 1990 average (Garnaut 2011).

Tidal gauges and satellite altimeter data show an increase in global sea levels since 1970 of about 1.7 mm per year (Church 2011). The most rapid increases (3.1 mm/year) have occurred since 1993 and is the result of both thermal expansion (about 45%) and land-based ice contributions (about 40%) (Steffen 2006; Church 2011). As a result, sea level rise is currently tracking at or near the upper limit of the IPCC projections (Garnaut 2011) (Figure 7). Ocean salinity and current changes globally now confirm the changes expected due to changes to rainfall and increased ice melt in Artic regions and Antarctic regions (Garnaut 2011; Rintoul, Sallee et al. 2011).

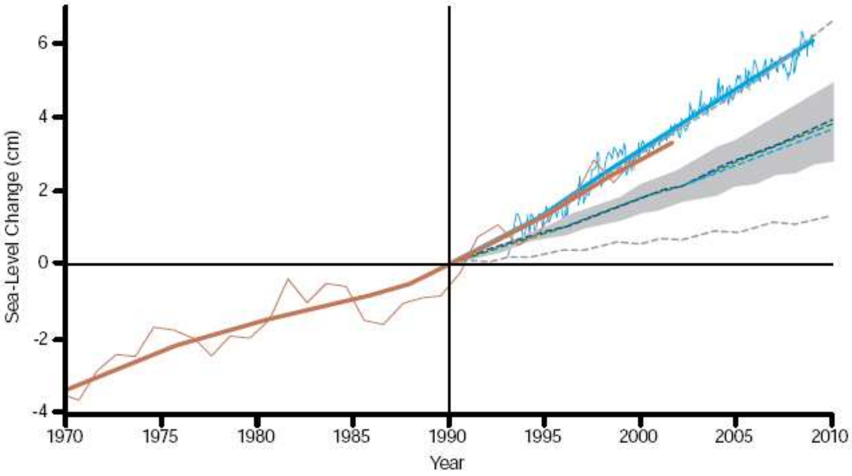

Figure 7: Sea level changes from 1970 – 2008. The envelope of IPCC projections is shown for comparison (Steffen 2009).

The average rate of sea level rise around Australia was about 1.2 mm/year over the period 1920 – 2000 (Church, Hunter et al. 2004). As with most large coastlines, the measured increases in sea level along the South Australian coast vary as a result of tectonic movement, climatic influences including the El Niño Southern Oscillation (ENSO), and anthropogenic changes such as subsidence due to the draining of wetlands and other modifications. Data from the early 1990s to June 2010 show increases in sea level around Australia of between 2.1 – 7.4 mm/year (Figure 8). There has been a sea level rise at the Thevanard tidal gauge (considered the most accurate and with the longest record) of approximately 4.5 mm/year. All measurements are adjusted for tectonic movement, seasonal climate variations and anthropogenic land changes (National Tidal Centre 2010).

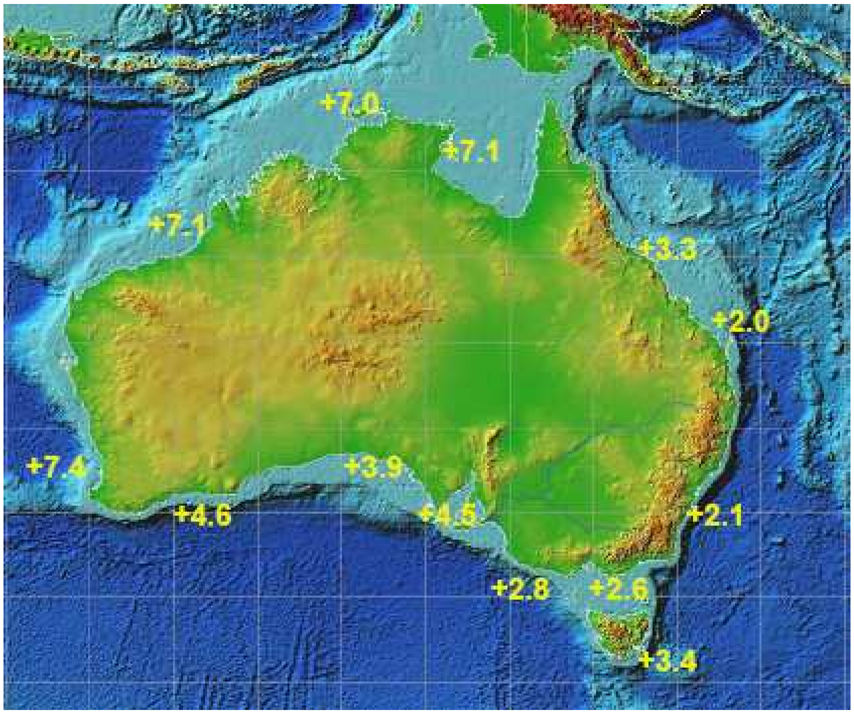

Figure 8: Sea level changes (mm/year) from the early 1990s when the National Tidal Centre Sea Level Rise project started to end June 2010. The measurements take into account changes due to tectonic subsidence and uplift and seasonal climatic influences (Source: National Tidal Centre 2010).

About a quarter of all human emissions of CO_2 have been absorbed by the oceans in a process that converts it to carbonic acid and subsequently drops in the pH of the water. Recent measurements indicate that the oceans are now about 0.1 pH unit lower than they were prior to the industrial era (30% more acid) (Allison, Bindoff et al. 2009). This level of acidity is the highest recorded in the past 25 million years and is fast approaching one that is unfavourable for coral formation and leads to the erosion of calcium carbonate shells built by organisms such as oysters, sea urchins, mussels, crustaceans and calcifying plankton species (Steffen 2009). Calcification of *Porites sp.* corals on the Great Barrier Reef has declined by 14% since 1990 (De'ath, Lough et al. 2009). Warming of the oceans has also led to a measurable decrease in dissolved oxygen (Allison, Bindoff et al. 2009).

Extreme events
Globally, hot days and nights and the frequency of heatwaves have increased in many areas (Allison, Bindoff et al. 2009). Since 1970 the number of very hot days (days above 40^oC) in South Australia has increased by between 4.5 and 9.0 days. In March 2008 Adelaide had a record 15 days over 35^oC and 11 days over 38^oC (Bureau of Meteorology 2009).

Across the country the trend for the number of very heavy rain days has decreased, in South Australia by approximately 4 days / 100 years since 1970 (Bureau of Meteorology 2009). A trend towards extreme hot and extreme wet conditions occurring at the same time is not consistent with processes that cause natural climate variability (Garnaut 2011). For most of South Australia the trend in maximum one-day rainfall has also decreased by approximately 40 mm/day/100 years since 1970 (Bureau of Meteorology 2009).

Bushfire incidence
The intensity of bushfires is a combination of a number of factors including temperature, fuel loads, humidity and wind. The recent drying trend across southern Australia has made the fuel load more susceptible to burning (Steffen 2009). Over the past decade an upward trend in the median seasonal Forest Fire Danger Index (FFDI), a measure of fire risk, indicates increased fire danger across south-east Australia, and fire danger weather has increased in many areas by 10 – 40% from 2001 – 2007 compared to the 1980 – 2000 period (Steffen 2009). In addition, four of the last five fire seasons (to 2007) have been among the longest on record since 1942, a trend that has increased since the early 1990s (Lucas, Hennessy et al. 2007). Conditions recorded in the 2010 “Black Saturday” fires in Victoria are considered to be consistent with expectations for a warming world (Garnaut 2011).

Climate change – future trends

Projections of future changes in the climate are made by using global climate models that have been tested for accuracy against historical data. As the climate moves further into unknown territory there are uncertainties that will affect how accurate the estimates will be. Uncertainties include how much aerosols and clouds will influence future temperatures (Sherwood 2011), what the future emissions of greenhouse gases will be and how sensitive the climate is to the extra warming. For these reasons future projections of climate are expressed as a range of different emissions scenarios and climate sensitivity scenarios. In 2007, the IPCC estimated that the global average temperature was likely to rise by 3^oC with a doubling of greenhouse gases in the atmosphere, an estimate that has been since confirmed by further research (Garnaut 2011).

For Australia, there have been no updated climate projections since the IPCC AR4 scenarios were undertaken by CSIRO in 2007. For the IPCC AR4, climate projections made by global climate models were based on future emissions scenarios in the Special Report on Emissions Scenarios (SRES) used in previous assessments (Figure 2). For the upcoming IPCC Fifth Assessment Report (AR5), new emissions scenarios to be known as “Representative

Concentration Pathways" (Figure 9) will be used instead (Moss, Edmonds et al. 2010). The four pathways will represent the full range of greenhouse gas emission concentrations that may occur in the atmosphere by the year 2100 and will range from 450 ppm up to 1300 ppm CO_2 equivalents. The projections from these scenarios are expected to be released in 2014.

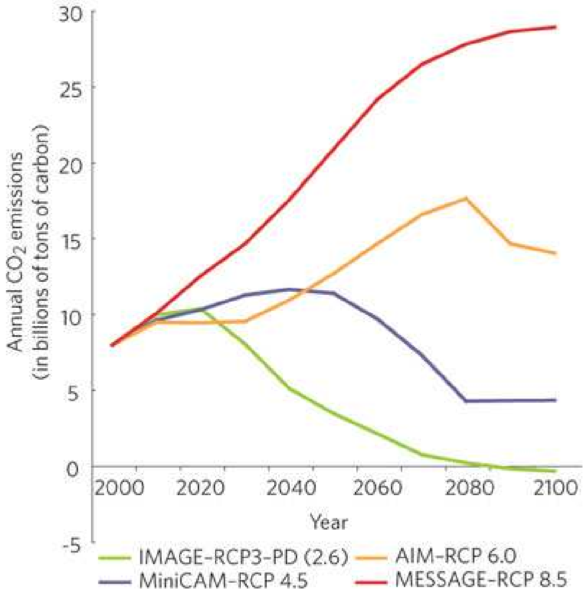

Figure 9: Annual CO_2 equivalent emissions "representative concentration pathways" scenarios to be used in the IPCC AR5 global climate model simulations for future climate projections (Source: Moss, Edmonds et al. 2010)

Greenhouse gas emissions

Regardless of efforts to reduce greenhouse gas emissions in the future, much of the climate change over the coming years will be the result of greenhouse gases already in the atmosphere – "committed warming" (IPCC 2007). It is likely that the earth is now committed to at least 2.4°C of warming above pre-industrial levels since the concentration of greenhouse gas emissions has exceeded the 450 ppm level and it is likely there will be future reductions of aerosols from Asia (Ramanathan and Feng 2008). Carbon dioxide remains in the atmosphere for many centuries and so despite the best efforts to reduce future emissions the planet will continue to warm into the future because of a lag in the climate system. Greenhouse gas concentrations of 650 ppm (likely without the severe and prompt emissions reductions required) will likely see global temperatures soar over 4°C (Nature Reports - Climate Change 2009).

Temperature

The AR4 predicted mean global temperature to increase by 1.1 to 6.4°C over the 1990 – 2100 period (IPCC 2007), although if greenhouse gas emissions continue at the high end of the scale the increase in global temperature may be as much as 7.0°C (Allison, Bindoff et al. 2009). Globally averaged sea surface temperatures are also expected to increase with a trend towards more 'El Niño like' conditions (IPCC 2007), although, changes to the frequency and intensity of these El Niño events is still unclear. It is highly likely that hot days and heat waves will become more frequent with greatest increases over land areas where soil moisture decreases will occur. Cold events and frosts are likely to decrease in frequency (IPCC 2007).

An increase in average annual temperature of between 0.6°C and 2.0°C by 2030 and 1.0°C and 5°C by 2070 is predicted for South Australia. Spatial patterns of warming are expected to be consistent with current observations – greater warming inland and less along the coastal strip (Figure 10).

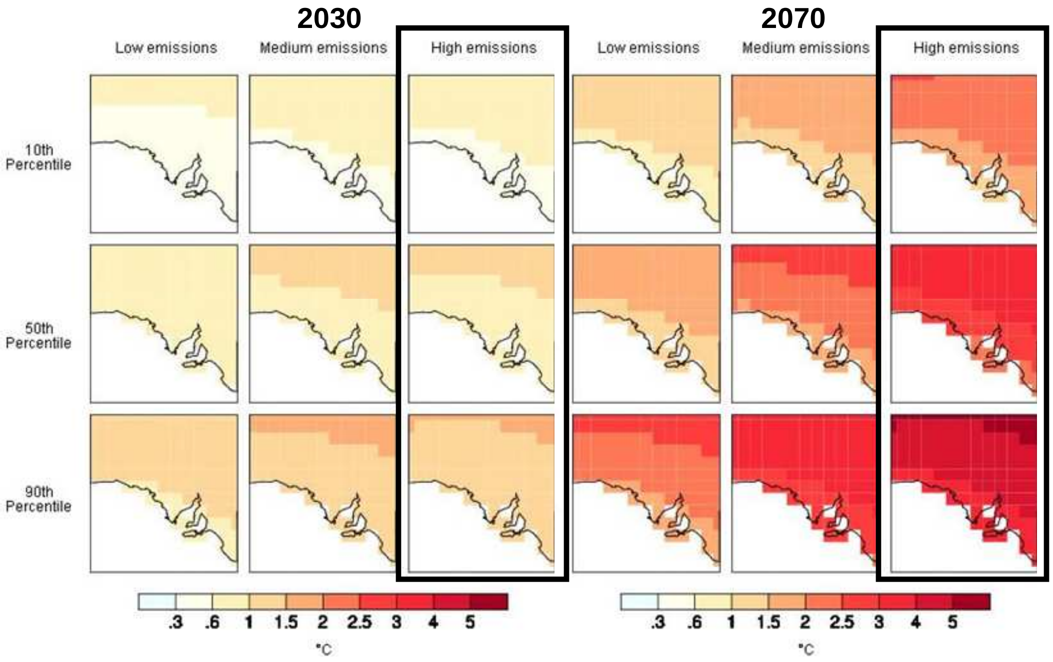

Figure 10: Expected range of changes to annual temperature (°C) for South Australia as predicted by a suite of Global Climate Models under low medium and high greenhouse gas emissions scenarios for the year 2030 (left) and 2070 (right) (Source: Bureau of Meteorology 2009). The median change across all models is shown in the 50th percentile row.

Rainfall

Globally averaged atmospheric water vapour, evaporation and precipitation are all projected to increase under climate change. Increases in rainfall are very likely in the tropics, while decreases are likely in most subtropical land regions (IPCC 2007).

The majority of models predict a future that is drier for southern Australia than was experienced from 1900 to 2000 (Garnaut 2011). The increase in the number of both El Nino events and positive IOD events over the past decades are thought to be a result of global warming and each results in drier conditions across eastern and southern Australia (Cai 2011). Climate projections for the South Australian region indicate that annual rainfall is expected to change by -20% to +10% by 2030 and by –60% to +20% by 2070 (Figure 11) (Bureau of Meteorology 2009). However, recent CSIRO and Bureau of Meteorology model projections show with a very high level of confidence (up to 90%) that there will be a drop in winter rainfall across Victoria and southern South Australia (Steffen 2009).

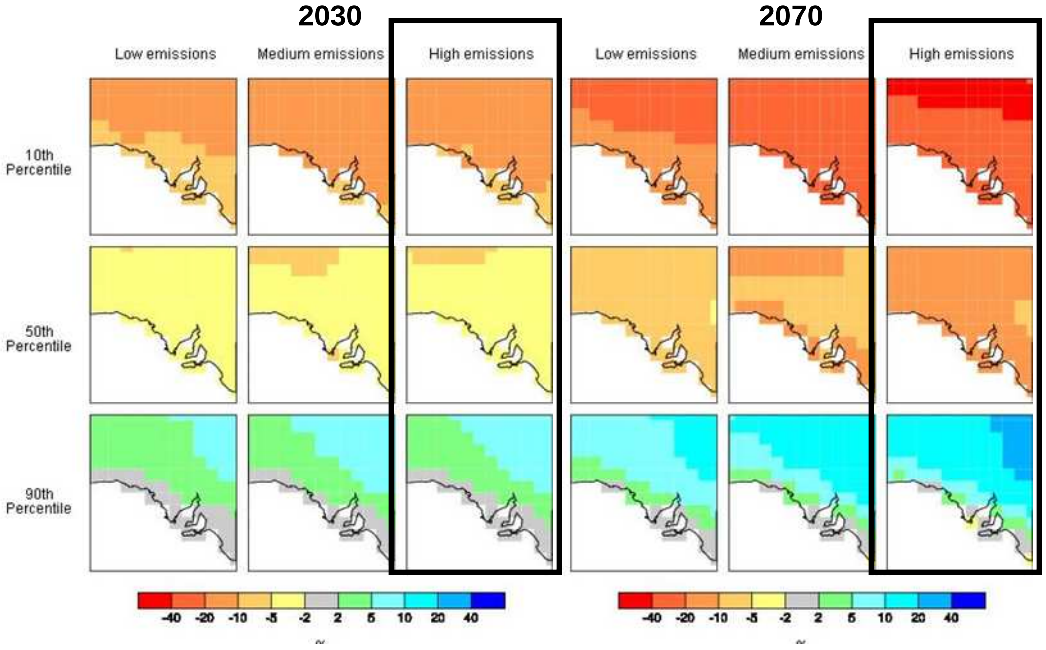

Figure 11: Expected range of changes to annual rainfall (% change) for South Australia as predicted by a suite of Global Climate Models under low, medium and high emissions scenario for the year 2030 (left) and 2070 (right) (Source: Bureau of Meteorology 2009). The median change across all models is shown in the 50th percentile row.

Available water

Most studies agree that increased temperatures will lead to hotter and drier droughts across Australia even if rainfall totals remain largely unaffected (Nicholls 2003). Exceptionally dry years are likely to occur more often and over larger areas, especially in the south and southwest of the country (Garnaut 2011). However, some researchers propose that evaporation will decrease as the humidity increases (Roderick and Farquhar 2004). Regardless to changes in evaporation, the level of evapotranspiration (the combination of evaporation from soils and transpiration from plants) is likely to increase across South Australia under most climate change scenarios (Bureau of Meteorology 2009). Available surface water is likely to be reduced, particularly in south-eastern Australia where declines may be as much as 13% by 2030 (Garnaut 2011).

Ocean changes

The AR4 projections for global sea level rise were between 0.20 and 0.59 m by 2090 – 2099 across the range of climate scenarios (IPCC 2007). These estimates included thermal expansion from oceans and freshwater contributions from glaciers, Greenland and Antarctica, but did not include uncertainties pertaining to changes in ice sheet flow. It has been estimated that if the West Antarctic Ice Sheet were to collapse (i.e. the currently grounded ice), sea levels could be expected to rise by between 4 – 6 m (Oppenheimer 1998). Research since AR4 suggests that there is now a “considerable body of evidence now that points toward a sea level rise of 0.5 – 1.0 m by 2100” and that “sea level rise… towards 1.5 m cannot be ruled out” (Steffen 2009). There is certainly no credible research that predicts sea levels to be less than that predicted in the AR4 (Garnaut 2011).

It should be noted that even moderate increases in sea level rise can result in extreme sea level events associated with high tides and storm surges to occur hundreds of times more frequently than they currently do. As an example, an event that now occurs once every 100 years could be expected to occur two or three times *every* year by the end of the century (Steffen 2009). In Australia more than 85% of the population lives in coastal regions and so the impacts of sea level rise may be significant (Garnaut 2011).

Business as usual trajectories of greenhouse gas emissions and associated increases in ocean acidification and warming are likely to “overwhelm even the most resilient of reefs sometime in the second half of the century” (Hoegh-Guldberg, Mumby et al. 2007) and hinder the production of shells for invertebrates. It is now predicted that by 2050 that ocean acidity could increase by 150% (Garnaut 2011). Reductions in dissolved oxygen levels will cause severe difficulties for many species.

Extreme events

As has been the trend since 1970, the number of extreme hot days is likely to increase under climate change. Projections indicate that by 2030 in Adelaide there will be several more days/year above 35^{o}C and that by the year 2070 under a high greenhouse gas emissions scenario there may be twice as many extreme hot days as are experienced now (Bureau of Meteorology 2009). Cold events and frost will decrease in a warmer world (Garnaut 2011).

Rainfall intensity across Australia is expected to increase generally, particularly in tropical areas. For South Australia, global climate models suggest an increase of 1 to 2% in autumn by 2050 and only small changes in the return periods of such rainfall events in the Adelaide region. Slight *decreases* are possible in other seasons, a trend that has been observed already in southern South Australia (Darren Ray, Climatologist, Bureau of Meteorology South Australia, *pers. comm*. March 2011). There are likely to be fewer severe wind events.

It is expected that the number of tropical cyclones in a warmer world will decrease but those that do affect the Australian region are likely to be more intense, and produce more rainfall and stronger winds (Knutson 2011). The range of tropical cyclones is expected to extend further south (Lavender and Walsh 2011).

Bushfire

For the high greenhouse gas emissions scenarios, the number of “very high” fire days (when the FFDI>25) are expected to increase by between 20 – 100% by 2050 and the number of “extreme” fire days (when the FFDI>50) is expected to increase by 100 – 300%. In addition, it is expected that fire seasons will start earlier, end later and be “generally more intense throughout their length”. In some regions (e.g. the interior of New South Wales), recent jumps in the number of very high and extreme fire danger days have already exceeded these projections – either a result of decadal variability in climate or because of conservative modelling or projections (Lucas, Hennessy et al. 2007). The link between positive cycles of the IOD and resultant drought conditions and increased bushfire events across southern Australia is also likely to increase the frequency of intense fire conditions in these areas (Cowan and Cai 2011).

Unknowns

As greenhouse gas emissions continue to increase, the impact of exceeding various “tipping points” such as the melting of Arctic summer ice, the Himalayan glaciers and Greenland icesheet, collapse of the Amazon rainforest and change to grass dominant ecosystem or changes to ENSO and the ocean circulations (which would have far reaching impacts on climate globally), are now a serious concern (Ramanathan and Feng 2008). The likely temperatures at which each of these tipping points may occur, and the current range of committed warming as calculated in 2005, are shown in Figure 12.

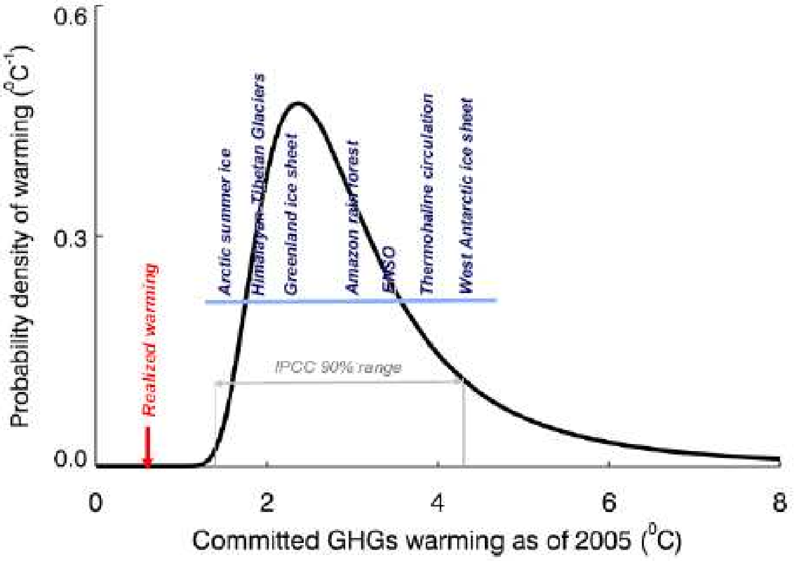

Figure 12: Likely global "tipping points" in response to global temperature increases. The black line shows the probability that we have already exceeded the temperatures on the x-axis as calculated in 2005 (Source: Ramanathan and Feng 2008).

Research continues to determine how and when these tipping points occur. In many cases tipping points lead to a "positive feedback loop", in other words, the change that occurs after the tipping point increases the warming of the planet. For example, severe drought in the Amazon Basin rainforest in 2005 released an estimated five billion tonnes of carbon dioxide as trees died and rotted (Garnaut 2011) and over 1,700 billion tonnes of carbon is currently stored in permafrost (about twice the amount in the atmosphere at present) and so is at risk of melting over the coming centuries (Garnaut 2011). The melting of ice caps and glaciers would reveal darker substrates (water or soil) that increases the albedo of the ocean/land and further heats the planet by absorbing more heat, collapse of the Amazonian rainforest would release significantly more amounts of CO_2 currently locked in the forest, and melting of the tundra regions would release these massive volumes of methane that are currently frozen. If any of these events occurs it is likely that regardless of human reductions in greenhouse emissions, it will be virtually impossible to prevent severe and prolonged climate change - halted only when the earth's natural balance is restored (e.g. when the planet becomes ice free).

The Copenhagen Accord signed by member states of the United Nations Convention on Climate Change in 2010 agreed that deep cuts in global greenhouse gas emissions were required to "reduce global emissions so as to hold the increase in global temperature below two degrees celsius" (United Nations Framework Convention on Climate Change 2010). However, it is now proposed that a 2^{o}C global temperature increase marks the boundary between "dangerous climate change" and "extremely dangerous climate change" and that "temperature changes above 2^{o}C will be difficult for contemporary societies to cope with, and are likely to cause major societal and environmental disruptions throughout the rest of the century and beyond (Garnaut 2011). As global greenhouse gas emissions have already exceeded the 450 ppm level and will likely result in global temperature increases of at least 2^{o}C, it is now essential that emissions reductions strategies are promptly and strongly implemented as soon as possible.

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